Economic Evaluation of CO$_2$ Storage and Sink Enhancement Options

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REPORT SUMMARY

This project developed life-cycle costs for the major technologies and practices under development for CO_2 storage and sink enhancement. The technologies evaluated included options for storing captured CO_2 in active oil reservoirs, depleted oil and gas reservoirs, deep aquifers, coal beds, and oceans, as well as the enhancement of the carbon sequestration in forests and croplands. The capture costs for a nominal 500 MW_e integrated gasification combined cycle plant from an earlier study were combined with the storage costs from this study to allow comparison among capture and storage approaches as well as sink enhancements.

Background

In order to plan for potential CO_2 mitigation mandates, energy companies need better cost information on CO_2 mitigation options, especially storage and sink enhancement options that involve non-energy company operations. One of the major difficulties in evaluating CO_2 storage and sink enhancement options is obtaining consistent, transparent, accurate, and comparable economics.

Objective

To develop consistent, transparent, accurate, and comparable economics of direct and indirect sequestration of CO_2 to allow comparison between alternatives.

Approach

An international group of experts developed economic premises and cost evaluations to allow the comparison of a wide range of CO_2 sequestration options. The project team calculated material balances, developed equipment lists and prices, and estimated installation costs. Economic evaluations for this project were estimated to ±25 to 30 percent, with the ability to modify values to be relatively site-specific. The economics of sequestration in this project are consistent with economics of advanced power generation with CO_2 capture EPRI is developing for DOE. The economic framework also includes life cycle analysis for the various sequestration options— all greenhouse gas emissions from cradle to grave were estimated and considered in the analysis. The economic analysis used spreadsheet models that are flexible enough to allow a wide variation in the range of parameters to be evaluated and the sensitivity cases to be run. The carbon equivalent (CE) life-cycle greenhouse gas (LC GHG) emissions avoided by the capture and storage options assume CO_2 capture and injection into storage reservoirs during the 20-year book life of the capture and storage plants and storage of injected CO_2 for another 80 years.

Results

Costs for the base cases ranged from $-43 to 39/tonne of CO_2 equivalent LC GHG avoided. The forestry options are the least expensive except for the U.S. Pine case. Several forestry options would generate a positive return on investment. Next least expensive are the active oil reservoir and coalbed options followed by most of the cropland options. The other capture and storage options tend to be more expensive.

Base-case forest and cropland areas required to offset LC GHG emissions avoided by base-case CO_2 capture and storage are generally ten times more for cropland than forest land.

EPRI Perspective

Making these comparisons was a challenge due to the differences between direct and indirect cases. The resulting numbers should only be used as a relative indication of cost. Site-specific characteristics could significantly change the outcome of the comparisons. In this study, the forestry options are very attractive along with capture using active oil reservoirs for storage. Other factors, such as land availability and storage option location and capacity will also play a significant part in which options make the most sense at a given site.

The current work should be considered only a starting point. Better cost information and improvements to processes are likely to be developed and need to be incorporated into updates of this information. In addition, there are plans to update and add to portions of the current work to answer questions that arose but were beyond the scope of the current effort. For example, what happens to the costs if the power plant operates for longer than the plant book life? Also, how do the economics look for other power generation options? These and other questions will be evaluated in updates to this work.

Keywords

Carbon dioxide
Sequestration
CO_2 capture and storage
CO_2 sink enhancement

ACKNOWLEDGMENTS

EXECUTIVE SUMMARY

Introduction

In order to plan for potential CO_2 mitigation mandates, energy companies need better information on the costs of alternative CO_2 mitigation options, especially storage and sink enhancement options that involve non-energy company operations. One of the major difficulties in evaluating CO_2 storage and sink enhancement options is obtaining consistent, transparent, accurate, and comparable economics. This project compares the economics of major technologies and practices under development for CO_2 storage and sink enhancement, including options for storing captured CO_2, such as active oil reservoirs, depleted oil and gas reservoirs, deep aquifers, coal beds, and oceans, as well as the enhancement of biological sinks such as forests and croplands.

The primary funding source for the project was the Department of Energy (DOE). The Tennessee Valley Authority (TVA) and the Electric Power Research Institute (EPRI) also provided additional funds. An international group of experts was assembled to develop the technology/ practice designs, the economic premises, and cost evaluations. TVA was the prime contractor for this project, responsible for overall completion of the effort. EPRI organized efforts to select specific sequestration processes to be evaluated for captured CO_2 and coordinated the efforts of consultants from MIT, SFA Pacific, and the IEA Greenhouse Gas Programme to develop and refine the framework for the economic evaluations. MIT and Parsons Infrastructure and Technology developed process designs for captured CO_2 storage processes and helped TVA develop economic models for comparing technologies and practices. The University of Tennessee Agricultural Policy Research Center, in collaboration with TVA, evaluated the economics of enhancing CO_2 sequestration in croplands. The IEA Greenhouse Gas Programme and the Edinburgh Centre for Carbon Management (ECCM) developed the concept design for evaluating the forest sequestration options.

Economic Framework

Most of the cost comparisons to date have concentrated on CO_2 capture, with the assumption that CO_2 sequestration is a small part of these costs. In addition, these comparisons have used information supplied from studies of specific technologies, and the variability in costs due to variability in assumptions and lack of visibility into assumptions lessens the usefulness of the results. In the case of sequestration, virtually no comparative economic evaluations of processes have been done.

Methodologies for developing economic comparisons are generally available. They range from very detailed ±10 percent for site-specific evaluations, where final decisions are made between

options, to very general economics with little insight into the economic premises that were used to develop the economics. The latter is usually a simplification of more detailed economics for very high-level comparisons. In some cases, probability analyses are included to help evaluate risks. This usually adds significantly to the complexity of the model and the time to develop results. The model may use simplified economics to allow probability analysis without making the model too complex to run in a reasonable time.

The economic evaluations developed for this project are between the ranges described above and are typical of prior EPRI economics where a ±25 to 30 percent estimate is made, with the ability to modify values to be relatively site-specific. Material balances are made, equipment lists and pricing are developed, and installation costs are estimated. These types of evaluations are intended to be transparent, consistent, and comparable. They are consistent with the EPRI economics of advanced power generation with CO_2 capture being developed for DOE. Probability analysis was not included to keep the results consistent with other EPRI studies.

The economic framework also included life cycle analysis for the various sequestration options. This means that all greenhouse gas emissions from cradle to grave were estimated and considered in the analysis. The economic analysis used spreadsheet models that are flexible enough to allow a wide variation in the range of parameters to be evaluated and the sensitivity cases to be run. The CO_2 storage options were sized to accommodate the CO_2 from our base case capture plant (see the design basis in the CO_2 capture, transport and storage section). In addition, the amount of forest and cropland required to sequester the same amount of CO_2 over a 100-year planning horizon was calculated.

Concepts Evaluated

The potential processes and concepts to be evaluated were initially prioritized, and the concepts were placed into three categories—(1) included, (2) may be included but more information is needed before a final decision can be made, and (3) not included due to the lack of good information at this time. Because one of the most unique aspects of this work is the comparison between storage of captured CO_2 and sink enhancement, it was felt that at least one of each type should be included. The list of concepts and their final status is presented in Table ES-1.

Table ES-1
Concepts status

Included	Not Included
Aquifers	Ocean Fertilization
Oil Reservoirs	Mineralization
Depleted Oil and Gas Reservoirs	
Ocean Storage	
Forests	
Croplands	
Coal Beds	

In the case of ocean fertilization and mineralization, it is felt that at this time there is not enough reasonable information to develop a meaningful concept description and that these processes should not be included until more R&D is performed.

The following three sections cover the results of the cases for (1) CO_2 capture, transport and storage, (2) forestry, and (3) croplands. The last section presents the comparisons between cases.

CO_2 Capture, Transport and Storage

Overview

This section summarizes the basis of design, methodology, and results for calculating the costs for transport and storage of captured CO_2. Additional details and background information are contained in Chapters 3-9. At the end of this section, the capture costs from the DOE/EPRI study referenced in the next section are combined to get the capture, transport and storage costs.

In conjunction with overland transport via pipeline, the following storage options were evaluated:

- Enhanced oil recovery
- Enhanced coalbed methane recovery
- Depleted oil reservoir storage
- Depleted gas reservoir storage
- Deep saline aquifer storage
- Ocean storage via pipeline
- Ocean storage via tanker

For each option, a baseline conceptual design was generated. From the baseline conceptual design, capital and O&M costs, and an economic analysis with several figures of merits were developed in a spreadsheet format. These were then used to develop sensitivity analyses and life cycle analyses, again in a spreadsheet format.

Design Basis

A nominal 500 MW_e gross integrated gasification combined cycle (IGCC) plant operating at an 80 percent capacity factor was utilized as the production source of CO_2. This was based on the DOE/EPRI's recent study on the "Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal"[1]. Table ES-2 shows a summary of the parameters used in this study taken from the DOE/EPRI report for Case 3a, "IGCC with CO_2 Removal".

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[1] "Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal," EPRI Report No. 1000316, Interim Report, December 2000, Cosponsors: U.S. Department of Energy/Office of Fossil Energy and U.S. Department of Energy/NETL, EPRI Project Manager N. A. H. Holt.

Table ES-2
Summary of parameters for IGCC power plant with CO$_2$ removal

Parameter	Unit	Value
Thermal Input, HHV	10^6 Btu/h	3,723
Gross Power Output	MW	490.4
Net Power Output	MW	403.5
Efficiency, HHV	%	37.0
Capacity Factor	%	80
CO$_2$ Captured	t/d	7,389
	million scm/d	3.76
CO$_2$ Emitted	kg/kWh	0.073
CO$_2$ Avoided in Capture	t/d	6,246
CO$_2$ Capture Cost	$/t captured	14.55
CO$_2$ Capture Cost	$/t avoided in capture	17.21
Plant Life	y	20
Capital Charge Factor	%	15.0
Fuel Cost	$/GJ	1.18
Fuel Real Esc. Rate	%/y	0.00
Fuel Levelization Factor		1.00
TPC	$/kW	1,642
Fixed O&M	$/kW-y	32.98
Variable O&M	$/MWh	3.90
Heat Rate, HHV	kJ/kWh	9,727
Capital	$/MWh	35.04
O&M	$/MWh	8.61
Fuel	$/MWh	11.44
LCOE	$/MWh	55.08

10^{6}Btu = 1.06 GJ

In the case of the ocean storage options, it is assumed that three IGCC power plants supply CO$_2$ to a shoreline collection point. It was felt that this provided a more realistic evaluation for this option. Based on this, the ocean storage systems need to be designed to handle three times the quantity of CO$_2$, i.e. 11.29 million scm (22,167 tonnes), as opposed to 3.76 million scm (7,389 tonnes), of CO$_2$ per day.

A pipeline specification of (152 bar, -40ºC dewpoint, $N_2 < 300$ ppmv, $O_2 < 40$ ppmv, $Ar < 10$ ppmv) was used for the quality of the CO_2. The DOE/EPRI study is consistent with this except for the CO_2 pressure. The DOE/EPRI study was based on compressing the CO_2 to 83 bar. This study includes additional compression to 152 bar.

Methodology

Pipeline Transport

The pipeline inlet CO_2 pressure is set equal to 152 bar, which is equivalent to the pressure of the CO_2 supplied by the base case IGCC plant. Based on a recommendation that the pipeline CO_2 pressure not be allowed to fall below 103 bar, this latter value is used for the pipeline outlet CO_2 pressure. The maximum allowable pressure drop per unit length ($\bullet P / \bullet L$) is found as the difference between the pipeline inlet and outlet CO_2 pressures divided by the pipeline length. The pipeline diameter is then calculated using the equations for pressure drop and head loss due to frictional resistance in a pipe, assuming turbulent flow.

Land construction cost data for natural gas pipelines was used to estimate construction costs for CO_2 pipelines. The cost data found for natural gas pipelines consists of cost estimates filed with the United States' Federal Energy Regulatory Commission (FERC), and reported in the Oil and Gas Journal. A regression analysis on this data yields a pipeline construction cost of $20,989/in/km ($33,853/in/mile). O&M costs are estimated to be $3,100/km ($5,000/mile), independent of pipeline diameter.

The total annual cost per tonne of CO_2 is found by annualizing the construction cost using a capital charge rate of 15% per year and adding this to the annual O&M cost. Figure ES-1 shows the cost per tonne of CO_2 per 100 km as a function of CO_2 mass flow rate. Economies of scale are reached with annual CO_2 flow rates in excess of 10 million tonnes per year. At these rates, transport costs are less than $1 per tonne of CO_2 per 100 km. Note that the annual flows evaluated in this study, corresponding to the IGCC plant described above, are 2.16 million tonnes per year (7,389 tonnes per day with an 80% capacity factor).

Total Annual Cost
Construction and O&M
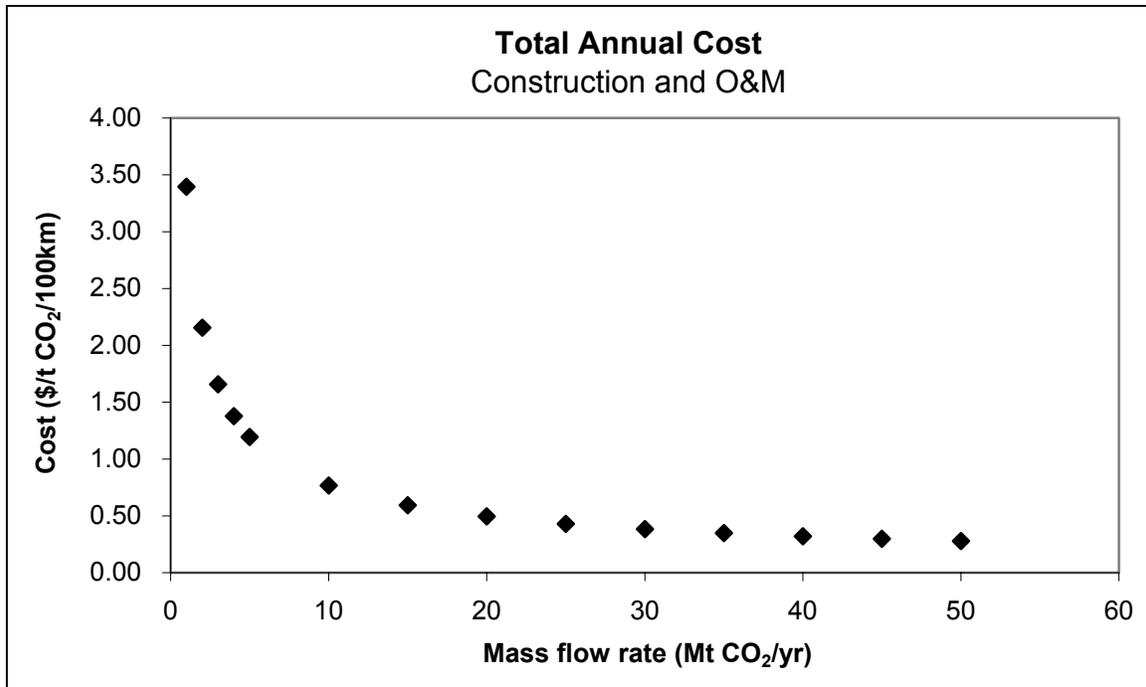
Figure ES-1
Cost for CO₂ transport via pipeline as a function of CO₂ mass flow rate

Note that these costs are not on a CO_2 equivalent life cycle greenhouse gas basis. This information was developed using an MIT pipeline model. Transport values used for the rest of the transport and storage cases are on an equivalent life cycle greenhouse gas basis.

Enhanced Oil Recovery

For specific projects, the complex interactions between the injected CO_2 and reservoir oil would be modeled to assess the likely performance of a proposed CO_2-EOR project. Based on the output of this modeling, the cost of the proposed CO_2 flood is calculated. However, for our purposes of developing general costing algorithms, 'rules of thumb' are used to define the engineering parameters needed to estimate the cost of a CO_2-EOR project. These 'rules of thumb' have been derived based on information from experts in the field and the literature.

The method used for costing the EOR process can be split up into a number of steps. The illustration presented here uses numbers from our base case (see Table ES-3). First, the average amount of enhanced oil produced per day for the given CO_2 mass flow rate is determined using a CO_2 effectiveness factor of 170 standard cubic meters (6,000 standard cubic feet) of new CO_2 per bbl of enhanced oil. Second, the number of production wells is found by dividing this total amount of enhanced oil produced per day by an assumed average of 40 bbl of enhanced oil per day being produced at each well. Third, a ratio of producers to injectors of 1 to 1.1 is used to calculate the number of injection wells from the number of production wells. Fourth, the capital cost of the CO_2 recycle plant is determined based on a maximum CO_2 recycle ratio of 3, with an average recycle ratio of 1.1 being used for the plant's O&M costs. Finally, the capital and O&M costs associated with the wells and the field equipment are calculated.

The EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations'[2] report was used as the basis for field equipment and production operations costs. Costs and indices for additional secondary oil recovery equipment and its operation were provided for a representative lease, located in west Texas. This lease, or module, comprises 10 production wells, 11 water injection wells and 1 disposal well, and the wells are nominally 4,000 feet, or 1,219 m, deep.

Table ES-3 below defines three cases, a base case, a high cost case, and a low cost case. We analysed typical EOR operating data to determine a base case and range for each critical variable. These values were then used to define the cases described in Table ES-3. Costs for EOR and the other CO_2 storage options assessed in this project were calculated on a CO_2 equivalent life-cycle (LC) GHG avoided basis as described in Chapter 2.

Table ES-3
EOR case descriptions and costing results

Parameter	Units	EOR Base Case	EOR High Cost Case	EOR Low Cost Case
CO₂ Effectiveness	scm/bbl enhanced oil	170	227	85
Oil Production per Well	bbl enhanced oil/d/well	40	20	70
Maximum Recycle Ratio		3	4	1
Oil Price	$/bbl	15	12	20
Depth	m	1,219	2,438	610
Pipeline Distance	km	100	300	0
Previous Waterflooding		Yes	No	Yes
Total Oil Production*	bbl enhanced oil/d	22,142	16,582	44,285
Number of 10/11 Well Modules*		56	83	64
New CO₂*	scm/day/module	68,000	45,000	59,000
Maximum Recycled CO₂*	scm/day/module	204,000	182,000	59,000
Levelized Annual CO₂ Net Storage Cost*	$/tonne CO₂ eq. LC GHG avoided	(12.21)	73.84	(91.26)

* calculated

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[2] Energy Information Administration (Office of Oil and Gas), "Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations," [Online document], Mar. 2000, [cited Jan. 2002], Available HTTP:

http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/cost_indices/c_i.html

Enhanced Coalbed Methane Recovery

As in the case of the CO_2-EOR concept design, 'rules of thumb' are used to define the engineering parameters needed to estimate the cost of a CO_2-ECBMR project. The illustration presented here uses numbers from our base case (see Table ES-4). First, the total amount of enhanced CBM produced per day for the given CO_2 mass flow rate is determined using a CO_2 effectiveness factor of two scm CO_2 per scm of enhanced CBM. Second, the number of production wells is found by dividing this total amount of enhanced CBM produced per day by an assumed 14,000 scm of enhanced CBM per day being produced at each well. Third, a ratio of producers to injectors of 1 to 1 is used to calculate the number of injection wells from the number of production wells. Fourth, it is assumed that no recycling of CO_2 is required. Finally, the cost of drilling and equipping the required production and injection wells is calculated.

Prior to acquiring a lease position, geological expenditures, geophysical expenditures, and engineering-based feasibility studies are often conducted. In addition, outlays are generally required for obtaining the lease and its associated permits. These front-end costs will vary greatly but may range from $20,000 to $30,000 per well for a commercial project. For this study, a cost of $25,000 per well is assumed.

All of the other field costs, except for the well drilling cost, are based on data contained in the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report. A representative ECBMR lease, or module, comprising 10 CO_2 injection wells and 10 producing wells with dewatering facilities is used for the design basis. The 10 CO_2 injection wells are drilled to a depth of 610 m and equipped with a battery of lease equipment, which includes distribution lines, headers, electrical service, and controls. The 10 producing wells, also drilled to a depth of 610 m, are equipped with beam balanced/sucker rod dewatering.

The well drilling cost is calculated based on a relationship derived from data contained in the '1998 Joint Association Survey (JAS) on Drilling Costs' report.[3] This relationship between well depth and drilling cost is shown in Figure ES-2. To determine the relationship, regression analysis was performed on drilling cost data for onshore gas and oil wells. The total well drilling cost is found by multiplying the cost of drilling a single well for the given reservoir depth, taken from the graph, by the required number of wells.

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[3] American Petroleum Institute – Policy Analysis and Statistics Department, "1998 Joint Association Survey on Drilling Costs," [Online document], Nov. 1999, Available HTTP:

http://www.api.org/axs-api/products/joint.htm

Well Drilling Cost as a Function of Depth
1998 Onshore Gas & Oil Well Data

$$y = 0.0888e^{0.0008x}$$

(Cost ($M) vs. Depth (m))
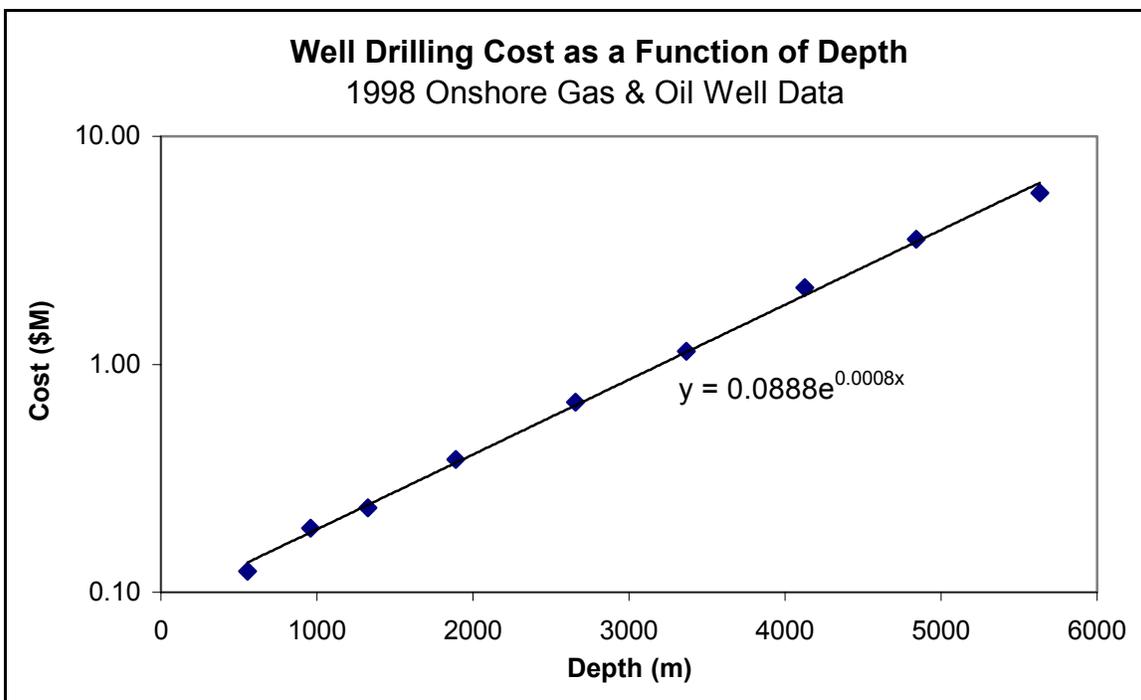
Figure ES-2
Well drilling cost as a function of depth

Table ES-4 defines a base case, a high cost case, and a low cost case derived from an analysis of typical ECBMR operating data.

Table ES-4
ECBMR case descriptions and costing results

Parameter	Units	ECBMR Base Case	ECBMR High Cost Case	ECBMR Low Cost Case
CO$_2$ Effectiveness	scm/scm enhanced CBM	2	10	1.5
CBM Production per Well	scm enhanced CBM/d/well	14,000	3,000	30,000
Gas Price	$/10^6 Btu	2	1.80	3
Depth	m	610	1,219	610
Pipeline Distance	km	100	300	0
Total CBM Production*	million scm enhanced CBM/d	1.88	0.38	2.51
Number of 10/10 Well Modules*		135	126	84
Number of CO$_2$ Wells*		135	126	84
New CO$_2$*	scm/d/well	28,000	30,000	45,000
Levelized Annual CO$_2$ Net Storage Cost*	$/tonne CO$_2$ eq. LC GHG avoided	(5.59)	18.88	(25.72)

* calculated

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Depleted Gas and Oil Reservoir/Aquifer Storage

Depleted natural gas and oil reservoirs, and deep saline aquifers, differ quite substantially from one another in terms of typical values of reservoir parameters such as pressure, thickness, depth, and permeability. The processes that govern the rate at which CO_2 can be injected at a well, and thus the number of wells required, are however essentially identical for the three types of reservoir. Given this, the same costing methodology is applied to each of the three geologic CO_2 storage options.

The cost model for the geologic CO_2 storage options can be broken down into a number of components. First, there is a relationship for calculating the number of wells required for a given CO_2 flow rate, CO_2 downhole injection pressure, and set of reservoir parameters. Second, an iterative procedure is used to take into account the interdependent relationship between CO_2 downhole injection pressure and well number. Third, a set of capital and O&M cost factors are used to determine cost based on well number.

The well number calculation requires inputs for CO_2 mass flow rate, CO_2 downhole injection pressure, and reservoir pressure, thickness, depth, and permeability. The relationship shown in Figure ES-3 is used to determine CO_2 injectivity from CO_2 mobility[4]. CO_2 injectivity is defined as the mass flow rate of CO_2 (m) that can be injected per unit of reservoir thickness (h) and per unit of downhole pressure difference ($P_{inj} - P_{res}$). CO_2 mobility is defined as the CO_2 absolute permeability divided by the CO_2 viscosity. Given the CO_2 injectivity, the CO_2 injection rate per well (Q) can be calculated as

$$Q = CO_2 \text{ injectivity} \times h \times (P_{inj} - P_{res})$$

Finally, the number of wells required (n) is given by

$$n = m/Q$$

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[4] Law, D. and S. Bachu, "Hydrogeological and numerical analysis of CO_2 disposal in deep aquifers in the Alberta sedimentary basin," *Energy Convers. Mgmt.*, 37:6-8, pp. 1167-1174, 1996.

CO$_2$ Injectivity as a Function of CO$_2$ Mobility

$y = 0.0208x$
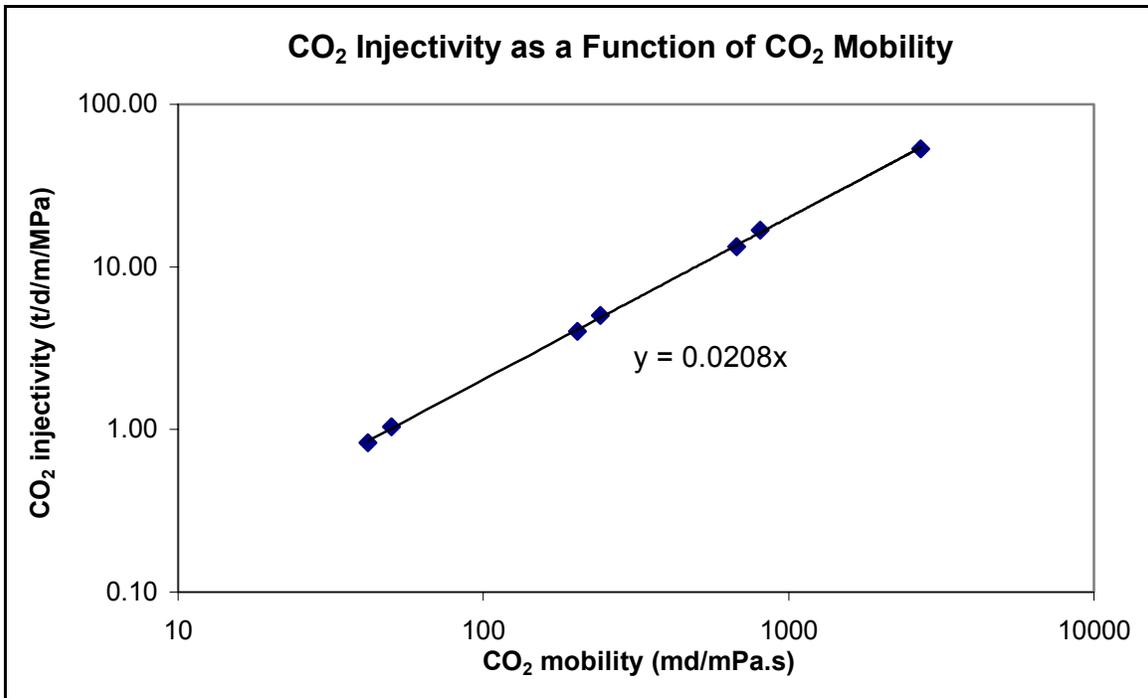
Figure ES-3
CO$_2$ injectivity as a function of CO$_2$ mobility

The capital cost for site screening and evaluation is based on an estimate given in a recent study by the Battelle Memorial Institute.[5] This study estimated the costs for preliminary site screening and candidate evaluation at $1,685,000.

All of the other costs, except for the well drilling cost, are calculated based on values given in the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report. Average lease equipment costs and O&M costs were developed on a per well basis. In the case of the injection equipment and surface maintenance, these average cost values are adjusted to take into account the number of wells. Similarly, the average cost value for subsurface maintenance is adjusted to take into account the well depth. These capital and O&M cost factors/functions are given in Table ES-5.

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[5] Smith, L.A. et al, "Engineering and Economic Assessment of Carbon Dioxide Sequestration in Saline Formations," presented at the First National Conference on Carbon Sequestration, May 14-17, 2001, Washington D.C.

Table ES-5
Capital and O&M cost estimation factors/functions

Parameter	Unit	Value
CAPITAL COSTS		
Injection Equipment (Flowlines & Connections)	$/well	43,600*(7,389/(280*Number_of_wells))^0.5
O&M COSTS		
Normal Daily Expenses	$/well	6,700
Consumables	$/well	17,900
Surface Maintenance (Repair & Services)	$/well	13,600*(7,389/(280*Number_of_wells))^0.5
Subsurface Maintenance (Repair & Services)	$/well	5,000*Well_depth/1219

The well drilling cost is calculated based on the relationship derived from data contained in the '1998 Joint Association Survey (JAS) on Drilling Costs' report.

Table ES-6, Table ES-7, and Table ES-8 define a base case, a high cost case, and a low cost case derived from an analysis of typical data for depleted gas reservoirs, depleted oil reservoirs, and deep, brine aquifers, respectively.

Table ES-6
Depleted Gas Reservoir Case Descriptions and Costing Results

Parameter	Units	Gas Reservoir Base Case	Gas Reservoir High Cost Case	Gas Reservoir Low Cost Case
Pressure	MPa	3.5	6.9	2.1
Thickness	m	31	15	61
Depth	m	1,524	3,048	610
Permeability	md	1	0.8	10
Pipeline Distance	km	100	300	0
Injection Rate per Well*	t/d	156	57	2,975
Number of Wells*		48	129	3
Levelized Annual CO_2 Storage Cost*	$/tonne CO_2 eq. LC GHG avoided	4.87	19.43	1.20

* calculated

Table ES-7
Depleted oil reservoir case descriptions and costing results

Parameter	Units	Oil Reservoir Base Case	Oil Reservoir High Cost Case	Oil Reservoir Low Cost Case
Pressure	MPa	13.8	20.7	3.5
Thickness	m	43	21	61
Depth	m	1,554	2,134	1,524
Permeability	md	5	5	19
Pipeline Distance	km	100	300	0
Injection Rate per Well*	t/d	360	115	5,690
Number of Wells*		21	65	2
Levelized Annual CO_2 Storage Cost*	$/tonne CO_2 eq. LC GHG avoided	3.82	11.16	1.21

* calculated

Table ES-8
Deep, brine aquifer case descriptions and costing results

Parameter	Units	Aquifer Base Case	Aquifer High Cost Case	Aquifer Low Cost Case
Pressure	MPa	8.4	11.8	5.0
Thickness	m	171	42	703
Depth	m	1,239	1,784	694
Permeability	md	22	0.8	585
Pipeline Distance	km	100	300	0
Injection Rate per Well*	t/d	9,363	82	889,495
Number of Wells*		1	91	1
Levelized Annual CO_2 Storage Cost*	$/tonne CO_2 eq. LC GHG avoided	2.93	11.71	1.14

* calculated

Ocean Via Pipeline

The ocean pipeline storage option assumes that three IGCC power plants supply CO_2 to a shoreline collection point. The CO_2 is then transported via a subsea pipeline from the shoreline to a depth of 2,000 m, at which depth the CO_2 is discharged into the deep ocean via a diffuser unit. The method used for calculating the cost of this process can be broken down into two steps.

First, the diameter of the subsea pipeline is determined. It is then possible, as a second step, to calculate the capital and O&M costs as well as the cost per tonne of CO_2.

The pipeline diameter is calculated using the same method as is used in the CO_2 overland pipeline transport model. The only difference is the means by which the maximum allowable pressure drop per unit length ($\bullet P/\bullet L$) is determined. In the case of CO_2 overland pipeline transport, the pressure drop per unit length is simply found as the difference between the pipeline CO_2 inlet and outlet pressures divided by the pipeline length. The pipeline ocean CO_2 storage model however requires that the pressure drop per unit length calculation also take into account the gravity head gain and diffuser head loss. In addition, it is necessary that the CO_2 be discharged at a pressure equal to the hydrostatic pressure.

The cost of the subsea pipeline has been determined based on cost information contained in McDermott's phase II final report on 'Large-scale CO_2 Transportation and Deep Ocean Sequestration.'[6] The capital cost of an injector unit, based on an estimate given in an IEA report,[7] is taken to be $14.5 million. The results are shown in Table ES-9.

Table ES-9
Ocean pipeline storage case descriptions and costing results

Parameter	Units	Ocean Pipeline Base Case	Ocean Pipeline High Cost Case	Ocean Pipeline Low Cost Case
Pipeline Distance	km	100	300	0
Offshore Distance	km	100	300	50
Pressure Drop per Unit Length*	Pa/m	126	42	251
Pipe Diameter*	inches	14.2	17.5	12.4
Nominal Pipe Size*	inches	16	20	14
Levelized Annual CO₂ Storage Cost*	$/tonne CO₂ eq. LC GHG avoided	5.53	14.23	2.90

* calculated, 1 inch = 0.0254 m

[6] Sarv, H., "Large-scale CO_2 transportation and deep ocean sequestration – Phase II final report," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, 2001.

[7] Ormerod, B., "The disposal of carbon dioxide from fossil fuel fired power stations," IEA Greenhouse R&D Programme, Cheltenham. Tech. Rep. IEAGHG/SR3, Jun. 1994.

Ocean Via Tanker

The storage option has been modeled based on design and cost information obtained from McDermott's Phase I and Phase II[8] final reports on 'Large-scale CO_2 Transportation and Deep Ocean Sequestration' as well as e-mail communications with the reports' author. The method used for a conceptual design of this process can be broken down into a number of steps. First, the number of tankers required to transport the CO_2 to the offshore platform is determined. Second, the diameter of the vertical pipe to carry the CO_2 from the platform to the injection depth is calculated. Third, the amount of CO_2 emitted by the tankers travelling to and from the offshore storage site, and emitted due to boil off, is found. It is then possible, as a final step, to calculate the capital cost of the tankers, port facility, offshore floating platform, and vertical pipe, and the non-fuel and fuel O&M costs as well as the cost per tonne of CO_2.

The total capital cost of the tanker ocean CO_2 storage option comprises the capital cost of the three required tankers, the offshore floating platform, the port facility, and a 2,000-m long, 8-inch diameter vertical pipe. The total O&M cost is calculated as the sum of the non-fuel and fuel O&M costs. From e-mail communications with Hamid Sarv of McDermott Technology, Inc., it was learned that the total annual O&M cost in the case studies was taken as the sum of 5.6 percent and 0.02 percent of the total tanker and non-tanker capital costs, respectively, where the fuel cost comprised 16.5 percent of the tanker O&M cost. The non-fuel O&M cost is calculated in the model as 4.7 percent of the total tanker capital cost, thus excluding the fuel cost, plus 0.02 percent of the total non-tanker capital costs. The fuel O&M cost is determined as the product of the total annual fuel usage, found from multiplying the tanker fuel usage by the total annual distance traveled, and a diesel fuel price of $0.566/gal.

The capital and O&M cost estimation factors are summarized in Table ES-10. Table ES-11 defines a base case, a high cost case, and a low cost case for the ocean tanker storage option.

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[8] Sarv, H., "Large-scale CO_2 transportation and deep ocean sequestration," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, Mar. 1999.

Table ES-10
Capital and O&M cost estimation factors for ocean tanker storage

Parameter	Unit	Value
CAPITAL COSTS		
Tanker	$/tanker	55,263,000
Offshore Platform	$	200,000,000
Onshore Port Facility	$	50,000,000
Vertical Pipeline:		
Construction	**$/in/km**	**351,445**
Towing to Offshore Structure	$	300,000
Upending, Securing & Anchoring	$	3,000,000
General Facilities, Engineering, Permitting etc.	$	0.3*(Tanker_capital_cost + Offshore_platform_capital_cost + Onshore_port_facility_capital_cost + Vertical_pipeline_capital_cost)
O&M COSTS		
Non-fuel	$/y	(Tanker_capital_cost*0.047) + ((Offshore_platform_capital_cost + Onshore_port_facility_capital_cost + Vertical_pipeline_capital_cost)*0.02)
Fuel	$/gal	0.566

1 inch = 0.0254 m, 1 gal = 3.79 liters

Table ES-11
Ocean tanker storage case descriptions and costing results

Parameter	Units	Ocean Tanker Base Case	Ocean Tanker High Cost Case	Ocean Tanker Low Cost Case
Pipeline Distance	km	100	300	0
Offshore Distance	km	100	300	50
Boil Off	%/d	1	2	0.5
Diesel Price	$/gal	0.566	0.8	0.45
Number of Tankers*		3	3	3
Total Annual Fuel Usage*	gal/y	249,001	747,004	124,501
CO_2 Emitted by Tankers*	t/y	2,395	7,186	1,198
CO_2 Emitted by Boil Off*	t/y	53,362	139,415	24,638
Levelized Annual CO_2 Storage Cost*	$/tonne CO_2 eq. LC GHG avoided	17.64	22.79	15.76

* calculated
1 gal = 3.79 liters

Summary of Results

Figure ES-4 and Figure ES-5 summarize the results for the cost of the various carbon storage technologies analyzed in this study on a life-cycle greenhouse gas avoided basis. Figure ES-4 includes all the direct storage technologies, while Figure ES-5 expands the scale for storage technologies with no commercial by-products. The points on the graphs are for the base case conditions, while the bars represent the range between the high and low cost cases as outlined in the Tables above.

Several observations about these results are offered below:

- Excluding the more expensive ocean tanker option, the typical base case costs for CO_2 storage (transport + injection) without oil or gas by-product credit is in the range of $3-5.50 per tonne CO_2 ($11-20 per tonne C). The cost range can be characterized as $2-15 per tonne CO_2 ($7-55 per tonne C).

- With a by-product credit for the gas or oil, the credit will offset the storage costs in many instances. For example, in the base EOR case, one can afford to pay $12.21 per tonne of CO_2 and still breakeven (i.e., the costs equal the by-product credit).

- With an oil or gas by-product, the net costs have a large range. The parameters most responsible for this variability are the by-product (i.e., the gas or oil) price and the ratio of CO_2 stored to the oil or gas produced. With more oil or gas produced per unit of CO_2 stored, the lower net CO_2 storage cost, but the less CO_2 stored.

Finally, Table ES-12 combines the capture and compression costs from our base IGCC plant with the transport and injection costs to give a total cost of sequestration on an NPV basis. These costs can be compared with costs of CO_2 sink enhancement via forestry and reducing tillage on cropland.
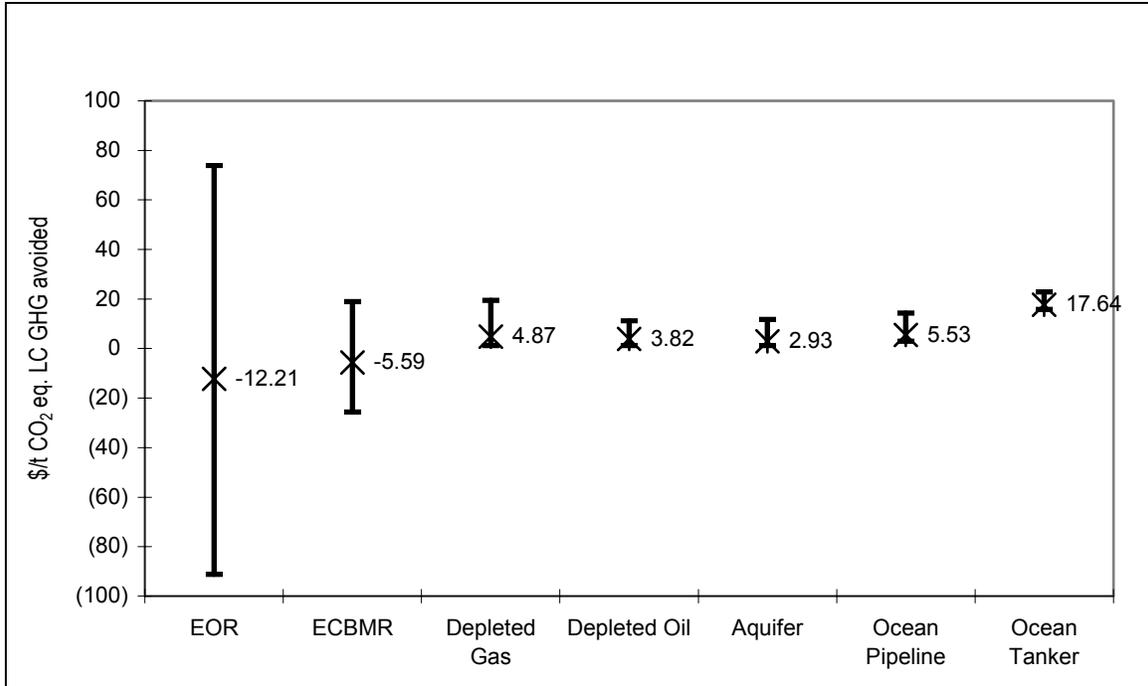
Figure ES-4
**Levelized annual cost comparison of carbon sequestration technologies**
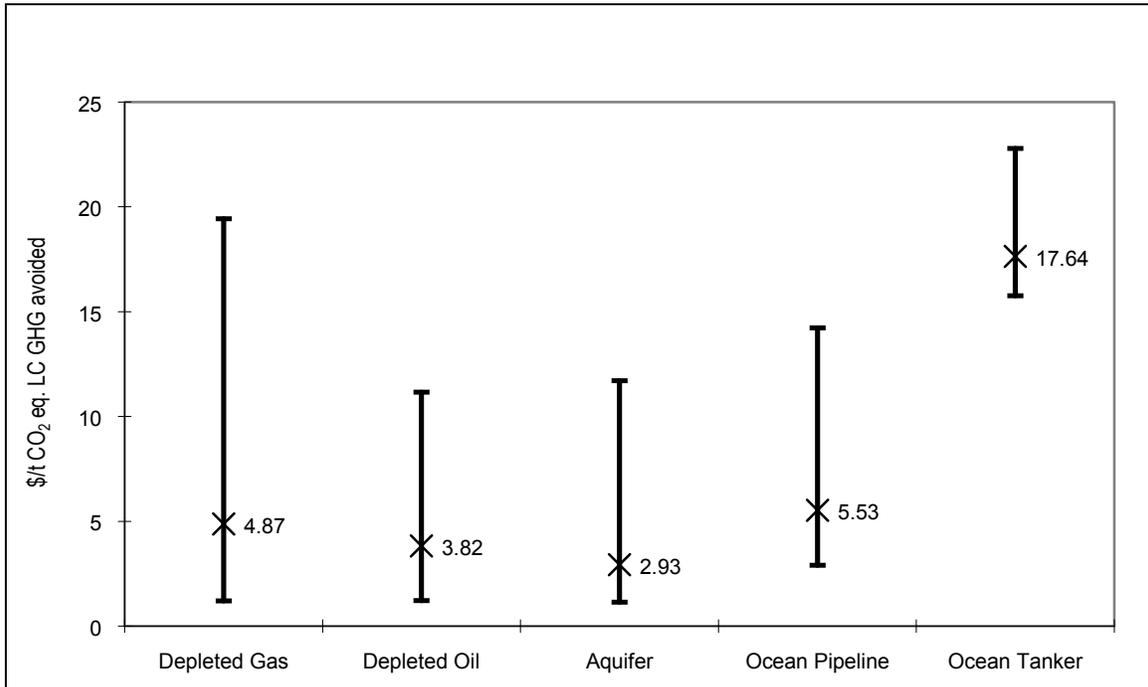
Figure ES-5
Levelized annual cost comparison of carbon sequestration technologies

Table ES-12
CO$_2$ Capture + Net Storage Costs: Base Cases, NPV Basis

CO$_2$ Storage Process	LC GHG avoided	
	$/tonne CO$_2$ eq.	$/tonne C eq.
Enhanced Oil Recovery	4	15
Enhanced Coalbed Methane Recovery	11	41
Depleted Gas Reservoir	23	86
Depleted Oil Reservoir	22	81
Deep Saline Aquifer	21	77
Ocean Pipeline	24	89
Ocean Tanker	39	143

CO$_2$ Sink Enhancement via Improved Forest Management

Basis and Approach

Costs of the CO$_2$ sink enhancement via improved forest management were estimated from an energy company perspective (i.e., the amount an energy company would have to pay forest product companies to manage their systems to sequester additional CO$_2$ to serve as CO$_2$ offsets for the company). From an energy company perspective, the cost of GHG emission offsets ($/tonne C equivalent LC GHG avoided) from forestry options depends on the following: (1) levels of CO$_2$ sink enhancement, (2) changes in GHG emissions other than from CO$_2$ sink enhancement (e.g., from methane and nitrous oxide emissions), (3) reimbursement of forest management companies for net costs of changes in forest land area and/or management, (4) transaction costs for aggregating and brokering GHG credits, and (5) monitoring costs for assuring that contractual obligations are fulfilled.

The same financial parameters were used for forestry options as for CO$_2$ capture and storage options included in this project. The rationale is that we assume that funding for both types of projects would come from an energy company seeking to receive credits for reducing GHG emissions. An energy company likely would use the same financial parameters for evaluating GHG abatement investments regardless of whether the investments involve CO$_2$ capture and storage or CO$_2$ sink enhancement. Costs of GHG mitigation ($/tonne C equivalent LC (life-cycle) GHG avoided) were calculated on an NPV basis with a 100-year planning horizon as described in detail in Chapter 2 and can be compared on an NPV basis with other CO$_2$ storage and sink enhancement options that differ in timing of costs and timing of avoidance of GHG emissions.

Additional C can be sequestered in forests by establishing new plantations, restoring existing forests, or by avoiding deforestation. Cases representing a wide range of management types, trees, and geographic locations were included in this study (Table ES-13). All cases were

assessed assuming medium productivity levels. Where data were available, cases were also assessed, assuming low and high productivity levels.

Table ES-13
Forestry case studies

Type of Management	Type of Trees	Country/region
Plantation	Loblolly pine	USA (South)
Plantation	Douglas Fir	USA (Pacific NW)
Plantation	Spanish Cedar	Mexico
Restoration	Pine-oak	Mexico
Restoration	Miombo	Southern Africa
Agro-forestry	Mango-Tamarind	India (South)
Avoidance of deforestation	Various	Mexico

Summary of Costs

Costs ($/tonne C equivalent) are presented in Figure ES-6 for medium productivity on an aboveground basis (costs/aboveground C) and a C equivalent life-cycle (LC) GHG avoided basis with product revenues (net costs after product revenues/aboveground C + below ground C + product C + non-CO_2 GHG C equivalent). These two accounting bases bracket the costs ($/Mg C equivalent) for each of the cases. The former accounting basis has most commonly been used in the past in order simplify monitoring and verification. The latter accounting basis is comparable with the basis used for CO_2 storage options with revenues (e.g., enhanced oil recovery) and was used to calculate base-case costs. Base-case costs also assumed medium productivity. The Mango-Tamarind costs are relatively high on an aboveground basis because costs for the ago-forestry system are high and no credit is taken for the relatively high value agricultural products. The Mango-Tamarind costs are relatively low on the aboveground C + below ground C + product C + non-CO_2 GHG C equivalent basis because credit is taken for both more C and products that more than offset costs.
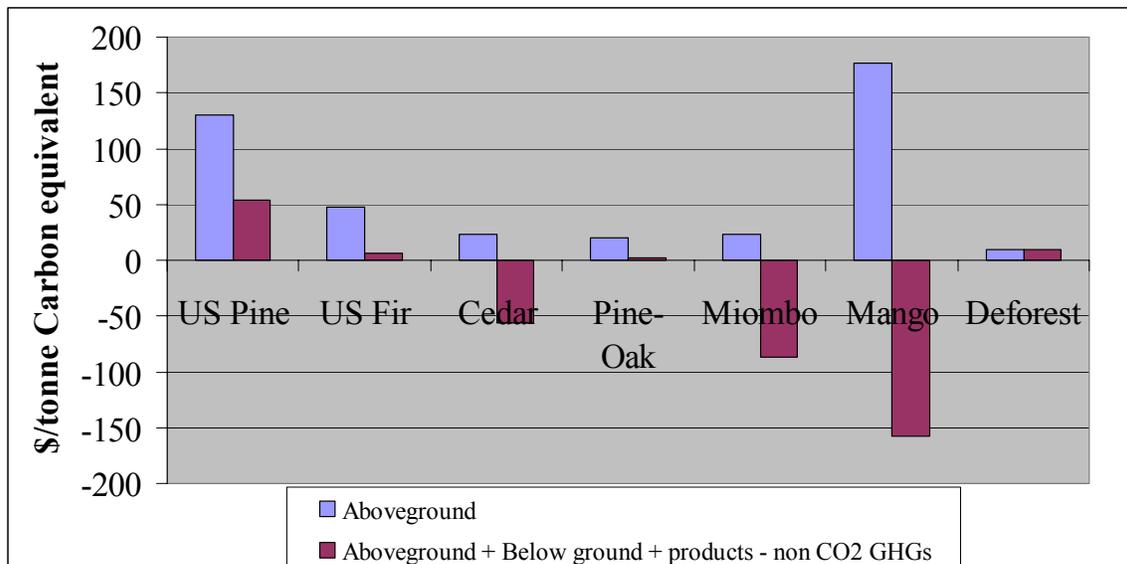
Figure ES-6
Forestry costs for medium productivity levels on two accounting bases

Costs are summarized in Table ES-14 for three productivity levels on both a CO_2 equivalent LC GHG avoided and a C equivalent LC GHG avoided basis.

Table ES-14
Forestry costs for three productivity levels and CO_2 and C bases

Case	Base Case-Medium Productivity	Low Cost Case-High Productivity	High Cost Case-Low Productivity	Base Case-Medium Productivity	Low Cost Case-High Productivity	High Cost Case-Low Productivity
	$/tonne CO_2	$/tonne CO_2	$/tonne CO_2	$/tonne C	$/tonne C	$/tonne C
US Pine	15	11		54	40	
USFir	2	1		7	3	
Cedar	(15)	(14)	(11)	(56)	(51)	(39)
Pine-Oak	1	(1)	2	2	(3)	6
Miombo	(24)			(87)		
Mango	(43)			(158)		
Deforest	3			10		

CO$_2$ Sink Enhancement via Reducing Tillage on U.S. Cropland

Basis and Approach

Reducing tillage on cropland slows the rate of organic matter decomposition and increases soil organic matter levels until a new equilibrium level is attained (typically about 20 to 30 years after shifting from intensive tillage to no tillage). Carbon is sequestered in the added soil organic matter, resulting in an increase in soil organic carbon (SOC). Reducing tillage reduces equipment and fuel use, increases herbicide use, and can affect the amount of nitrogen fertilizer required and N$_2$O emissions from the soil; these factors combined with the added carbon sequestered in soil organic matter determine the life-cycle (LC) GHG emissions avoided by reducing tillage. Effects of reducing tillage on equipment, fuel, herbicide, and nitrogen (N) fertilizer use and on N$_2$O emissions continue as long as the switch to reduced-tillage continues. Costs to an energy company are an adoption incentive to get farmers to switch from intensive tillage to moderate- or no-tillage, transaction costs for aggregating and brokering GHG credits, and monitoring costs for assuring that contractual obligations are met. Costs ($/hectare) divided by the tonnes C equivalent (CE) LC GHG avoided/hectare give the cost in $/tonne CE LC GHG avoided.

The same financial parameters were used for cropland options as for CO$_2$ capture and storage options included in this project. The rationale is that we assume that funding for both types of projects would come from an energy company seeking to receive credits for reducing GHG emissions. An energy company likely would use the same financial parameters for evaluating GHG abatement investments regardless of whether the investments involve CO$_2$ capture and storage or CO$_2$ sink enhancement. Costs of GHG mitigation ($/tonne C equivalent LC (life-cycle) GHG avoided) were calculated on an NPV basis with a 100-year planning horizon as described in detail in Chapter 2 and can be compared on an NPV basis with other CO$_2$ storage and sink enhancement options that differ in timing of costs and timing of avoidance of GHG emissions.

The following regional cropland cases were included in this study, the goal being to both (1) include cases representing the greatest amount of avoided GHG emissions that could be achieved by reducing tillage and (2) illustrate the range of amounts per hectare and costs of avoided GHG emissions that could be achieved by reducing tillage.

1. Chapter 19: Corn/soybean rotations in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N$_2$O emissions.

2. Chapter 20: Continuous corn cropping systems in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N$_2$O emissions.

3. Chapter 21: Wheat/fallow rotations in the western Great Plains being converted from intensive-till to no-till. This case includes variations in the amount of SOC sequestered and amount of N$_2$O emissions due to reducing tillage.

4. Chapter 22: Intensive-till cotton to no-till cotton in the southeastern U.S. This case includes variations in the amount of soil SOC sequestered and amount of N_2O emissions due to reducing tillage.

Summary of Costs

Base-case costs of avoided CO_2 are presented in Table ES-14 for the four regional cropping systems included in this study, assuming that an annual adoption incentive is paid for 5, 10, 15, or 20 years after switching to no-till. These costs are based on the assumption that, due to soil quality and crop yield benefits that develop over time, a farmer would continue the no-till practice after the adoption incentive stops.

Table ES-14
Base-case costs of CO_2 sink enhancement on U.S. cropland: intensive-till to no- till

| | | Continuous corn | | |
	Corn/soybean		Wheat/fallow	Cotton
Incentive period, years	Cost (NPV basis, 100-year planning horizon) $/tonne CE LC GHG avoided			
5	30 (8)[1/]	30 (8)	32 (9)	54 (15)
10	48 (13)	51 (14)	49 (13)	88 (24)
15	62 (17)	66 (18)	61 (17)	113 (31)
20	72 (20)	77 (21)	71 (19)	132 (36)

[1/] Values in parenthesis are $/tonne CO_2 equivalent LC GHG avoided

Inputs used to estimate the base-case costs of CO_2 sink enhancement via reducing tillage on U.S. cropland are presented in Table ES-15. Costs in Table ES-15 assume that an adoption incentive is paid for 20 years.

Costs of CO_2 abatement are similar for corn/soybean rotations and continuous corn because of two offsetting factors. Relative to corn/soybean rotations, switching to no-till continuous corn sequesters nearly twice as much additional carbon in soil organic matter but also requires twice as large an adoption incentive. With continuous corn, more carbon is sequestered in SOC mainly because more crop residues are produced and returned to the soil and a larger adoption incentive is required mainly because corn is less well adapted to no-till than are soybeans.

Costs of CO_2 abatement are similar for corn/soybean rotations and wheat/fallow because of offsetting factors. Relative to corn/soybean rotations, switching to no-till wheat/fallow sequesters less additional carbon in soil organic matter but also requires a smaller adoption incentive and results in a decrease rather than in increase in N_2O emissions.

Table ES-15
Base-case inputs and costs of CO$_2$ sink enhancement on U.S. cropland: intensive-till to no-till

Region	Corn Belt	Corn Belt	Western Great Plains	SE U.S.
Cropping system	Corn/ soybean	Continuous corn	Wheat/ fallow	Cotton
Quadratic SOC response curve				
ΔSOCs, kg C/ha	7221	13104		
E (slope factor)	53.1	92.0		
kg SOC/ha/y			200	300
Years to new steady state (Ys)	27	28	20	20
Average annual increase in SOC (years 1 to Ys), kg C/ha/y				
	267	468	200	300
GHG emissions from tillage-system inputs and N$_2$O (years 1-100), kg CE/ha/y:				
Δ Fuel use	-22.3	-22.9	-10.3	-23.8
Δ Machinery maint., trans., and repair	-4	-4	-1.9	-4.3
Δ N fertilizer use	0	0	0	0
Δ Herbicide use	3	4	11.7	0
Δ Total GHG emissions from inputs	-23.3	-22.7	-0.5	-28.1
Δ N$_2$O emissions from soil	30.3	30.3	-25.3	63.2
Δ Total GHG emissions	7.0	7.6	-25.8	35.1
Average LC GHG avoided (kg CE/ha/y)				
Years 1 to Ys	260	460	226	265
Years Ys to 100	-7	-8	26	--35
Total LC GHG avoided (years 1-100), tonne CE/ha	6.5	12.3	6.6	1.0
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	4.3	7.7	2.7	2.3
Costs, $/ha/y				
Transaction (year 1)	5	5	5	5
Adoption incentive (years 1-20)	25	50	15	25
Monitoring (years 1-100)	1	1	1	1
Total costs (years 1-100), $/ha	605	1105	405	605
NPV Total costs (years 1-100), $/ha	306	590	195	306
Cost (NPV basis), $/tonne CE LC GHG avoided	72	77	71	132
Cost (NPV basis), $/tonne CO$_2$ equivalent LC GHG avoided	20	21	19	36

With wheat/fallow, less carbon is sequestered in SOC mainly because less crop residue is produced and returned to the soil on an annual basis and a smaller adoption incentive is required because increases in wheat yields partially offset higher production costs with no-till. Mainly because of the dry climate in which wheat/fallow systems are used, switching to no-till wheat/fallow reduces N_2O emissions whereas switching to no-till corn/soybeans increases N_2O emissions.

Costs of CO_2 abatement are significantly higher for cotton than for corn/soybean rotations, mainly because switching to no-till increases N_2O emissions significantly more with cotton than with corn/soybean rotations. The greater increase in N_2O emissions with no-till cotton than with no-till corn/soybeans is apparently due to the warmer, wetter climate in the southeastern U.S. where most of the cotton is grown.

Switching from intensive-till to no-till corn/soybean rotations or to no-till continuous corn can result in significantly higher N fertilizer requirements and N_2O emissions unless N fertilizer is managed efficiently. This can greatly reduce the amount of GHG emissions avoided because production and use of N fertilizer is very energy intensive and N_2O has a radiative forcing factor 296 times greater the CO_2 on a mass basis. Effects of increases in N fertilizer rate and N_2O emissions on LC GHG avoided and costs of GHG avoidance are discussed below.

Examples of the large effects of N rate and N_2O emissions on amount of GHG emissions avoided and cost per tonne of GHG avoided are presented in Table ES-16. The scenarios in Table 3 are for switching from intensive-till to no-till in a corn/soybean rotation in the Corn Belt. No significant change in N_2O emissions due switching from intensive-till to no-till is a possibility with good N management, especially on well-drained soils. The increases in N rate and N_2O emissions in Table 3 due to switching from intensive-till to no-till are possibilities with poor N management. Amounts of GHG avoided range from 9.6 tonnes CE LC GHG avoided/ha (35.3 tonnes CO_2 equivalent LC GHG avoided/ha) with a best-case N rate and N_2O scenario to -3.0 tonnes CE LC GHG avoided/ha (-11.0 tonnes CO_2 equivalent LC GHG avoided/ha) for a worst-case scenario. Costs on an NPV basis range from $64/tonne CE LC GHG avoided ($17/tonne CO_2 equivalent LC GHG avoided) with a best-case N rate and N_2O scenario to $113/tonne CE LC GHG avoided ($31/tonne CO_2 equivalent LC GHG avoided) for a worst-case scenario. Differences between the best-case and worst-case scenarios regarding amount of GHG avoided are very large because the annual effects are manifested over the entire 100-year planning horizon. In order for reducing tillage on corn/soybean rotations to be a viable option for avoiding GHG emissions, N fertilizer will have to be managed efficiently so that the amount of N fertilizer used and the N_2O emissions are not significantly increased. This conclusion is also applicable to continuous corn in the Corn Belt.

Table ES-16
Effects of increases in N rate and N$_2$O emissions on amounts and costs of avoided GHG via switching from intensive-till to no-till in a Corn/Soybean rotation

ΔN rate		ΔN$_2$O rate	Years 1-100	NPV basis, years 1-100	
kg N/ha/yr	kg/CE/ha/yr	kg/CE/ha/yr	tonne CE LC GHG avoided/ha	tonne CE LC GHG avoided/ha	$/tonne CE LC GHG avoided[1]
0	0	0	9.6	4.8	64 [2]
0	0	30.3	6.5	4.3	72 [3]
25	14.4	63.5	1.8	3.5	88 [4]
50	28.8	96.6	-3.0	2.7	113 [5]

[1] Assumes incentive payments for 20 years.

[2] Base case except for no change in N$_2$O emissions due to switching to no-till.

[3] Base case.

[4] Base case except for an increase in N rate due to switching from to no-till.
[5] Base case except for an additional increase in N rate due to switching from to no-till.

Summary Comparisons and Conclusions

Presented in this section are comparisons among options evaluated in this project and between CO$_2$ capture, transport and storage and indirect capture by forests and cropland via reducing tillage.

Direct Verses Indirect Sequestration

Shown in Figure ES-7 is a comparison of all of the base case values in $/tonne of CO$_2$ equivalent LC GHG avoided on a NPV basis plotted from lowest to highest cost.
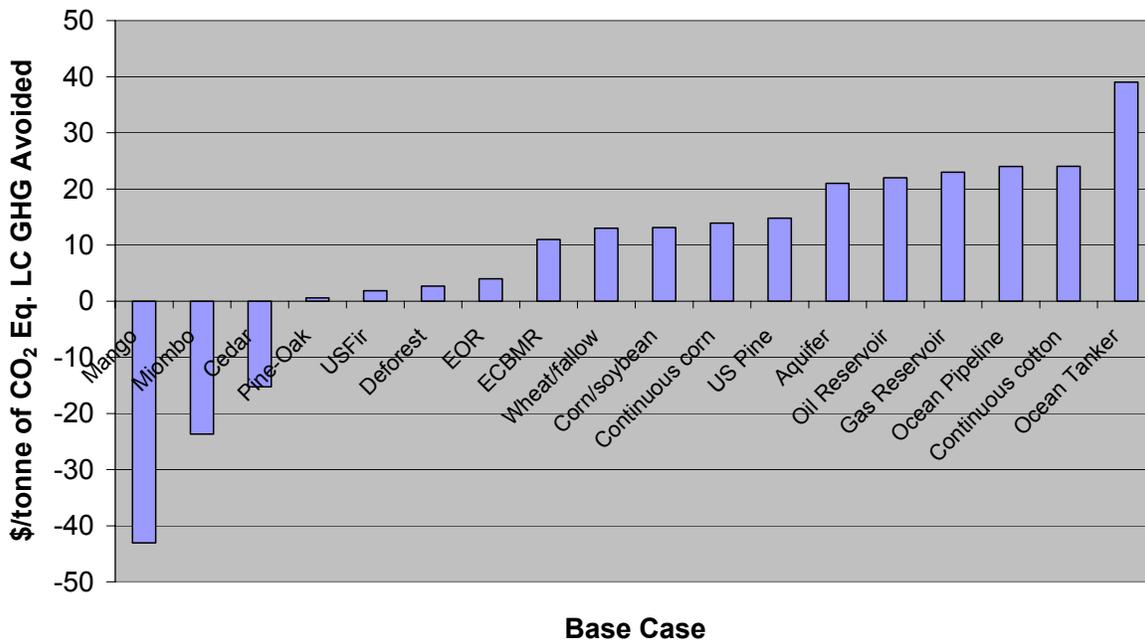
Figure ES-7
Comparison of direct and indirect sequestration cases.

As shown in Figure ES-7, all of the forestry options are the least expensive except for the US Pine case. Next are the EOR and ECBMR options followed by most of the cropland options. Figure ES-8 includes the available high and low cases. The main impact of these cases is on the cropland cases where the low cases would make them competitive with ECBMR and the high cases would make them about the same as the other geologic storage cases.
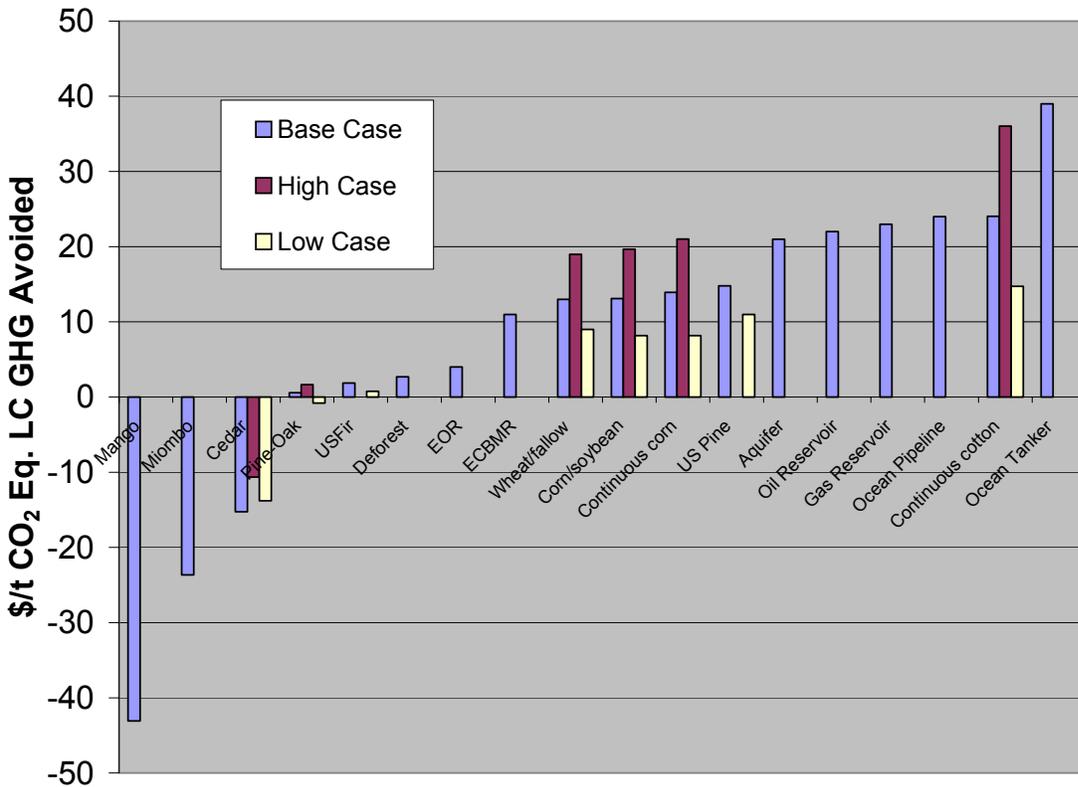
Figure ES-8
Comparison of direct and indirect sequestration cases including high and low cases

Base-case forest and cropland areas required to offset LC GHG emissions avoided by base-case CO_2 capture and storage options are presented in Table ES-17. These land area equivalents are for a 100-year planning horizon. The carbon equivalent (CE) LC GHG emissions avoided by the capture and storage options assume CO_2 capture and injection into storage reservoirs during the 20-year book life of the capture and storage plants and storage of injected CO_2 for another 80 years. For the ocean storage options, the CE LC GHG avoided is reduced for leakage of CO_2 throughout the 100-year storage period. Zero CO_2 leakage is assumed for the other CO_2 storage options. The CE LC GHG emissions avoided by the forest and cropland options assume that the improved forestry or cropland practices are maintained for 100 years. Generally, ten times or more cropland than forest land is required to offset the CO_2 storage options.

Table ES-17
Base-case forest and cropland areas required to offset LC GHG emissions avoided by base-case CO$_2$ capture and storage options.

Equivalent Forestry / Cropland Area Required to
Offset Geologic & Ocean Options
LC Avoided GHG Basis (100 year summation)

Forestry System - Medium Productivity (Above/below ground C, non-CO2 GHGs, & timber products/revenues)	(tonne CE/ha)	Aquifer Storage (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Enhanced Oil Recovery (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Depleted Oil Reservoirs (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Depleted Gas Reservoirs (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Coal Bed Methane Recovery (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Ocean Pipeline Storage (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)	Ocean Tanker Storage (Mtonne CE)	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage (Mha)
Plantation, USA, Loblolly Pine	183.14	9.81	0.05	9.09	0.05	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.15	28.00	0.15
Plantation, USA, Douglas Fir	452.65	9.81	0.02	9.09	0.02	9.81	0.02	9.81	0.02	9.54	0.02	28.28	0.06	28.00	0.06
Plantation (Taungya), Mexico, Spanish cedar	277.40	9.81	0.04	9.09	0.03	9.81	0.04	9.81	0.04	9.54	0.03	28.28	0.10	28.00	0.10
Restoration, Mexico, Pine-oak	183.39	9.81	0.05	9.09	0.05	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.15	28.00	0.15
Restoration, Southern Africa, Miombo	59.26	9.81	0.17	9.09	0.15	9.81	0.17	9.81	0.17	9.54	0.16	28.28	0.48	28.00	0.47
Agro- forestry, Southern India, Mango- tamarind	71.53	9.81	0.14	9.09	0.13	9.81	0.14	9.81	0.14	9.54	0.13	28.28	0.40	28.00	0.39
Avoidance of deforestation, Mexico,Various	207.66	9.81	0.05	9.09	0.04	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.14	28.00	0.13
Cropland System Two Year Corn/Soybean Rotation *(Intensive-till to No-till)*	6.51	9.81	1.51	9.09	1.39	9.81	1.51	9.81	1.51	9.54	1.46	28.28	4.34	28.00	4.30
Continuous Corn *(Intensive-till to No-till)*	12.33	9.81	0.80	9.09	0.74	9.81	0.80	9.81	0.80	9.54	0.77	28.28	2.29	28.00	2.27
Continuous Cotton *(Intensive-till to No-till)*	0.99	9.81	9.90	9.09	9.18	9.81	9.90	9.81	9.90	9.54	9.64	28.28	28.56	28.00	28.28
Two Year Wheat / Fallow Rotation *(Intensive-till to No-till)*	6.58	9.81	1.49	9.09	1.38	9.81	1.49	9.81	1.49	9.54	1.45	28.28	4.30	28.00	4.26

Conclusions

Making these comparisons was a challenge due to the differences between direct and indirect cases. The resulting numbers should only be used as a relative indication of cost. Site-specific characteristics could significantly change the outcome of the comparisons. In this study, the forestry options are very attractive along with capture using EOR for storage. Other factors, such as land availability and storage option location and capacity will also play a significant part in which options make the most sense at a given site.

The current work should only be considered a starting point. Better cost information and improvements to processes are likely to be developed and need to be incorporated into updates of this information. In addition, there are plans to update and add to portions of the current work to answer questions that arose but were beyond the scope of the current effort. For example, what happens to the costs if the power plant operates for longer than the plant book life? Also, how do the economics look for other power generation options? These and other questions will be evaluated in updates to this work.

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1
INTRODUCTION

In order to plan for potential CO_2 mitigation mandates, energy companies need better cost information on CO_2 mitigation options, especially storage and sink enhancement options that involve non-energy company operations. One of the major difficulties in evaluating CO_2 storage and sink enhancement options is obtaining consistent, transparent, accurate, and comparable economics. This project compares the economics of major technologies and practices under development for CO_2 storage and sink enhancement, including options for storing captured CO_2, such as active oil reservoirs, depleted oil and gas reservoirs, deep aquifers, coal beds, and oceans, as well as the enhancement of biological sinks such as forests and croplands.

The primary funding source for the project was the Department of Energy (DOE with the Tennessee Valley Authority (TVA) and the Electric Power Research Institute (EPRI) also providing additional funds. An international group of experts in this area was assembled to develop the technology/ practice designs, the economic premises, and cost evaluations. TVA was the prime for this project, responsible for overall completion of the effort. EPRI organized efforts to select specific sequestration processes to be evaluated for captured CO_2 and coordinated the efforts of consultants from the MIT, SFA Pacific, and the IEA Greenhouse Gas Programme and the Edinburgh Centre for Carbon Management (ECCM) to develop and refine the framework for the economic evaluations. MIT and Parsons Infrastructure and Technology developed process designs for captured CO_2 storage processes and helped TVA develop economic models for comparing technologies and practices. The University of Tennessee Agricultural Policy Research Center, in collaboration with TVA, evaluated the economics of enhancing CO_2 sequestration in croplands. The IEA Greenhouse Gas Programme developed the concept design for evaluating the forest sequestration options.

1.1 Economic Framework

Most of the cost comparisons to date have concentrated on CO_2 capture, with the assumption that CO_2 sequestration is a small part of these costs. In addition, these comparisons have used information supplied from studies of specific technologies, and the variability in costs due to variability in assumptions and lack of visibility into assumptions lessens the usefulness of the results. In the case of sequestration, virtually no comparative economic evaluations of processes have been done.

Methodologies for developing economic comparisons are generally available. They range from very detailed ±10 percent for site-specific evaluations, where final decisions are made between options, to very general economics with little insight into the economic premises that were used to develop the economics. The latter is usually a simplification of more detailed economics for

very high-level comparisons. In some cases, probability analyses are included to help evaluate risks. This usually adds significantly to the complexity of the model and the time to develop results. The model may use simplified economics to allow probability analysis without making the model too complex to run in a reasonable time.

The economic evaluations developed for this project are between the ranges described above and are typical of prior EPRI economics where a ±25 to 30 percent estimate is made, with the ability to modify values to be relatively site-specific. Material balances are made, equipment lists and pricing are developed, installation costs are estimated and contingencies are estimated for project and process uncertainties. These types of evaluations are intended to be transparent, consistent, and comparable. They are consistent with the EPRI economics of advanced power generation with CO_2 capture being developed for DOE. Probability analysis was not included to keep the results consistent with other EPRI studies.

The economic framework also included life cycle analysis for the various sequestration options. This means that all greenhouse gas emissions from cradle to grave were estimated and considered in the analysis. The economic analysis used spreadsheet models that are flexible enough to allow a wide variation in the range of parameters to be evaluated and the sensitivity cases to be run. The CO_2 storage options were sized to accommodate the CO_2 from our base case capture plant (see the design basis in Chapter 3). In addition, the amount of forest and cropland required to sequester the same amount of CO_2 over a 100-year planning horizon was calculated.

1.2 Concepts Evaluated

The potential processes and concepts to be evaluated were initially prioritized, and the concepts were placed into three categories—(1) included, (2) may be included but more information is needed before a final decision can be made, and (3) not included due to the lack of good information at this time. Because one of the most unique aspects of this work is the comparison between storage of captured CO_2 and sink enhancement, it was felt that at least one of each type should be included. The list of concepts and their final status is presented in Table 1-1.

Table 1-1
Concepts Status

Included	Not Included
Aquifers	Ocean Fertilization
Oil Reservoirs	Mineralization
Depleted Oil and Gas Reservoirs	
Ocean Storage	
Forests	
Croplands	
Coal Beds	

In the case of ocean fertilization and mineralization, it is felt that at this time there is not enough reasonable information to develop a meaningful concept description and that these processes should not be included until more R&D is performed.

1.2.1 Aquifer Storage

Shown below is the preliminary block diagram for the Aquifer Storage concept. This concept is simple in application. The complexity comes from deciding on the nature of the distribution and number of wells.

Pipeline CO_2
(7,389 tpd)

Distribution

CO_2 Injection
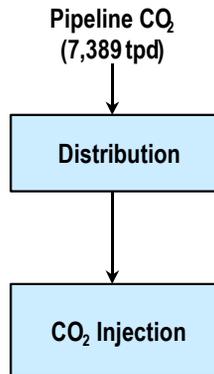
Figure 1-1
Preliminary Block Diagram for Aquifer Storage Concept

The rationale for including the aquifer concept in the economic evaluation is summarized in Table 1-2 below. This concept has the largest storage capacity of all the concepts, except the ocean, and is widespread throughout the United States. In addition, it is at commercial scale, although not in the United States. Sufficient data is believed to be available.

Table 1-2
Rationale for Including Aquifers in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• Best potential CO_2 storage capacity of all geological storage options • Retention time predicted to be thousands of years • Offshore aquifers eliminate most safety concerns	• Understanding risk of catastrophic or slow release of CO_2	• Ubiquitous and large, so widespread availability	• Some experience of aquifer storage for chemicals, etc. • Little actual experience for this specific application	• Many studies on this storage option • Specific reservoir characterization is lacking	• Commercial application - CO_2 has been injected into the Utsira formation under the North Sea since August 1996, as part of the Sleipner Vest project • Accepted for materials other than CO_2	• Excellent

1.2.2 Oil Reservoir Storage with Enhanced Oil Recovery (EOR)

Shown below is the preliminary block diagram for the EOR storage concept.
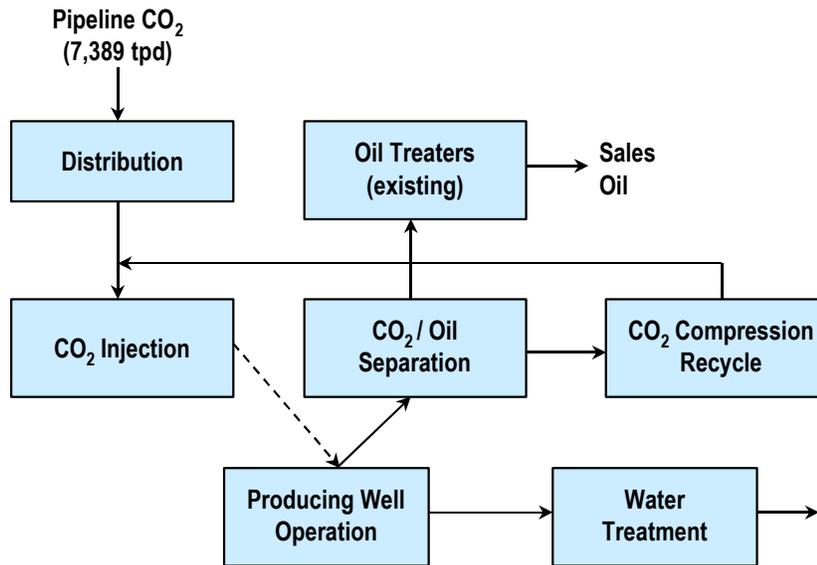
Figure 1-2
Preliminary Block Diagram for EOR Concept

The rationale for including the EOR concept in the economic evaluation is summarized in Table 1-3 below. While this concept has a more limited storage capacity and is not as widespread, it is likely to be an early application due to the potential for low-cost storage. It is also commercial in the United States. However, it has not been optimized for maximum CO_2 storage, and its compatibility with power systems is of some concern. Sufficient data is believed to be available.

Table 1-3
Rationale for Including EOR in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• Oil by-product makes option economically attractive • Not considered to involve any undue risks to man or the natural environment • Injection of CO_2 done commercially today	• Could often be cheaper to obtain CO_2 from natural sources • Global storage capacity may be limited (e.g., to 65 Gt C) (2) • For today's blowdown, reservoir operations need to store CO_2 under pressure	• Limited to areas where there are active oil fields	• EOR practiced on a significant scale for last 25 years	• Excellent	• EOR is widely used, in 1998 more than 65 oil fields in the U.S. were being injected with CO_2 • Industry actively investigating the option of using captured CO_2	• Oil operations require continuous supply (versus intermittent) • Issues with fluctuation in the quantity of CO_2 needed over time

1.2.3 Depleted Oil and Gas Reservoir Storage

Shown in Figure 1-3 is the preliminary block diagram for the Depleted Oil and Gas Reservoir Storage concept.

Pipeline CO$_2$
(7,389 tpd)

Distribution

CO$_2$ Injection
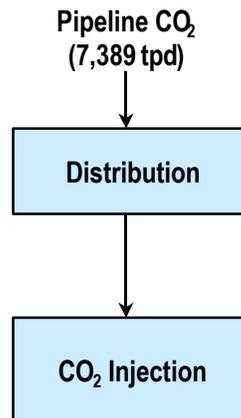
Figure 1-3
Preliminary Block Diagram for Depleted Oil and Gas Reservoir Storage

The rationale for including the Depleted Oil and Gas Reservoir Storage concept in the economic evaluation is summarized in Table 1-4 below. This concept is similar to the EOR, except the storage location is simply used for storage without recovery of oil or gas. Since the storage location has a known integrity, it should be relatively straightforward to use. The gas reservoirs may be the easiest since gas should be depleted and the reservoir can just be repressurized. The data is believed to be sufficient, since it is so similar to EOR.

Table 1-4
Rationale for Including Depleted Oil and Gas Reservoirs in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• Global storage capacity as much as 140 Gt C for disused gas fields and 40 Gt C for disused oil fields (3) • Reservoirs have proven containment over geological time frames • Knowledge about reservoir already exists	• Today very few reservoirs depleted • Understanding risk of catastrophic or slow release of CO_2	• Limited to areas where there are disused oil and gas reservoirs	• Uses similar technology to EOR	• Good	• No commercial scheme involving such fields as yet exists • May be liability issues	• May need multiple reservoirs for large power plants

1.2.4 Coal Bed Storage

Shown below is a preliminary block diagram for the Coal Bed Storage concept.

Pipeline CO$_2$
(7,389 tpd)

Distribution

CO$_2$ Injection
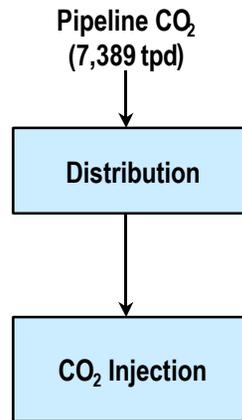
Figure 1-4
Preliminary Block Diagram for Coal Bed Storage Concept

The rationale for including the Coal Bed Storage concept in the economic evaluation is summarized in Table 1-5 below. While the data is limited, CH$_4$ by-product production credits and significant coal deposits make a good argument for inclusion. Data availability is limited.

Table 1-5
Rationale for Including Coal Bed Storage in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• CH_4 by-product makes option economically attractive • CO_2 strongly sequestered by adsorption on coal matrix • Worldwide large coal deposits means potentially large CO_2 storage capacity	• Enhanced gas recovery (EGR) methods for coal bed CH_4 exploitation require further refinement	• Unclear as to how many types of coal formations will be practical to use for coal bed CH_4 production	• Injection of CO_2 into coal beds already used to enhance CH_4 recovery, although process is still at an early stage of development	• Limited	• Well accepted	• Could be used to develop a zero greenhouse gas emissions power plant fueled by coalbed CH_4, where waste CO_2 produced by plant is injected into coalbed CH_4 reservoirs to produce more CH_4

1.2.5 Ocean Storage

Shown in Figure 1-5 is a preliminary block diagram for the Ocean Storage concept.
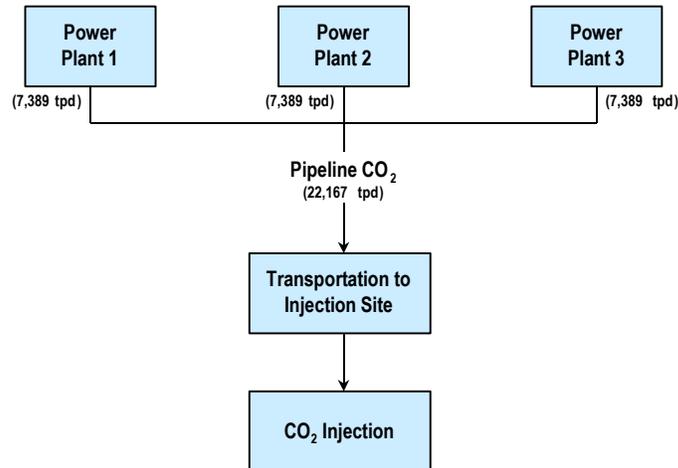
Figure 1-5
Preliminary Block Diagram for Ocean Storage Concept

The rationale for including the Ocean Storage concept in the economic evaluation is summarized in Table 1-6 below. The ocean has the largest storage capacity of any of the concepts, and much work has been done to study ways to store CO_2 in the ocean. Sufficient data should be available.

Table 1-6
Rationale for Including Ocean Storage in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• Largest potential sink for CO_2, storage capacity estimated to be upwards of 1000 Gt C (4) • Leaks do not pose safety issues	• Could have a negative impact on local marine environment • Significant legal and jurisdictional issues to be overcome • Negatively perceived by non governmental organizations (NGOs) • Retention time, on the order of hundreds of years, less than for underground storage	• Best suited to countries situated adjacent to ocean trenches and that do not have access to suitable underground reservoirs, for example Japan • Populated areas are near coastlines	• Much experience from offshore exploration/ production is applicable	• Modest	• Not well perceived compared to geological storage options • Field experiment to take place off the coast of Hawaii in 2001, this should help to reduce some of the uncertainties	• Excellent for plants situated on coastline

1.2.6 Forest Sink Enhancement

Shown in Figure 1-6 is a preliminary block diagram for the Forest Sink Enhancement concept.
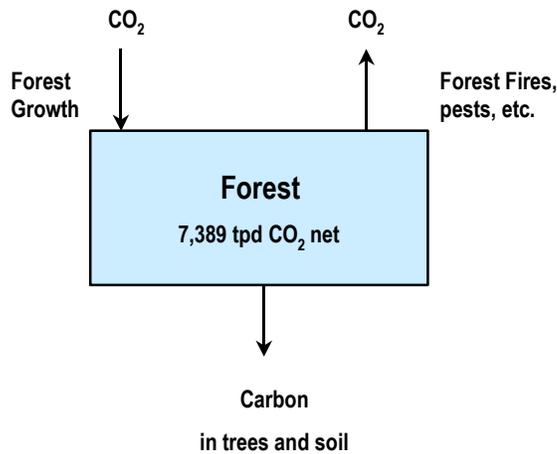
Figure 1-6
Preliminary Block Diagram for Forest Storage Concept

The rationale for including the Forest Sink Enhancement concept in the economic evaluation is summarized in Table 1-7 below. Forests are generally considered the lowest-cost storage option, and a great deal of work has been done on them. This is the basic sink comparison to be made with the captured storage concept. A number of concerns still remain, and matching the economics will be difficult. Sufficient data should be available.

Table 1-7
Rationale for Including Forest Sinks in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility with power systems
• Low cost • Significant forest available • Provides funding and employment in rural areas and developing countries. • Preservation of biodiversity	• Monitoring and verification of carbon storage • Opportunities for fraud • "Leakage" minimization • Short-term storage • Risks of forest loss through fires, pests and social factors	• Particularly applicable to areas of low population with few other land use options • Changes to albedo may make forests less effective in high latitudes • Global capacity limited and costs increase substantially as less favorable sites are used	• Forestry is technically mature • Land owners and farmers need to be educated on merits of forestry for carbon storage • Monitoring and verification services offered but further developments would be beneficial to increase accuracy and reduce costs	• Good • Current projects small and may not be representative of large schemes • Current large-scale projects are mainly deforestation avoidance	• Still being debated at the COP 6 meeting • Considered the easy, low-cost option • Some companies already buying forestry carbon credits • Still concerns over "leakage" and risks	• Applicable to all power systems since there is no direct link to the power plant

1.2.7 Cropland Sink Enhancement

Shown in Figure 1-7 is a preliminary block diagram for the Cropland Sink Enhancement concept. The cropland concept involves enhancing soil carbon sequestration by switching from conventional- to conservation-tillage systems and improving residue management. Conservation-tillage systems use less intensive tillage, often no tillage, and leave at least 30 percent of the crop residues on the soil surface. Conservation-tillage systems also sometimes include a winter cover crop that remains on the soil surface to reduce soil erosion. The winter cover crop is not harvested and adds additional crop residue to soil organic matter.

General parameters for estimating the net cost of switching to conservation-tillage systems are presented in the block diagram below. The net cost of switching to conservation-tillage systems is the change in cost of tillage-system inputs, plus or minus the change in revenue and risk from changes in crop yield.

General parameters for estimating the additional CO_2 sequestered in soil organic matter are also presented in the block diagram. These parameters are (1) the increase in crop residue carbon added to soil organic matter, (2) the reduced rate of soil organic matter decomposition to CO_2, and (3) the reduced soil erosion and the associated reduction of CO_2 emitted from eroded soil.
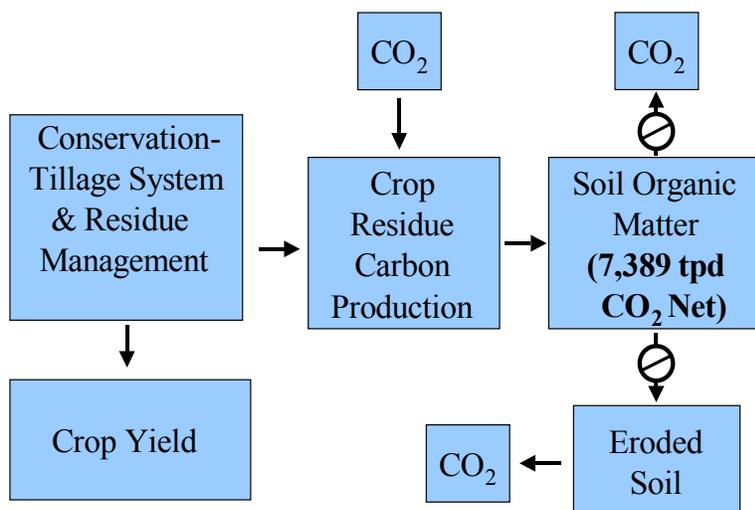
Figure 1-7
Preliminary Block Diagram for Cropland Sink Concept

The rationale for including the Cropland Sink Enhancement concept in the economic evaluation is summarized in Table 1-8 below. The cropland component of this project will estimate added costs of converting from conventional-tillage systems to conservation-tillage systems that sequester additional carbon in soil organic matter. Increased adoption of conservation-tillage systems and improved residue management accounts for about one-half of the potential for reducing greenhouse (GHG) emissions from U.S. croplands. The remaining one-half of the potential for reducing GHG emissions from U.S. croplands is highly fragmented and beyond the scope and resources of this project.

Table 1-8
Rationale for Including Cropland Sinks in the Economic Study

Merits	Potential Challenges	Applicability	Technical Maturity	Data Availability	Industrial Acceptance	Compatibility With Power Systems
• Relatively low projected cost/ton of CO_2 • Collateral benefits of conservation tillage—improved soil quality, reduced soil erosion, improved water-use efficiency, improved crop productivity where well adapted	• Possible need for periodic use of conventional tillage to maintain crop productivity, resulting in partial loss of sequestered CO_2 • Possible reversion to conventional tillage due to changes in land ownership • Resistance to including biological sinks in GHG polices • Poorly developed infrastructure for CO2 credits and markets • Good base for infrastructure	• Excellent in well-drained soils, water deficient cropping systems, and highly erosive soils • Moderately good in most other cropping systems	• Conservation tillage systems under development since early 1970s • ~35% adoption achieved to date in U.S. • Technology ready for rapid adoption, given additional economic incentives	• Good for costs of tillage systems • Moderately good for CO_2 sequestration rates • Lacking for equilibrium levels of sequestered carbon and time to equilibrium • Good for CO_2 emissions factors associated with tillage-system inputs	• Generally good farmer acceptance because of collateral benefits • Somewhat greater economic risk to farmers • May require moderate adoption incentives to achieve rapid additional adoption	• Good compatibility via combining farm-level CO_2 sequestration credits into bundles of sufficient size to match power project needs

In conventional-tillage systems, soil is plowed or otherwise thoroughly tilled and all of the crop residues are mixed with soil. In contrast, conservation-tillage systems involve less intensive tillage (often no tillage), leave 30 percent or more of the crop residues on the soil surface, and sequester additional carbon in soil organic matter that otherwise would be emitted to the atmosphere as CO_2. In addition to sequestering more carbon, conservation-tillage systems also have lower emissions associated with production and use of tillage-system inputs, dramatically reduce soil erosion and CO_2 emissions from eroded soil, improve soil quality, and conserve soil water by reducing water runoff and evaporation from the soil.

1.3 Report Organization

Presented in Chapter 2 is a summary of the methodology used in developing the costs. Chapters 3-9 contain the information on the captured CO_2 storage concepts. Chapters 10-17 contain the information on the forestry options. Chapters 18-22 contain the information on the croplands options. Chapter 23 contains the summary comparisons between options and conclusions.

1.4 References

1   DOE/EPRI. 2000. Evaluation of innovative fossil fuel power plants with CO_2 removal. EPRI., Palo Alto, California; U.S. Department of Energy–Office of Fossil Energy, Germantown, Maryland, and U.S. Department of Energy/NETL, Pittsburgh, Pennsylvania: 1000316.

2

METHODOLOGIES FOR CALCULATING THE COST OF CAPTURING AND STORING CO_2

General procedures for calculating the cost of capturing and storing CO_2 are overviewed in this chapter. They include:

- Calculating costs using revenue requirement methodology

- Defining the three cost bases used in this report: CO_2 captured, CO_2 avoided, and CO_2 equivalent life-cycle (LC) greenhouse gas (GHG) avoided

- Combining CO_2 capture and storage costs

- Accounting for differences in timing of CO_2 sequestration profiles and for leaking reservoirs

Specific procedures are provided in Chapter 3.

2.1 Revenue Requirement Methodology

Costs of storing captured CO_2 were calculated using the same general approach as for CO_2 capture costs that have already been calculated by EPRI and DOE for several power plant CO_2 capture technologies[1]. This allowed CO_2 capture and storage costs to be combined on an equal basis.

2.1.1 Approach for CO_2 Capture

In the DOE/EPRI project, EPRI revenue requirement (RR) methodology was used[2]. Revenue requirement methodology is used for regulated economics (i.e., return on equity and debt are set at regulated levels) and focuses on minimizing annual revenue requirements, whereas unregulated economics focus on maximizing return on investment. With regulated economics, utilities are allowed to charge a price for electricity that recovers revenue requirements for prudent investments. A levelized RR ($/yr) was calculated for each year of the 20-year plant book life as follows:

Levelized RR = Levelized Carrying Charge (LCC) + Expenses

$\qquad$ = Levelized annual cost of electricity $\qquad\qquad\qquad\qquad$ (1)

where LCC = Total Plant Cost (or TPC) x Levelized Carrying Charge Factor (or LCCF), and Expenses include O&M and fuel costs. The TPC includes process facilities capital, general

Methodologies for Calculating the Cost of Capturing and Storing CO2

facilities capital, engineering and home office overhead, project and process contingencies, and miscellaneous expenses generally included under owners costs.

A levelized revenue requirement was calculated for an integrated gasification combined cycle (IGCC) plant without CO_2 capture (Case 3b of reference 1) and for the same IGCC plant converted to capture CO_2 (Case 3a of reference 1) as shown in Equation 1.   A value of 0.15 for the LCCF was based on assumptions specified in the DOE/EPRI report for return on debt, return on equity, federal and state income taxes, book depreciation, property taxes, and insurance. The same financial parameters and associated LCCF of 0.15 were used for calculating the base case for cost of storing captured CO_2. Assumptions for return on debt, return on equity, and federal and state income taxes are presented in Table 2-1.

The cost of electricity (COE) for the capture and non-capture power plants was calculated based on their respective LCC and expenses. The difference in COE ($/MWh) for capture and non-capture IGCC plants was used as a basis for calculating the cost of CO_2 captured (more details provided in Section 2.2).

Table 2-1
Financial parameters for calculating the levelized carrying charge factor

	Percent of total	Cost, %	Current dollars	Constant dollars	
			Return, %	Cost, %	Return, %
Debt	45	9.0	4.05	5.83	2.62
Preferred stock	10	8.5	0.85	5.34	0.53
Common stock	45	12.0	5.40	8.74	3.93
Total annual return	100		10.30		7.09
Inflation rate, %		3.00			
Federal tax, %		34.00			
State tax, %		4.15			
Federal and state tax, %		38.00			
Discount rates					
After tax			8.76		6.09
Before tax			10.3		7.09

2.1.2 Adjustment for CO_2 Storage

In calculating the costs of storing captured CO_2, the RR methodology for CO_2 capture was generalized to accommodate options for enhanced revenues from CO_2 storage. These adjustments were required because CO_2 storage options such as enhanced oil recovery (EOR) and enhanced coal bed methane recovery (ECBMR) generate revenues that at least partially offset the cost of CO_2 storage. This required that the RR methodology for CO_2 capture be generalized as follows:

Levelized RR = LCC + O&M costs - Enhanced revenues

$$= \text{Levelized annual net cost of storing } CO_2 \tag{2}$$

A positive net storage cost equals the breakeven CO_2 tipping fee for EOR. A negative net storage cost equals the breakeven CO_2 purchase price for EOR.

2.1.3 Adjustment of Levelized Carrying Charge Factor as a Function of Discount Rate

Costs of capturing and storing CO_2 were calculated on a constant 1999 dollar basis. Financial parameters in Table 2-1 result in a LCC factor of 0.150 and an after-tax discount rate (r) of 6.09 percent on a constant-dollar basis. Discounted costs and revenues were used to compare CO_2 storage and sink enhancement options differing in timing of costs and in timing and permanence of CO_2 storage and sink enhancement (see Section 2.4). The discount rate used in Section 2.4 calculations needs to be consistent with the LCC factor. The discount rate and LCC factor are related by Equation (3).

$$\text{LCC factor} = 0.0738 + 0.01 \, r + 0.0004 \, r^2 \tag{3}$$

Equation (3) is based on the regression in Figure 2-1. Levelized carrying charge factors were calculated for the range of after-tax discount rates (r) in Figure 2-1 by varying return to debt and equity and holding other financial parameters constant. Procedures from reference 2 were used for these calculations.

The chart shows levelized carrying charge factor (y-axis, 0.000 to 0.250) vs. after-tax discount rate (x-axis, 0.00 to 10.00 %) with fitted curve:

$$y = 0.0004x^2 + 0.01x + 0.0738$$
$$R^2 = 1$$
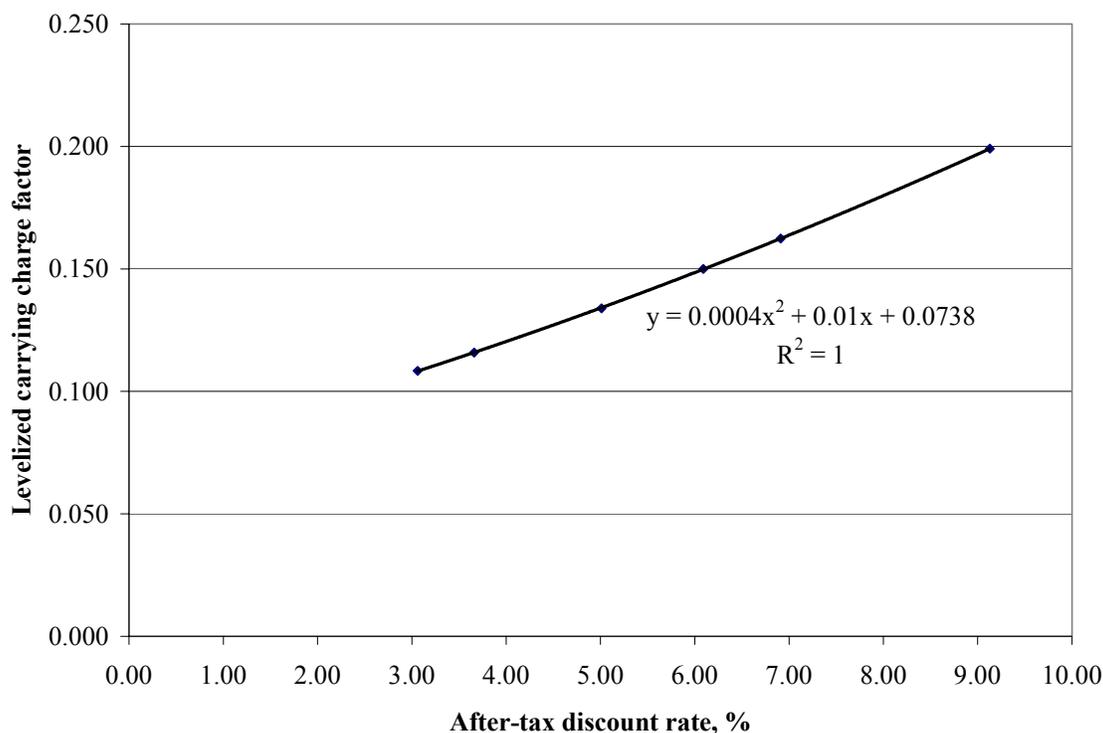
Figure 2-1
Carrying charge factor vs. after-tax discount rate
(based on constant dollar analysis)

2.1.4 Impact of CO_2 Storage Costs on Cost of Electricity

The COE for the IGCC CO_2 capture plant was adjusted for the net cost of CO_2 storage (i.e., storage costs minus enhanced oil or gas revenues). The increase in COE due to CO_2 storage was calculated by dividing the total revenue requirement for CO_2 storage by the total MWh of electricity produced. Consistent with revenue requirement methodology, CO_2 storage operations were assumed to be owned by a regulated utility or reimbursed by a regulated utility for net storage costs (including return on equity), in which case enhanced oil or gas revenues were assumed to have no impact on income taxes. The reason is that regulated utilities are allowed to charge a price for electricity that recovers revenue requirements for prudent investments. Within this context, enhanced oil or gas revenues reduce the revenue requirement for CO_2 storage, and thereby, reduce any increase in electricity prices that a regulated utility would be allowed to charge to cover CO_2 storage costs. The end result is no additional income tax burden beyond that built into the carrying charge. In some EOR and ECBMR scenarios, enhanced oil or gas revenues are large enough to result in a negative revenue requirement for storing CO_2.

In these cases, it was assumed that the negative revenue requirement would be used to:

- Eliminate the increase in electricity prices that a regulated utility would normally be allowed to charge to cover CO_2 storage costs, and

2-4

- Reduce part of the increase in electricity prices that a regulated utility would normally be allowed to charge to cover CO_2 capture costs.

2.2 Capture Costs on CO_2 Captured, CO_2 Avoided, and Life-Cycle GHG Avoided Bases

2.2.1 CO_2 Captured Basis

The cost per tonne of CO_2 captured was calculated by subtracting the cost of electricity (COE, $/MWh) for the IGCC reference plant without CO_2 capture from the COE for the IGCC plant with CO_2 capture and dividing by the amount of CO_2 captured (tonne/MWh). Assuming no losses of captured CO_2 during transport and storage, this calculation also provides the capture cost per tonne of CO_2 stored. Inputs for calculating CO_2 capture costs on a CO_2 captured basis are presented in Table 2-2. For this case, the CO_2 capture cost on a CO_2 captured basis = (55.08-43.98)/0.763 = $14.55/tonne CO_2 captured.

Table 2-2
Calculation of CO_2 capture costs on CO_2 captured and CO_2 avoided bases[*]

Based on IGCC example from DOE/EPRI report[1]

	Capture plant	Reference plant	
COE, $/MWh	55.08	43.98	
CO_2 produced, tonne/MWh	0.836	0.718	
CO_2 captured, tonne/MWh	0.763	0.000	
Direct CO_2 emitted, tonne/MWh	0.073	0.718	
LC GHG emitted, tonne CO_2 eq./MWh (see Table 3)	0.111	0.750	
Cost, CO_2 captured basis:			**Costs**
CO_2 capture cost (CO_2 captured basis), $/tonne CO_2 captured			14.55
Costs, CO_2 avoided basis:			
CO_2 capture cost (CO_2 avoided basis), $/tonne CO_2 avoided			17.21
CO_2 capture cost (LC GHG avoided basis), $/tonne CO_2 eq. avoided			17.37

[*]Assumes 80% capacity factor.

2.2.2 CO$_2$ Avoided Basis

The primary difference in capturing CO_2 for commercial markets versus capturing CO_2 for sequestration is the role of energy. In the former case, energy is a commodity, and all we care about is its price. In the latter case, using energy generates more CO_2 emissions, which is precisely what we want to avoid. We can account for this "energy penalty" by calculating costs on a CO_2 avoided basis. As shown in Figure 2-2, due to the extra energy required to capture CO_2, the amount of CO_2 emissions avoided is always less than the amount of CO_2 captured. Therefore, capturing CO_2 for purposes of sequestration requires more emphasis on reducing energy inputs than in traditional commercial processes.
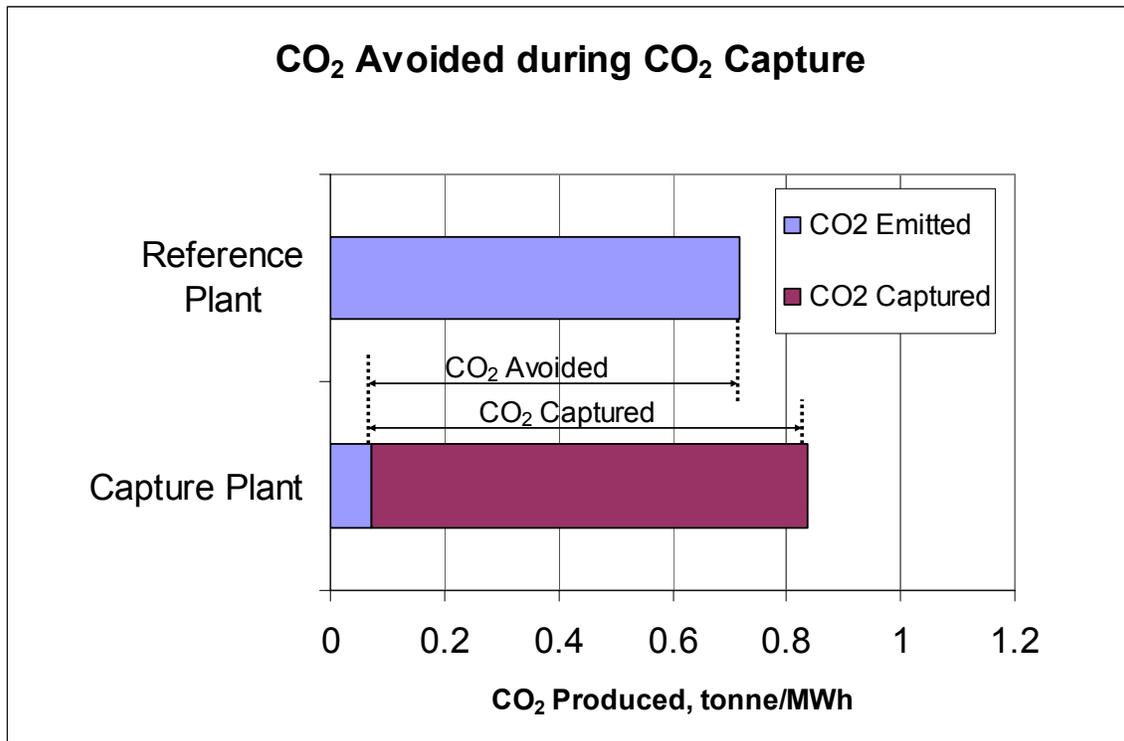
Figure 2-2
Relationships among CO$_2$ produced, captured, and avoided when comparing power plants with and without CO$_2$ capture (based on Table 2-2)

The cost per tonne of CO_2 avoided in the CO_2 capture process was calculated with Equation (4) from the EPRI/DOE report[1]:

$$Cost \ of \ CO_2 \ Avoided = \frac{\left(\$/MWh_{with \ capture}\right) - \left(\$/MWh_{without \ capture}\right)}{\left(tonne \ CO_2 \ emitted_{without \ capture} / MWh\right) - \left(tonne \ CO_2 \ emitted_{with \ capture} / MWh\right)} \quad (4)$$

Inputs for calculating CO_2 capture costs on a CO_2 avoided basis are presented in Table 2-2. For this case, the cost of CO_2 avoided = (55.08 – 43.98)/(0.718-0.073) = \$17.21/tonne CO_2 avoided.

2.2.3 LC GHG Avoided Basis

The calculation of CO_2 capture costs on a life-cycle greenhouse gas (LC GHG) avoided basis is the same as in the previous section except that the terms in the denominator of Equation (4) are tonne CO_2 equivalent LC GHG emitted/MWh instead of tonne CO_2 directly emitted from the power plant/MWh. Life-cycle GHG emissions are greater than direct CO_2 emissions for two reasons. First, greenhouse gases in addition to CO_2 were included in the analysis. Second, the system boundaries were expanded to include coal mining and manufacture and transportation, construction, and decommissioning of power plant equipment in addition to GHG emissions from power plant operations; this boundary expansion was required because of the energy penalty and associated added coal required for CO_2 capture and because of the energy use associated with added equipment required for CO_2 capture. Inputs for calculating CO_2 capture costs on a LC GHG avoided basis are presented in Table 2-3. For this case, the cost of GHG avoided on a LC GHG basis = (55.05-43.98)/(0.111-0.750) = $17.37/tonne CO_2 equivalent LC GHG avoided. Calculation of LC GHG emissions (values in the denominator of the equation in the previous sentence) is illustrated in Table 2-3. The 100-year warming potentials used are from the recent Intergovernmental Panel on Climate Change (IPCC) report[7].

2.3 Combining Capture and Storage Costs

The previous section described the bases based only on capture costs and emissions. In this section, we describe how these bases are modified to also consider storage costs and emissions. In addition, we describe the methodology for reporting storage costs alone on a LC GHG avoided basis.

2.3.1 CO$_2$ Captured Basis

Costs associated with CO_2 compression, transportation, and storage are included in the cost of electricity (COE, $/MWh) from a CO_2 capture plant. The cost per tonne of CO_2 captured is calculated by subtracting the COE for the reference power plant without CO_2 capture from the COE for the power plant with CO_2 capture, including costs for compression, transportation, and storage, and dividing the difference by the amount of CO_2 captured (tonne/MWh).

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Table 2-3
Summary of Enhanced Oil Recovery on a LC GHG avoided basis

Enhanced Oil Recovery: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

GHG (CO2 Equivalents) Emmited During CO2 Capture & Storage

With CO2 Capture (Case 3a)

IGCC Plant — GHG Emissions tonnes/year

		CO_2	N_2O	CH_4
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		243,338	3,433	66,762
Total (mg CO_2 Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (mg CO_2 Equivalent / kWh)		**110,876**		

Compression of Captured CO_2 to Pipeline Spec
CO_2 Compression

		CO_2	N_2O	CH_4
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO_2 Equivalent		1,605	23	438
CO_2 Compression Total (CO_2 Equivalent)		**2,066**		

Transportation & Sequestration of Captured CO_2
CO_2 Transportation

		CO_2	N_2O	CH_4
Pipeline Construction		913	0.0	0.0
Pipeline Decommissioning		91	0.0	0.0
Total		1,005	0	0
CO_2 Sequestration-EOR				
Power	25,142 kW	128,378	1	155
Plant Construction				
Aboveground Equipment		279	0.0	0.0
Subsurface Equipment		64	0.0	0.0
Plant Decommissioning		34	0.0	0.0
Total		128,755	1	155
$CO2$ Transportation & Sequestration Total		129,759	1	155
100 Year Multiplier		1	296	23
CO_2 Equivalent		129,759	210	3,569
Transportation & Sequestration Total (CO_2 Equivalent)		**133,538**		

Without CO2 Capture (Case 3b)

IGCC Plant — GHG Emissions tonnes/year

		CO_2	N_2O	CH_4
Coal Mine		30,417	0.5	1.4
Mine Methane Vented		577	minor	2,619
Coal Train		1,821	minor	minor
Power Plant Emissions		2,133,828	11.4	minor
Power Plant Construction		1,006	0.0	0.0
Power Plant Decommissioning		101	0.0	0.0
Total Power Plant		2,167,749	12	2,620
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		2,167,749	3,530	60,262
Total (mg CO_2 Equivalent / kWh)		728,612	1,186	20,255
Power Plant Total (mg CO_2 Equivalent / kWh)		**750,053**		

Amount of Emitted & Avoided GHG (*CO_2 Equivalents*)

Capture	With CO2 Capture	Without CO2 Capture	Difference
kg CO_2 equivalent emitted/kWh	0.111	0.750	0.639
CO_2 equivalent avoided, tonne/yr			1,807,446

Storage (CO2 Compression, Transportation, and Sequestration)

Compression CO_2 equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO_2 equivalent emitted, tonne/yr	133,538
Total CO_2 equivalent emitted, tonne/yr	135,604

Total System

CO_2 equivalent avoided by capture, tonne/yr	1,807,446
CO_2 equivalent emitted from storage, tonne/yr	135,604
CO_2 equivalent LC avoided, tonne/yr	1,671,842
CO_2 equivalent LC avoided, % of CO_2 captured	77.5%
CO_2 equivalent LC avoided, % of CO_2 equivalent avoided during capture	92.5%

2.3.2 CO$_2$ Avoided Basis (CO$_2$ Capture and Storage Combined)

In addition to the inclusion of CO$_2$ compression, transportation, and storage costs as described in section 2.3.1 above, this basis also considers the CO$_2$ emitted during CO$_2$ storage. Referencing Equation 4, including storage costs on a CO$_2$ avoided cost basis will increase the \$/MWh$_{with\ capture}$ and the tonne CO$_2$ emitted/MWh$_{with\ capture}$ terms.

2.3.3 GHG Avoided in CO$_2$ Capture and Storage Processes Combined on a Life-Cycle (LC) Basis

The concept of GHG emissions avoided on a LC GHG basis for capture and storage combined is illustrated in Figure 2-3. The LC GHG emissions from the reference and capture power plants were discussed in Section 2.2.3 and emissions levels from the reference and capture power plants are presented in Tables 2-2 and 2-3. The red bars in Figure 2-3 are the LC GHG emissions in addition to the direct CO$_2$ emissions from the reference and capture power plants. The LC GHG emissions avoided via CO$_2$ capture and storage combined are calculated as the LC GHG emitted from the reference plant (blue plus red bars) minus the LC GHG emitted from the capture plant and storage operation combined (blue plus red plus yellow bars).

To get the cost per tonne of LC GHG avoided via the capture and storage processes combined, the combined annual net cost of capturing and storing CO$_2$ was divided by the annual tonnes of CO$_2$ equivalent GHG avoided via capture and storage processes combined. For the EOR example in Table 2-3, the annual combined net cost of CO$_2$ capture and storage was \$6.70 million (data not shown). The annual tonnes of CO$_2$ equivalent GHG avoided in capture and storage processes combined was 1.67 million (see next paragraph for details). Dividing annual costs by annual tonnes gave a net cost of \$4.01/tonne CO$_2$ equivalent GHG avoided by capture and storage combined.

The difference in LC GHG emissions from the reference and capture plants is 0.750-0.111=0.639 tonnes CO$_2$ equivalent/MWh (Table 2-3). This difference in LC GHG emissions was multiplied by the MWh/year for the capture plant to get the annual tonnes of CO$_2$ equivalent GHG avoided via the capture process (1,807,446 tonnes CO$_2$ equivalent LC GHG avoided/yr). The LC GHG emissions from EOR CO$_2$ storage were 135,606 tonnes CO$_2$ equivalent LC GHG/yr, resulting in 1,807,466-135,606 = 1,671,840 tonnes CO$_2$ equivalent LC GHG avoided/yr for the CO$_2$ capture and storage processes combined.
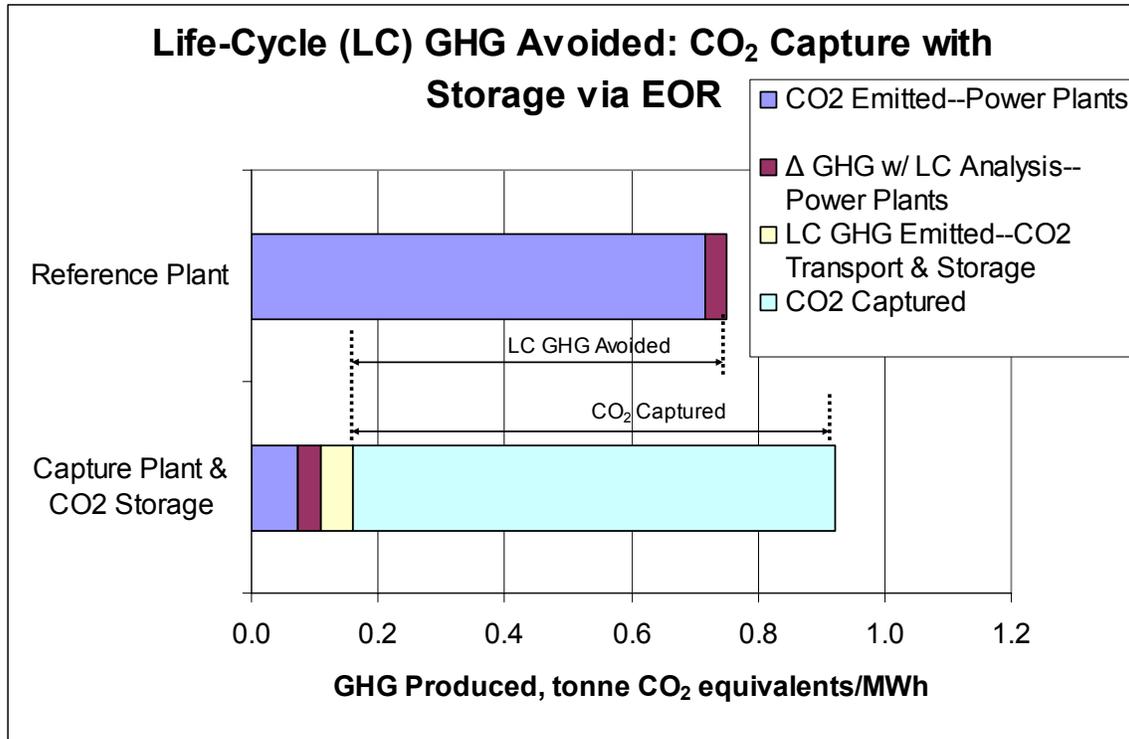
Figure 2-3
Relationships among GHG produced, CO_2 captured, and GHG avoided on a LC basis for CO_2 capture and storage (via EOR) combined; based on Tables 2-2 and 2-3

In the case of ocean storage, the portion of injected CO_2 predicted to leak back out of the ocean (3.1% in 100 years from an MIT model) was subtracted from the GHG emissions avoided during the CO_2 capture and storage processes to get a net GHG emissions avoided. For all other cases, the storage location leakage was assumed to be zero. The net GHG emissions avoided was used to calculate the cost of CO_2 capture and storage on a LC GHG avoided basis.

2.3.4 Costs of CO_2 Storage on a Life-Cycle GHG Avoided Basis (Storage Only)

The cost per tonne of CO_2 stored was calculated on a life-cycle GHG avoided basis (storage system only) by dividing the total annual revenue requirement for CO_2 storage by the difference between annual tonnes CO_2 stored and LC GHG emitted due to the storage operation (i.e., CO_2 compression, transportation, and sequestration). Examples of LC GHG emissions from CO_2 storage operations are presented for base cases in Table 2-4. This analysis included LC GHG emitted from energy consumption during equipment manufacture, transportation, construction, and decommissioning, and during the storage operation. Detailed LC GHG emissions from EOR storage (base case) are presented in Figure 2-3. Detailed LC GHG emissions from all the base-case CO_2 storage options in Table 2-4 are presented in Appendix A.

Table 2-4
Greenhouse gas emissions from CO$_2$ storage operations

CO$_2$ Storage Option	Direct CO$_2$ emitted	Total LC GHG emitted (includes direct CO$_2$ emissions)
	million tonnes CO$_2$ eq./y	
Storage of CO$_2$ from one power plant at 80% capacity factor[*]:		
Enhanced oil recovery	0.130	0.136
Enhanced coalbed methane recovery	0.049	0.052
Deep saline aquifers	0.002	0.003
Depleted oil reservoirs	0.002	0.003
Depleted gas reservoirs	0.002	0.003
Storage of CO$_2$ from three power plants at 80% capacity factor[**]:		
Ocean-pipeline	0.008	0.013
Ocean-tanker	0.061	0.064

[*]Assumes 100 km from power plant to storage operation and storage of 2.158 million tonnes CO$_2$/y

[**]Assumes 100 km from power plant to ocean shore and 100 km from shore to ocean injection point; and storage of 6.474 million tonnes CO$_2$/y.

2.4 Comparing the Economics of CO$_2$ Storage and Sink Enhancement Options Differing in Timing and Permanence of Sequestration

Carbon dioxide storage and sink enhancement options differ greatly in timing of costs, the uptake or sequestration of CO$_2$ and, in some cases, leakage of CO$_2$ back into the atmosphere. For options involving storage of captured CO$_2$, the primary costs and amounts of CO$_2$ stored are levelized over the book life of the CO$_2$ capture and storage plants which is assumed to be 20 years in this project. With storage of captured CO$_2$, there are also relatively small monitoring costs after 20 years, and in some cases, there may be additional transaction costs after 20 years. In some cases such as ocean storage, there are leaks of CO$_2$ back to the atmosphere that occur after 20 years. The costs and CO$_2$ sink enhancement for forestry projects usually extend over at least a 50- to 100-year period. In cropland systems involving reduction of tillage to achieve CO$_2$ sink enhancement, primary costs in the form of annual farmer adoption incentives will likely be required for 5 to 20 years after a farmer switches to a reduced-tillage system. Sink enhancement occurs over approximately the first 20 to 40 years after switching to reduced tillage practices, and changes in GHG emissions associated with crop production inputs such as reduced fuel use continue for as long as the reduced-tillage system is used. Monitoring costs, and perhaps

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additional transaction costs, will continue for as long as the reduced-tillage system is used. If a farmer permanently switches back to a more intensive tillage system because of crop production problems, the CO_2 sink reduces in size, resulting in CO_2 loss back to the atmosphere.

The differences in timing and permanence discussed above present a significant challenge in comparing the economics of diverse options such as storage of captured CO_2 and CO_2 sink enhancement in forests and cropland. There have been many suggestions on how to handle this challenge[4, 6]. We treat removals and emissions/leaks as separate events. The idea is that when one removes a ton of CO_2, one receives the going price of CO_2. When a ton of CO_2 is released, the owner of this CO_2 must then purchase a credit from elsewhere at the going price. CO_2 prices will be set as a result of government policy either through market mechanisms (e.g., a cap and trade system) or in the form of a tax (e.g., a carbon tax). As long as CO_2 can be emitted in the atmosphere for free, there will be no incentive to sequester CO_2 on a large-scale.

In order to implement this approach, one must make explicit assumptions concerning CO_2 prices and discount rates. We argue that no matter what methodology one adopts, they all must make assumptions about how to deal with CO_2 prices and discount rates. Some methods seem to avoid this task by making these assumptions implicitly. We prefer to confront the issue of the long-term value of CO_2 storage and sink enhancement and the discount rate directly as these are values, that while admittedly highly uncertain, where one can appeal to an underlying rationale.

The mathematical formulation for comparing the value and cost of CO_2 storage and sink enhancement options differing in timing of costs and in timing and permanence of storage and sink enhancement is shown below. This approach provides a breakeven CO_2 price ($/tonne of CO_2 sequestered) for each CO_2 storage and sink enhancement option that reflects differences in timing of costs and in timing and permanence of CO_2 storage and sink enhancement. If the calculated breakeven CO_2 price is less than the market CO_2 price, then the proposed project has favorable economics. However, if the calculated breakeven CO_2 price is greater than the market CO_2 price, then the proposed project is not economical. The breakeven carbon price is very project specific and care must be taken when trying to generalize the results beyond a given project. In this study, we look specifically at sequestration in conjunction with an IGCC power plant. Extrapolating the results to other types of power plants is not necessarily valid.

The net present value (NPV) of the revenues from CO_2 storage and sink enhancement options differing in timing and permanence is calculated as follows[3]:

$$NPV = \sum_{t=0}^{t=100} p(t)\, a(t)(1+r)^{-t} \qquad (5)$$

where **p** is the CO_2 price ($/tonne), **a** is the abatement or avoided emissions (tonnes/yr), **r** is the discount rate, and **t** is time (yrs). Based on the assessment of cases with constant and variable CO_2 prices, we concluded that considering variable CO_2 prices is beyond the scope of this project. Assuming a constant CO_2 price (p_o) results in the following form of Equation (5):

$$NPV = p_o \sum_{t=0}^{t=100} a(t)(1+r)^{-t} \tag{6}$$

The relative value of CO_2 offsets differing in timing and permanence is compared by setting the NPV of CO_2 abatement as calculated in Equation (6) equal to the discounted cost (**c**) of achieving the CO_2 offset and solving for a constant breakeven price as follows[5]:

$$p_o \sum_{t=0}^{t=100} a(t)(1+r)^{-t} = \sum_{t=0}^{t=100} c(t)(1+r)^{-t} \tag{7}$$

and

$$Breakeven \; p_o = \frac{\sum_{0}^{t=100} c(t)(1+r)^{-t}}{\sum_{t=0}^{100} a(t)(1+r)^{-t}} = Cost \; of \; CO_2 \; sequestration \tag{8}$$

Equation (8) is used in this project to compare breakeven prices (i.e., costs) for CO_2 storage and sink enhancement options differing in timing of costs and in timing and permanence of CO_2 storage and sink enhancement. Note that computationally a(t) appears to be discounted in Equation (8); however, the discount term in the denominator actually arises from discounting CO_2 revenues as shown in Equation (5).

In this project, Equation (8) is used with a planning horizon of 100. This planning horizon is long enough to reflect typical project life cycles for all the CO_2 storage and sink enhancement options included in this project.

Equation (8) reduces to a ratio of total CO_2 abatement costs to total avoided emissions for cases in which annual CO_2 storage costs and annual avoided emissions are in the same proportion over time. For the CO_2 capture and storage options in this project, CO_2 abatement costs and CO_2 avoided emissions are levelized over time for years 1-20. This means that for years 1-20 of the CO_2 capture and storage options, the breakeven price is the same on a discounted and a nondiscounted basis. However, when monitoring and/or transaction costs are included for years 21-100, the breakeven price is affected by discounting. For forestry and cropland options, the breakeven price is significantly affected by discounting.

The 6.09 percent after-tax discount rate (constant dollar basis) used for capture and storage of CO_2 (Table 2-1) was also used in base cases for cropland and forestry CO_2 sink enhancement options. The rationale for using the same discount rate for the CO_2 capture/storage and CO_2 sink enhancement options is that funding for both types of projects would come from an electric utility seeking to receive credits for reducing GHG emissions. A utility likely would use the same discount rate for evaluating GHG abatement investments regardless of whether the investments involve CO_2 capture and storage or CO_2 sink enhancement.

Methodologies for Calculating the Cost of Capturing and Storing CO2

2.5 References

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3
STORING CAPTURED CO$_2$ – BASIS & APPROACH

3.1 Technologies Evaluated

The following transportation and injection processes for captured CO$_2$ were evaluated in this study:

- Overland pipeline transport (Chapter 4)

- Enhanced oil recovery (Chapter 5)

- Enhanced coalbed methane recovery (Chapter 6)

- Depleted oil reservoir storage (Chapter 7)

- Depleted gas reservoir storage (Chapter 7)

- Deep saline aquifer storage (Chapter 7)

- Ocean storage via pipeline (Chapter 8)

- Ocean storage via tanker (Chapter 9)

For the processes of ocean fertilization and mineralization, it was determined that there was not enough information at this time to develop meaningful conceptual designs and cost estimates. Therefore, these were not included in the evaluations pending more R&D.

Initially, the same was thought to be true for coalbed methane. However, a recent IEA Greenhouse Gas R&D Programme Report[1] assessed the potential of enhanced coalbed methane recovery with CO$_2$ sequestration and concluded, "Injection of carbon dioxide into deep coal seams has the potential to enhance coal-bed methane recovery, while simultaneously sequestering carbon dioxide. Analysis of production operations from the world's first carbon dioxide-enhanced coal-bed methane demonstration plant, in the San Juan Basin, indicates that the process is technically and economically feasible. A recent pilot scheme in Alberta, Canada, should also help to confirm the technical and economic data of this process." Thus, while there is still uncertainty about the effectiveness of CO$_2$ in enhancing the recovery of coal-bed methane, the potential is such that it was included in the study.

3.2 Approach

Two key areas for all the geologic storage options are the injection/production wells and field equipment/production operations. Two annual surveys, "Joint Association Survey on Drilling Costs"[2] and "Costs and Indices for Domestic Field Equipment and Production Operations"[3],

have for many years tracked costs for drilling and operating domestic oil and gas fields. These costs are disaggregated by depth, regions, well type and production rate. Our options were tied as closely as possible to these surveys to provide both up-to-date costs and indices that measure the increase or decrease in costs from year to year.

A key area for all the options, including the ocean storage options, is the pipeline used to transport the captured CO_2. The MIT Pipeline Transport Model, developed by the MIT Energy Laboratory,[4] was used for pipeline sizing and costs.

For each option, a baseline conceptual design was generated based on the assumptions discussed below. From the baseline conceptual design, capital, O&M costs and an economic analysis with several figures of merits were developed in a spreadsheet format. These were then used to develop sensitivity analyses and life cycle analyses, again in a spreadsheet format.

3.3 Common Design Basis

A nominal 500 MW_e gross integrated gasification combined cycle (IGCC) plant operating at an 80 percent capacity factor was utilized as the production source of CO_2. This was based on the DOE/EPRI's recent study on the "Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal"[5]. Table 3-1 shows a summary of the parameters used in this study taken from the DOE/EPRI report for Case 3a, "IGCC with CO_2 Removal".

Table 3-1
Summary of parameters for IGCC power plant with CO_2 removal

Parameter	Unit	Value
Thermal Input, HHV	10^6 Btu/h	3,723
Gross Power Output	MW	490.4
Net Power Output	MW	403.5
Efficiency, HHV	%	37.0
Capacity Factor	%	80
CO_2 Captured	t/d	7,389
	million scm/d	3.76
CO_2 Emitted	kg/kWh	0.073
CO_2 Avoided in Capture	t/d	6,246
CO_2 Capture Cost	$/t captured	14.55
CO_2 Capture Cost	$/t avoided in capture	17.21
Plant Life	y	20
Capital Charge Factor	%	15.0
Fuel Cost	$/GJ	1.18
Fuel Real Esc. Rate	%/y	0.00
Fuel Levelization Factor		1.00
TPC	$/kW	1,642
Fixed O&M	$/kWy	32.98
Variable O&M	$/MWh	3.90
Heat Rate, HHV	kJ/kWh	9,727
Capital	$/MWh	35.04
O&M	$/MWh	8.61
Fuel	$/MWh	11.44
Levelized cost of Energy (LCOE)	$/MWh	55.08

10^6Btu = 1.06 GJ

The baseline IGCC plant produces two streams of CO_2 from the double-stage Selexol acid gas removal process. One stream is at 3.4 bar (50 psia), while the second stream produced at 1.0 bar (15 psia) is boosted to 3.4 bar (50 psia). The combined 3.4 bar (50 psia) CO_2 streams are further

compressed and dehydrated in a multi-stage, intercooled compressor to 83 bar (1,200 psia). The amount of CO_2 recovered from the IGCC plant that must be sequestered is 7,389 tonnes per day.

The existing pipeline specification (152 bar, -40°C dewpoint, N_2<300 ppmv, O_2<40 ppmv, Ar<10 ppmv) was used for the quality of the CO_2. The DOE/EPRI study is consistent with this except for the CO_2 pressure. The DOE/EPRI study was based on compressing the CO_2 to 83 bar, although a sensitivity study at 152 bar was done. Our study includes additional compression to 152 bar.

Referring to Figure 3-1, the CO_2 at 83 bar (1200 psia) and 41°C (105°F) is above and to the liquid side of the critical point 31.1°C (88°F) and 73.0 bar (1073 psi). By increasing pressure to 152 bar (2200 psi) and 38°C (100°F) or less, the pipeline pressure can drop to about 103 bar (1500 psi) before recompression, and the CO_2 mass is ensured of retaining flow properties approximating a liquid. This boost compression adds an additional power requirement of 2,650 kW_e. The CO_2 stream is dried to a -40°C dewpoint and contains N_2<300 ppmv, O_2<40 ppmv, and Ar<10 ppmv to prevent corrosion.
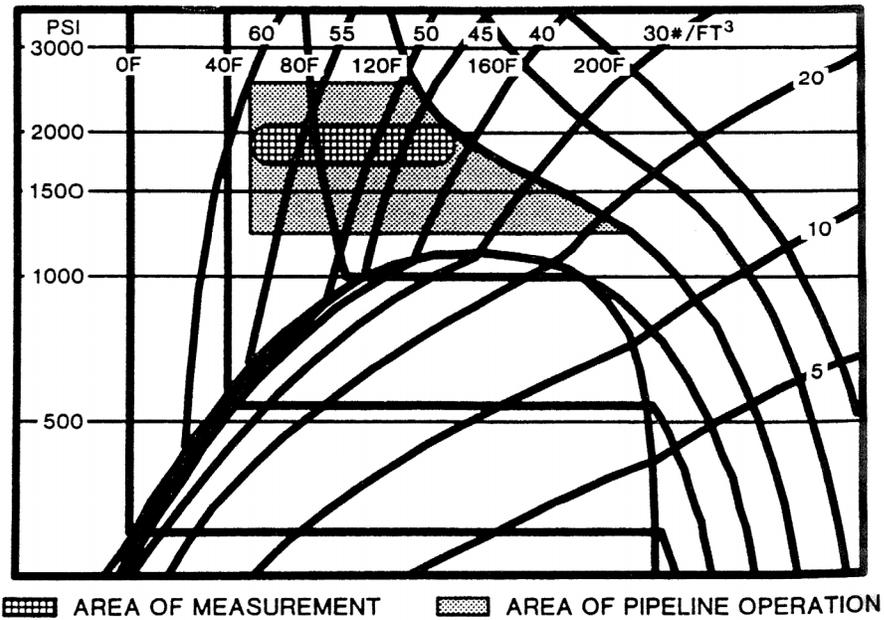
Note: °C=(°F-32)/1.8, 1bar=14.5 psi

Figure 3-1
Carbon dioxide pressure enthalpy diagram

3.4 Greenhouse Gas Emissions Inventory

The atmospheric greenhouse gas emissions for the full fuel cycle including coal mining, transportation, power conversion, and carbon sequestration for the EOR option are listed in Table 3-3. The emissions are presented in terms of tonnes per year of the gases emitted. These figures are based on the heat and material balance data for Case 3a presented in the DOE/EPRI recent study on the "Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal".[5]

Case 3a was based on an IGCC power system with an output of 404 MW_e and a HHV efficiency of 37.0 percent. Over 90 percent of the carbon in the coal was captured and sequestered as 7,389 tonnes per day of CO_2 (2.16 million tonnes per year). Annual emissions were based on a capacity factor of 80 percent.

Many of the assumptions for emissions from mining, coal transport, and construction, which are discussed below, were taken from previous studies, especially the ETSU study.[6] The emissions from the power plant were based on DOE/EPRI Case 3a material balance and emissions estimate.[5]

3.4.1 Emissions from Deep Mining

Based on DOE/EPRI Case 3a, the total coal feed to the IGCC plant is 1.01 million tonnes per year. The deep-mined coal source in the U.S. is expected to have high methane content. The methane content of coal mines can vary widely over short distances. In addition to the methane contained in the coal seams, methane also seeps from the strata surrounding the coal mine. The amount of pure CH_4 released is expected to be about 10 Nm^3/tonnes of coal mined.[7] This gas is partly recovered, mixed with air and other gases to give a total apparent gas release of about twice this flow rate. Table 3-2 gives the typical composition of gas recovered from a coal mine.

Table 3-2
Typical composition of recovered coal mine gas

Gas	% Volume
CH_4	50
VOCs	2
O_2	7
N_2	37
CO_2	4

For underground mining, methane collection of some of the gas is feasible and is required as a safety precaution. The gas is collected as a combustible fuel gas containing variable proportions of air up to 65 percent. The remainder of the released gas is removed from the mine in ventilation air in which the methane content is kept below 0.5 percent. The fraction of the total methane gas that can be recovered as a combustible fuel gas is site specific. For the purpose of this study, it is assumed that 60 percent of the methane released can be collected as combustible gas and burned usefully to generate power or is flared[7].

On the basis of the analysis of mine methane and 60 percent collection, the atmospheric emissions of unburned gas associated with the production of one tonne of clean coal is 2.86 kg of CH_4 and 0.63 kg of CO_2.

If it is assumed that all of the collected methane is sufficiently consistent in quality to be burned in an open cycle gas turbine operating at 33 percent efficiency for power generation, then 60 percent of the power requirements of the mine (38 kWh/tonne of coal) would be generated.

The balance of the power would be generated from natural gas. The emissions will be the products of combustion of 11.2 kg of CH_4 and 0.50 kg of VOCs per tonne of clean coal. This combustion will yield 33.2 kg of CO_2 per tonne of coal. Emissions of CH_4 and N_2O from burning mine gas are calculated based on the EPA emission factors for gas turbines resulting in emissions of CH_4 of 3.4×10^{-3} lb/tonne of coal and N_2O of 1.2×10^{-3} lb/tonne of coal.[8]

3.4.2 Emissions from Rail Transport

The fuel consumption for rail transport of coal in the U.S. is 0.25 MJ/tonne-kilometer.[9] For the IGCC case, based on the transport over 100 km of 1.01 million tonnes per year of U.S. coal, the total annual fuel energy consumption would be 25.36 TJ corresponding to 571 tonnes per year of diesel oil. The corresponding emissions, based on carbon content of 87 percent, would be 1821 tonnes per year of CO_2. Other emissions are calculated from EPA emission factors for locomotives.[10]

3.4.3 Emissions from the Operation of the Power Plant

The power plant data for IGCC is based on CO_2 abatement by shift conversion and scrubbing of CO_2 from the fuel gas prior to the combustion of hydrogen in a gas turbine. The CO_2 emissions are derived from the mass balance data reported in Reference 1. N_2O content of the IGCC gas turbine exhaust is estimated to be 0.5 ppm.[6] The N_2O emissions were calculated from the design flow rate of stack gas of 510 Nm^3/s, which is equivalent to 12.9×10^9 $Nm^3/year$. Since there are no hydrocarbons in the gas turbine fuel, the gas turbine exhaust will be free from methane.

3.4.4 Emissions from the Construction and Decommissioning of the Power Plant

The bulk construction materials required for power plants are essentially steel, cement and aggregate. The energy requirements of these commodities are reported as about 22, 5, and 0.12 GJ/tonne respectively.[6,11] The amount of material required for the construction of power plants is broadly proportional to the size and complexity of the power plant, which is in turn proportional to its cost. Analysis of the data available[6] showed typical steel, cement, and aggregate consumption in the ratio 1:1:6; therefore, the overall construction energy requirement for a power plant is estimated to be about 28 GJ/tonne of steel used in the plant.

Analysis of plant cost information[6] indicates a steel utilization in power plant projects of the order of one tonne of steel per $50,000 of total investment. On the basis of this rule of thumb, the energy requirement for construction of the IGCC power plant is estimated to be about 404,000 GJ. Other energy consumption on the construction site is assumed to be trivial in comparison with the energy requirement of the construction materials.

To determine the emissions associated with the energy expended in making the steel and cement, it is assumed that gas will be used to supply the energy for making construction materials. The total energy consumption in construction corresponds to 1.5 percent of the annual energy consumption of the power plant. The associated emissions are assumed to be equivalent to the emissions from natural gas combustion.[12] In addition, 0.4 tonnes of CO_2 is emitted from the manufacture of one tonne of cement. Therefore, an additional 6,000 tonnes of CO_2 arises from this source.

The decommissioning of the power plant at the end of its useful life will involve some expenditure of energy depending on the use that is made of the site. There will be some recycling of steel from the decommissioning operation that is a less energy intensive operation than the making of new steel; therefore, an energy credit could accrue. For the purpose of this study, it is assumed that there will be a net energy consumption for decommissioning equal to a nominal 10 percent of the energy consumed in the construction of the power plant. Emissions for decommissioning are therefore calculated on the basis of 10 percent of the emissions from the construction of the power plant.

For the purpose of the development of a single emissions inventory, the emissions associated with power plant construction and decommissioning are presented as if the emissions were produced continuously over the 20 year lifetime of the plant.

3.4.5 Emissions from the Compression of CO_2

Emissions for the power used for compression are based on the power plant's life cycle emissions. The emissions from the construction and decommissioning of the CO_2 compression unit located at the power plant were based on the same assumptions as were used for the power plant.

3.4.6 Emissions from the Transportation of CO_2

The amount of steel for the pipeline construction was based on the amount of steel needed for the size pipe used, 97.3 kg per m (65.4 lb per ft) for the 12-inch pipe. The emissions from the construction and decommissioning of the pipeline were based on the same energy assumptions (28 GJ/tonne of steel used) as were used for the power plant.

3.4.7 Emissions from the CO_2 Storage Options

Emissions for the power used for storage are based on the power plant's life cycle emissions. The emissions from the construction and decommissioning of the CO_2 storage systems were based on the same assumptions as were used for the power plant. In the case of ocean storage via tanker, it was also necessary to consider the CO_2 emitted by the tankers and due to boil off. The methodology used to calculate the CO_2 emitted from these sources is described in Section 9.4.3.

Storing Captured CO2 –Basis & Approach

Table 3-3
Greenhouse gas life cycle analysis

With CO_2 Capture (Case 3a)				
IGCC Plant		GHG Emissions tonnes/year		
		CO_2	N_2O	CH_4
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		243,338	3,433	66,762
Total (mg CO_2 Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO_2 Equivalent / kWh*)		**110,876**		
Compression of Captured CO_2 to Pipeline Spec				
CO_2 Compression				
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.1
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO_2 Equivalent		1,605	23	441
CO_2 Compression Total (*CO_2 Equivalent*)		**2,068**		
Transportation & Sequestration of Captured CO_2				
CO_2 Transportation				
Pipeline Construction		913	0.0	0.0
Pipeline Decommissioning		91	0.0	0.0
Total		1,005	0	0
CO_2 Sequestration-EOR				
Power	25,142 kW	128,378	1	155
Plant Construction				
Aboveground Equipment		279	0.0	0.0
Subsurface Equipment		64	0.0	0.0
Plant Decommissioning		34	0.0	0.0
Total		128,755	1	155
CO2 Transportation & Sequestration Total		129,759	1	155
100 Year Multiplier		1	296	23
CO_2 Equivalent		129,759	210	3,569
Transportation & Sequestration Total (*CO_2 Equivalent*)		**133,538**		

3.5 References

1   "Enhanced Coal Bed Methane Recovery with CO_2 Sequestration," IEA Greenhouse Gas R&D Programme, Report Number PH3/3, August 1998.

2   "1998 Joint Association Survey on Drilling Costs," American Petroleum Institute, Policy Analysis and Statistics Department, November 1999, http://www.api.org/axs-api/products/joint.htm

3   "Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations," Energy Information Administration, Office of Oil and Gas, March 2000. http://www.eia.doe.gov/oil_gas/natural_gas/data_publications/cost_indices/c_i.html

4   "A Cost Model for Transport of Carbon Dioxide," The Energy Laboratory, Massachusetts Institute of Technology, January 2000.

5   "Evaluation of Innovative Fossil Fuel Power Plants with CO_2 Removal," EPRI Report No. 1000316, Interim Report, December 2000, Cosponsors: U.S. Department of Energy/Office of Fossil Energy and U.S. Department of Energy/NETL, EPRI Project Manager N. A. H. Holt.

6   "Full Fuel Cycle Study on Power Generation Schemes Incorporating the Capture and Disposal of Carbon Dioxide," ETSU, United Kingdom, October 1994.

7   "Methane Emissions from Coal Mining," IEA GHG Report PH2/5, June 1996.

8   Gas Turbine Emission Factors, http://www.epa.gov/ttn/chief/ap42/ch03/final/c03s01.pdf

9   Khoury, "Coal Cleaning Technology," Edited by D. L. Khoury, Noyes Data Corporation, 1981.

10 Locomotive Emission Factors, http://www.epa.gov/oms/invntory/r92009.pdf

11 Boustead, I. and G. F. Hancock, "Handbook of Industrial Energy Analysis," Wiley and Sons, 1979.

12 Gas Combustion Emission Factors, http://www.epa.gov/ttn/chief/ap42/ch01/final/c01s04.pdf

4
PIPELINE TRANSPORT

4.1 Introduction

This chapter looks at the transport of CO_2 via pipeline from the base case IGCC power plant to the injection site, for the geologic storage options, and the shoreline collection point, in the case of the ocean storage options.

4.2 State of the Art

Over 110 million standard cubic meters (scm) per day of CO_2 are transported by pipeline in the United States, frequently for distances greater than 100 km. Details of currently operating CO_2 pipelines in the United States are given in Table 4-1.[1,2,3,4,5,6]

Pipeline Transport

Table 4-1
CO₂ pipelines in the United States

Name	Operator	Route	CO$_2$ Source	Length (km)	Diameter (in)	Capacity (10^6 scm per day)
Cortez Pipeline[2]	Kinder Morgan CO$_2$	McElmo Dome to Denver City CO$_2$ Hub	Natural CO$_2$ deposit	311	30	28
McElmo Creek Pipeline[2]	ExxonMobil	McElmo Dome to McElmo Creek Unit (UT)	Natural CO$_2$ deposit	25	8	2
Bravo Pipeline[2]	BP	Bravo Dome to Denver City CO$_2$ Hub	Natural CO$_2$ deposit	135	20	11
Sheep Mountain I[2]	BP	Sheep Mountain Field to Rosebud connection with Bravo Dome	Natural CO$_2$ deposit	114	20	9
Sheep Mountain II[2]	BP	Rosebud connection to Denver City CO$_2$ Hub and onward to Seminole San Andres Unit (TX)	Natural CO$_2$ deposit	139	24	14
Central Basin Pipeline[2]	Kinder Morgan CO$_2$	Denver City CO$_2$ Hub to McCamey, TX	-	-	26,16	17
Este Pipeline[2]	ExxonMobil	Denver City CO$_2$ Hub to Salt Creek, TX	-	74	12,14	7
Slaughter Pipeline[2]	ExxonMobil	Denver City CO$_2$ Hub to Hockley County, TX	-	25	12	5
West Texas Pipeline[2]	Trinity Pipeline	Denver City CO$_2$ Hub to Reeves County, TX	-	79	12,8	3

Table 4-1 (continued)
CO₂ pipelines in the United States

Name	Operator	Route	CO₂ Source	Length (km)	Diameter (in)	Capacity (10⁶ scm per day)
Llano Lateral Pipeline[2]	Trinity Pipeline	runs off Cortez main line to Llano, NM	Natural CO_2 deposit	33	12,8	3
Canyon Reef Carriers Pipeline[2]	Kinder Morgan CO_2	McCamey, TX to SACROC field	-	87	16	7
Val Verde Pipeline[5,6]	PSCC	connects Mitchell, Gray Ranch, Pucket and Terrell gas processing facilities to Canyon Reef Carriers main line	Gas processing facilities	51	10	4
Weyburn Pipeline[3]	Dakota Gasification Company	Great Plains Synfuels plant (Beulah, ND) to Weyburn field (Saskatchewan, Canada)	Coal gasification plant	127	14,12	3
Choctaw Pipeline[4]	Denbury Resources	Jackson Dome to Bayou Choctaw Field, LA	Natural CO_2 deposit	115	20	6

1 in = 0.0254m

Transported CO_2 is most commonly used for enhanced oil recovery (EOR). The use of CO_2 for EOR is a proven technology with 72 CO_2 floods in the United States.[7] Most of these floods are dependent upon naturally occurring CO_2, which is obtained from high-pressure, high-purity underground deposits. The most important of these natural CO_2 deposits, in decreasing order of current production, are the McElmo Dome, the Bravo Dome, the Sheep Mountain Field and the Jackson Dome.[4,8] A small fraction of the CO_2 supply comes from anthropogenic sources, including the Mitchell, Gray Ranch, Pucket and Terrell gas processing facilities in the southern Permian basin and the Great Plains coal gasification plant at Beulah, North Dakota.[3, 6]

The operation of the Canyon Reef Carriers pipeline, one of the first CO_2 pipelines constructed for EOR, provides a reference for future CO_2 handling systems. Put into operation in 1972, it recorded only five failures (with no injuries) during its first twelve years of operation. Two failures were explosions at compressor stations that resulted from air (oxygen) being drawn into the suction line from the extraction plant stack line. In order to rectify the problem, the emergency shutdown system was adjusted so that the loss of positive pressure on the suction line would cause the compressors to come to an immediate halt. The three other failures were ruptures at the injection station due to localized 'hot spots' in the tubes of the direct-fired line heater. The first was attributed to the build-up of a corrosion product in a pipe that took place before its installation and was not removed by initial cleaning. The other two ruptures occurred near support brackets where the distribution of flow through the parallel tube arrangement was not equal. Provisions for better temperature monitoring and flow distribution in the heater were put in place to prevent further such accidents.[9]

An important technical consideration in the design of pipelines for transport of supercritical CO_2 is that the CO_2 remains above critical pressure. This can be achieved by means of recompression of the CO_2 at certain points along the length of the pipeline. Recompression is often needed for pipelines over 150 km (90 miles) in length. It is important to note, however, that recompression may not be needed if a sufficient pipe diameter is used. For example, the Weyburn CO_2 pipeline runs for 330 km (205 miles) from North Dakota to Saskatchewan, Canada, without recompression.[10]

A survey of North American pipeline project costs yields several pertinent observations. First, for a given pipeline diameter, the per unit distance cost of construction is generally lower the longer the pipeline. Second, pipelines built nearer populated areas tend to be more expensive. Finally, road, highway, river, or channel crossings and marshy or rocky terrain also greatly increase the cost.[11]

4.3 Process Description

The CO_2 for pipeline transport is taken from Case 3a of the DOE/EPRI Report on CO_2 removal from fossil fuel power plants.[12] This case is used for the design basis since potential CO_2 sources from a coal-based power plant would most probably be associated with an IGCC plant. CO_2 recovery from IGCC is most economical because of the CO_2 concentration in syngas at a high partial pressure, enabling the use of conventional recovery processes. The pipeline is to be designed to handle 3.76 million scm (7,389 tonnes) of CO_2 per day. It is important to note that,

since the capacity factor of the IGCC power plant is assumed to be 80 percent, this CO_2 is only supplied 80 percent of the time.

The pipeline design must conform to the United States Department of Transportation (DOT) Codes 49 CFR 195, Transportation of Hazardous Liquids by Pipeline, and 49 CFR 192, Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards.

4.4 Methodology Used

The first stage of the CO_2 storage process involves the CO_2 being transported via pipeline from the base case IGCC plant to the injection site, for the geologic storage options, and to the shoreline collection point, in the case of the ocean storage options. Overland distances of 100 and 300 km, for the base and sensitivity cases respectively, are considered. The method used to calculate the cost of CO_2 pipeline transport can be broken down into a couple of steps. First, the diameter of the pipeline is calculated. Next, based on the calculated diameter, the capital and O&M costs as well as the total cost per tonne of CO_2 are found. An overview of the cost model is given in Figure 4-1. The diameter and cost calculations are explained in greater detail below.

Inputs:
CO_2 mass flow rate
Pipeline length
CO_2 inlet pressure
CO_2 outlet pressure
Capital charge rate

TRANSPORT MODEL
Internal Calcs:
CO_2 density
CO_2 viscosity
Pressure drop per unit length
Pipe diameter

Outputs:
Total capital cost
Total O&M cost
Total annual cost
Total cost per tonne
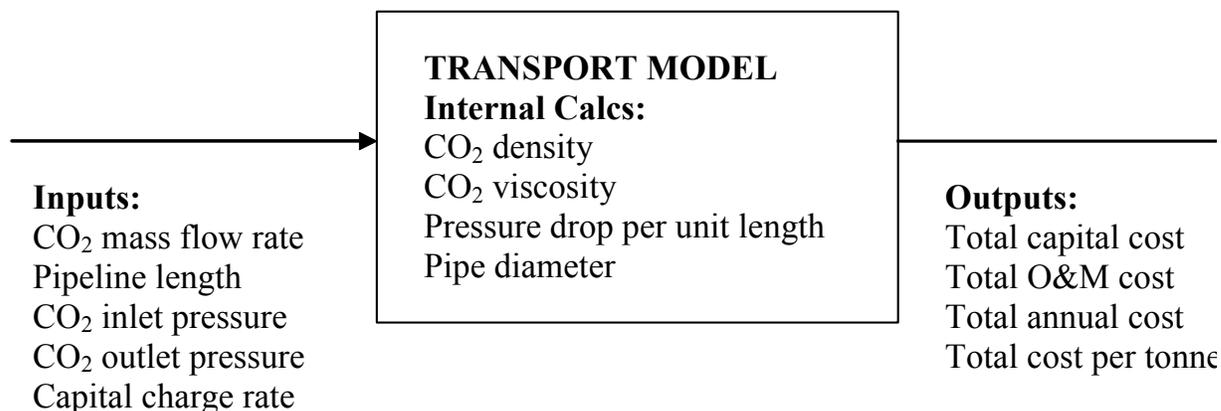
Figure 4-1
Pipeline transport cost model overview diagram

4.4.1 Diameter Calculation

The pipeline inlet CO_2 pressure is set equal to 152 bar, which is equivalent to the pressure of the CO_2 supplied by the base case IGCC plant. Based on a recommendation that the pipeline CO_2 pressure not be allowed to fall below 103 bar,[13] this latter value is used for the pipeline outlet CO_2 pressure. The maximum allowable pressure drop per unit length ($\Delta P/\Delta L$) is found as the difference between the pipeline inlet and outlet CO_2 pressures divided by the pipeline length.

Next, based on an assumed ambient temperature of 25ºC, the CO_2 density and viscosity are calculated. The CO_2 density (ρ) is calculated to be 884 kg/m^3, using a correlation based on data from the National Institute of Standards and Technology (NIST) for a temperature range of 5 to

Pipeline Transport

27°C and a pressure range of 80 to 140 bar.[14] The CO_2 viscosity (μ) is found, from a correlation published by Nihous and Bohn,[15] to be 6.06 x 10^{-5} N-s/m^2.

The pipeline diameter is calculated using the equations for pressure drop and head loss due to frictional resistance in a pipe, assuming turbulent flow. This calculation uses an iterative procedure, which initially requires that the diameter be guessed. This guessed value is used to find the Reynolds number (Re) given by

$$Re = 4m/\pi\mu D$$

where m is the CO_2 mass flow rate and D is the pipeline diameter. Based on this calculated Reynolds number and a roughness factor of 0.00015,[16] the Fanning friction factor (f) is then found using an empirical relationship based on the Moody chart. Combining the equations for pressure drop and head loss gives the simplified formula

$$D^5 = 32fm^2/\pi^2\rho(\Delta P/\Delta L)$$

from which the diameter is determined. This calculated value of diameter is then used for the next iteration, and so on. 1 in = 0.0254m

Figure 4-2 gives the diameter, calculated for the base case, as a function of CO_2 mass flow rate.
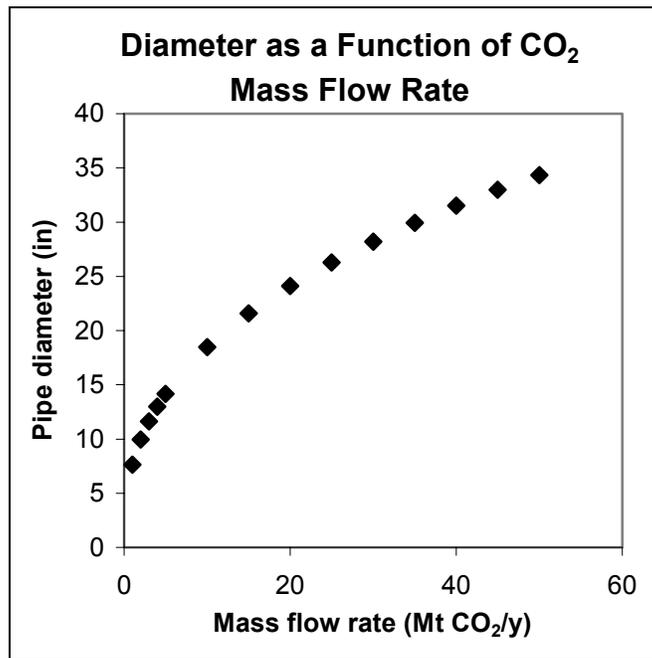
1 in = 0.0254m

Figure 4-2
Diameter for the base case as a function of CO_2 mass flow rate

4.4.2 Cost Calculations

The amount of cost data on CO_2 pipelines in the open literature is very limited, but there is an abundance of cost data for natural gas pipelines. For this reason, land construction cost data for natural gas pipelines were used to estimate construction costs for CO_2 pipelines. This is adequate given that there is little difference between land construction costs for these two types of pipeline.[8] It is worth noting, though, that CO_2 pipelines might be slightly more expensive because of the greater wall thickness needed to contain the CO_2, which is transported at higher pressures.

The cost data found for natural gas pipelines consists of cost estimates filed with the United States' Federal Energy Regulatory Commission (FERC), and reported in the Oil and Gas Journal. [11,17] Figure 4-3 gives the breakdown of costs on a dollar per mile basis for four pipeline diameters: 8, 16, 24 and 30 inches (0.20, 0.41, 0.61, and 0.76 m). Costs are broken down into material, labor, right-of-way (ROW) and miscellaneous components. Materials can include line pipe, pipe coating, cathodic protection and telecommunications equipment. Right-of-way costs include obtaining the right-of-way and allowing for damages. Miscellaneous costs generally cover surveying, engineering, supervision, contingencies, allowances for funds used during construction, administration and overheads, and regulatory filing fees.
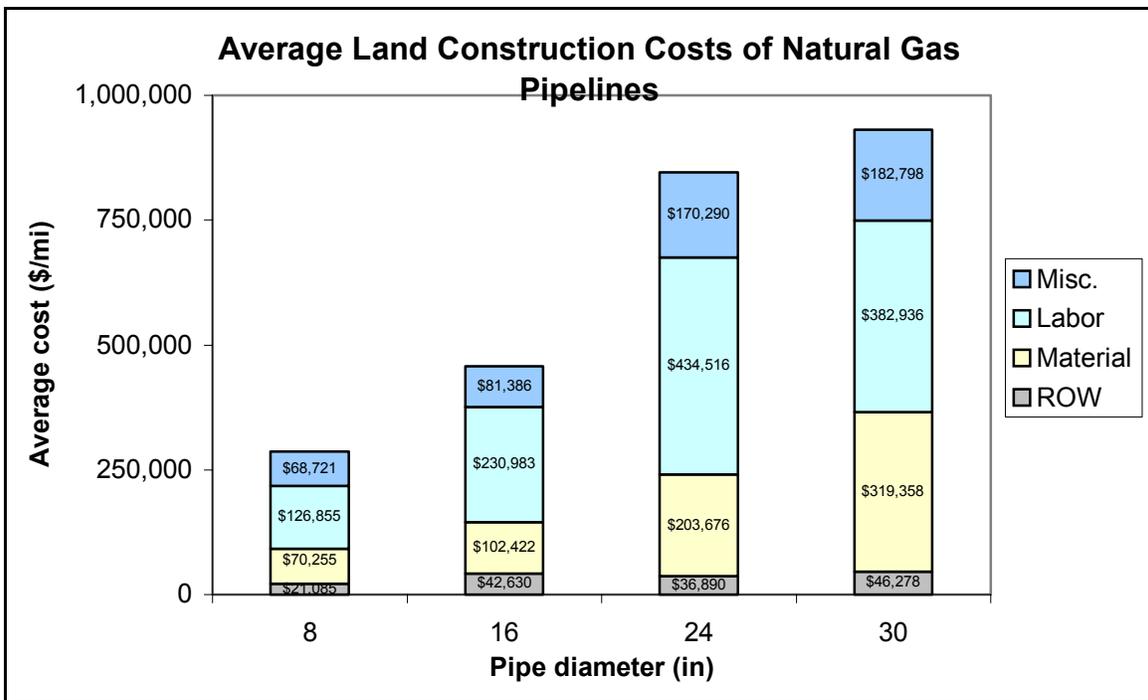
1 in = 0.0254m, 1 mi = 1.61 km

Figure 4-3
Breakdown of pipeline cost on a dollar per mile basis

A breakdown of costs on a percentage of total cost basis is given in Figure 4-4. The graph suggests that right-of-way costs can be estimated at 5% of total costs, while labor, material, and

miscellaneous costs appear to be random percentages of total costs. It is also important to note that each of these costs is independent of pipeline diameter.

Average Land Construction Costs of Natural Gas Pipelines

Pipe diameter (in)	%Misc.	%Labor	%Material	%ROW
8	22.9%	42.4%	23.5%	7.0%
16	17.8%	50.5%	22.4%	9.3%
24	20.1%	51.4%	24.1%	4.4%
30	19.6%	41.1%	34.3%	5.0%
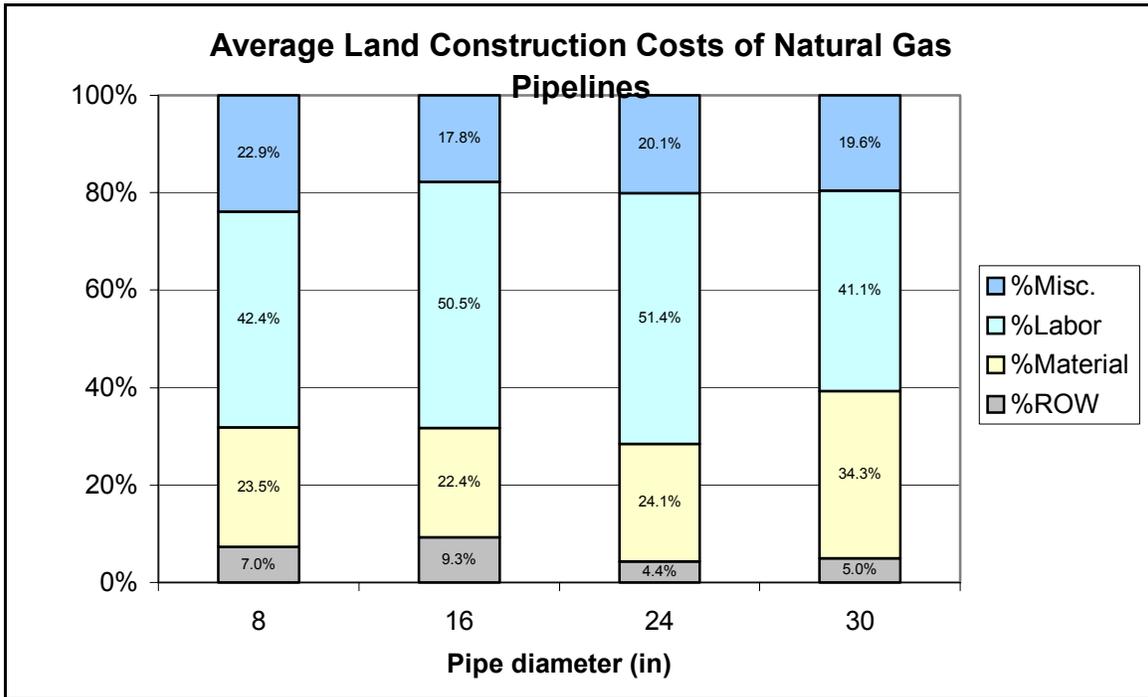
1 in = 0.0254m

Figure 4-4
Breakdown of pipeline cost on a percentage of total cost basis

Total costs in dollars per mile are plotted against pipeline diameter in Figure 4-5. A regression line fit to this data yields a pipeline construction cost of \$20,989/in/km (\$33,853/in/mile). According to an industry expert[13] the construction cost for CO_2 pipelines should be close to \$12,400/in/km (\$20,000/in/mile). One possible reason for this lower CO_2 pipeline construction cost estimate is that CO_2 pipelines are currently constructed in sparsely populated areas. Another is that the rock in New Mexico and West Texas where most CO_2 pipelines have been laid is easy to dig in. It is important to note that neither cost figure includes recompression costs.

Land Construction Cost Data for Natural Gas Pipelines 1989-1998

$y = 33853x$
$R^2 = 0.9363$

Error bars represent one standard deviation of cost data over a period of 10 years for a given diameter.

1 in = 0.0254m, 1 mi = 1.61 km
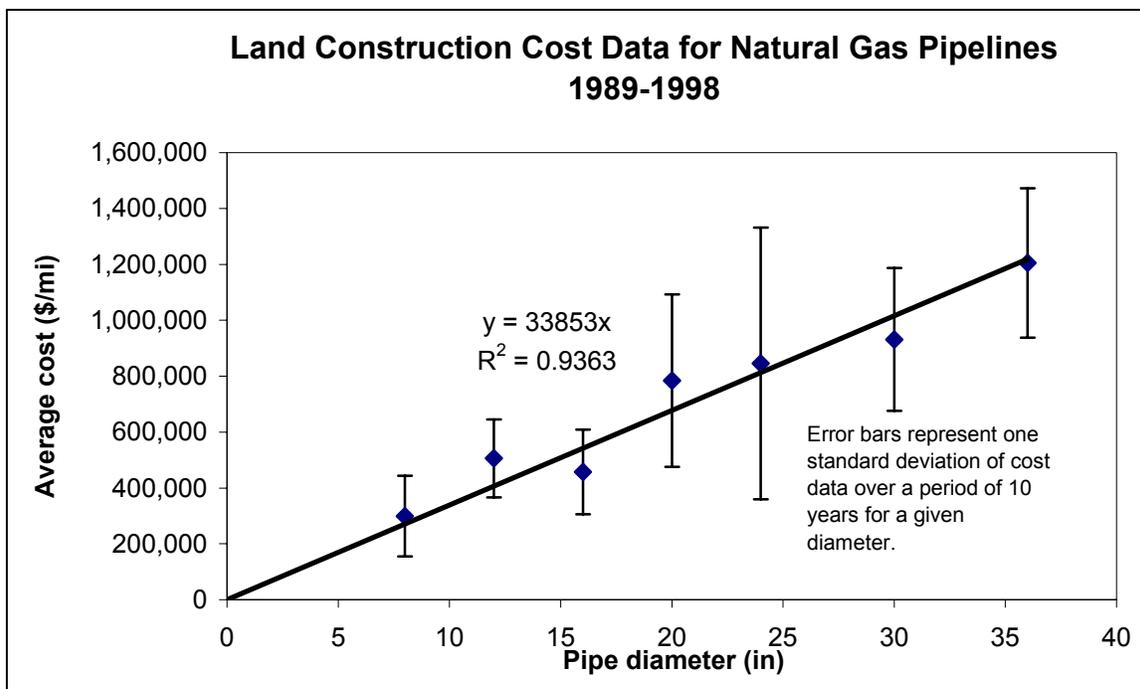
Figure 4-5
Regression analysis of pipeline construction cost data

It has been reported that it costs about $40,000 to $60,000 per month to operate 186 km (300 miles) of pipeline and that this figure should be doubled to account for associated overhead costs.[13] Taking the higher value to be on the conservative side, O&M costs are estimated to be $3,100/km ($5,000/mile) per year, independent of pipeline diameter. It should be noted that this O&M cost estimate does not account for pumping or its associated costs.

Total pipeline construction cost is found using the $20,989/in/km ($33,853/in/mile) cost factor. Applying the O&M cost factor of $3,100/km ($5,000/mile), gives the respective total O&M costs. Finally, the total annual cost per tonne of CO_2 is found by annualizing the construction cost using a capital charge rate of 15% per year and adding this to the annual O&M cost. Figure 4-6 shows the cost per tonne of CO_2, calculated for the base case, as a function of CO_2 mass flow rate.
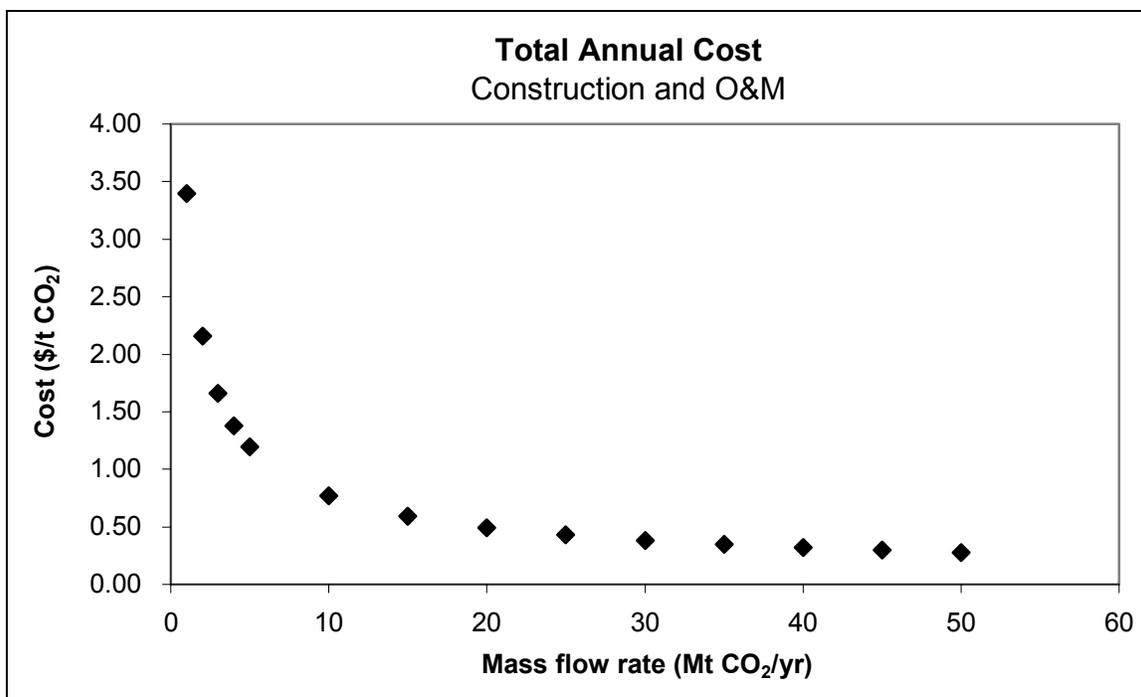
Figure 4-6
Total cost per tonne of CO$_2$ for the base case as a function of CO$_2$ mass flow rate

4.5 Design Basis

4.5.1 Pipeline Design

The methodology described in Section 4.4.1 was used to determine pressure drop per unit length and pipeline diameter for the base and sensitivity cases. The design bases for pipeline transport are summarized in Table 4-2.

Table 4-2
Design bases for pipeline transport

Parameter	Unit	Pipeline Transport Base Case	Pipeline Transport Sensitivity Case
Pipeline Length	km	100	300
CO$_2$ Inlet Pressure	MPa	15.2	15.2
CO$_2$ Outlet Pressure	MPa	10.3	10.3
Pressure Drop per Unit Length*	Pa/m	49	16
Pipe Diameter*	inches	11.2	13.8
Nominal Pipe Size*	inches	12	16

* calculated
1 in = 0.0254m

4.5.2 Capital and O&M Cost Inputs

The capital and O&M costs of the pipeline, for the base and sensitivity cases, were calculated using the methodology described in Section 4.4.2. Table 4-3 shows the results.

Table 4-3
Capital and O&M cost inputs for the pipeline transport base and sensitivity cases

Parameter	Unit	Pipeline Transport Base (100 km) Case	Pipeline Transport Sensitivity (300 km) Case
Pipe Diameter	inches	11.2	13.8
Capital Cost	$	23,500,000	87,100,000
O&M Cost	$	310,000	930,000

The total cost of constructing the pipeline is $23.5 and $87.1 million for the 100 and 300 km cases, respectively. The construction cost of the 300 km pipeline is more than three times the cost of the 100 km pipeline due to the fact that a larger diameter pipe is required, i.e. a 16-inch as opposed to 12-inch pipe.

4.6 MIT Model Results

Based on the model developed by MIT, the respective values of total cost per tonne of CO_2 for the base and sensitivity cases are $1.78 and $6.49. These are converted to CO_2 equivalent LC GHG avoided bases in Chapters 5-9 when they are combined with the storage concepts.

4.7 Comparison to Literature

4.7.1 Studies Used in Model Evaluation

Data related to overland pipeline transport of CO_2 were taken from the studies listed in Table 4-4.

Pipeline Transport

Table 4-4
Overland pipelines' characteristics

Study	CO$_2$ flow rate (Mt/yr)	Initial CO$_2$ pressure (bar)	Diameter (m)	Length (km)	Recompression station included
IEA aquifer[18]	3.90	208	0.400	30	No
IEA depleted reservoir[18]	3.16	110	0.400	50	No
British Coal[19]	3.63	136	0.350	425	Yes
Weyburn[10]	2.00	170	0.305	127	No

A pumping station is required for the 'British Coal' CO$_2$ pipeline, of which only the onshore section is considered here, due to its extreme length. For the purpose of comparing the capital cost of this pipeline with that determined by the model, the pumping station was ignored. It should also be noted that cost data were not available for the 'Weyburn' pipeline.

4.7.2 Comparison of Values from Model and Studies

The graph below in Figure 4-7 shows pipe diameter as a function of CO$_2$ mass flow rate. Also shown in the figure, is the value of pipe diameter, for a specific CO$_2$ mass flow rate, given in each of the four studies. The model's calculation of pipe diameter can be seen to strongly agree with this studies' estimate.

Diameter as a Function of CO$_2$ Mass Flow Rate

Figure 4-7 shows the chart with Pipe diameter (in) on the y-axis ranging from 0 to 40, and Mass flow rate (Mt CO$_2$/yr) on the x-axis ranging from 0 to 60.

Legend:
- Transport Model (Base Case)
- IEA aquifer study
- IEA depleted reservoir study
- British Coal
- Weyburn
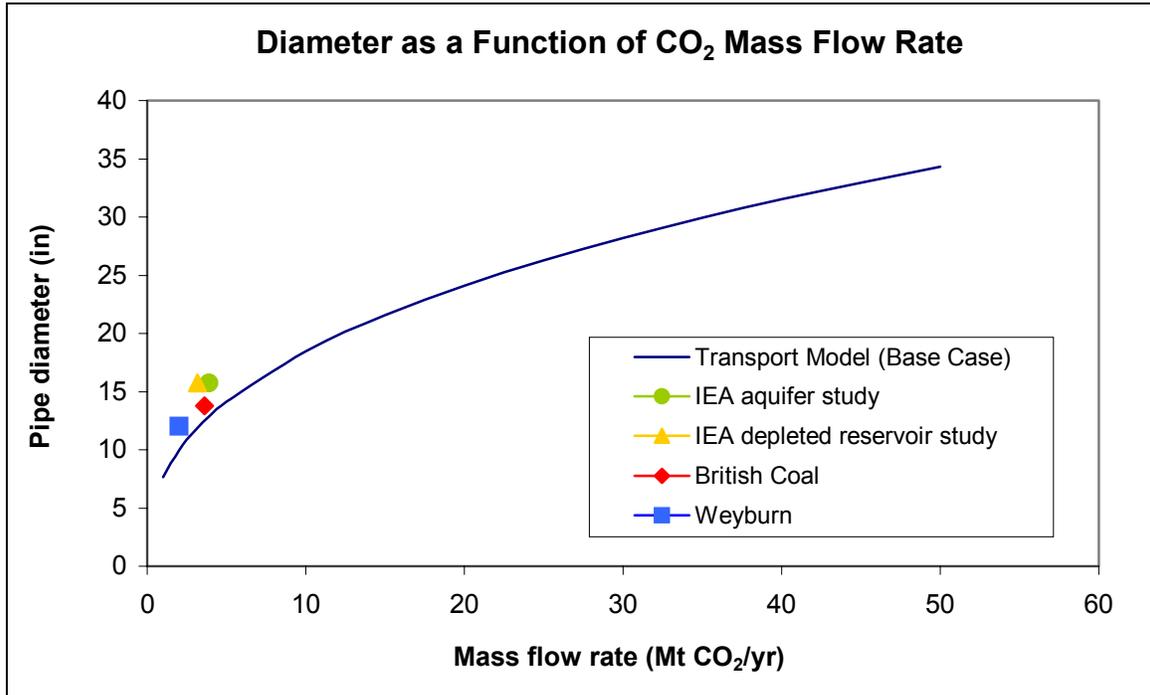
Figure 4-7
Comparison of pipe diameter values

Similarly, Figure 4-8 shows that there is general agreement within the uncertainties of the values between pipeline capital cost as calculated by the model and used in the studies. The discrepancy between modeled pipeline cost and that given in the case of the 'British Coal' pipeline can be attributed to the additional costs associated with the latter being located in a more populated area and in Europe as opposed to North America.

Pipeline Transport

Construction or Capital Cost

Figure showing Cost ($M/100 km) on the y-axis (0 to 120) versus Mass flow rate (Mt CO_2/yr) on the x-axis (0 to 60). Legend: Transport Model (Base Case), IEA aquifer study, IEA depleted reservoir study, British Coal.
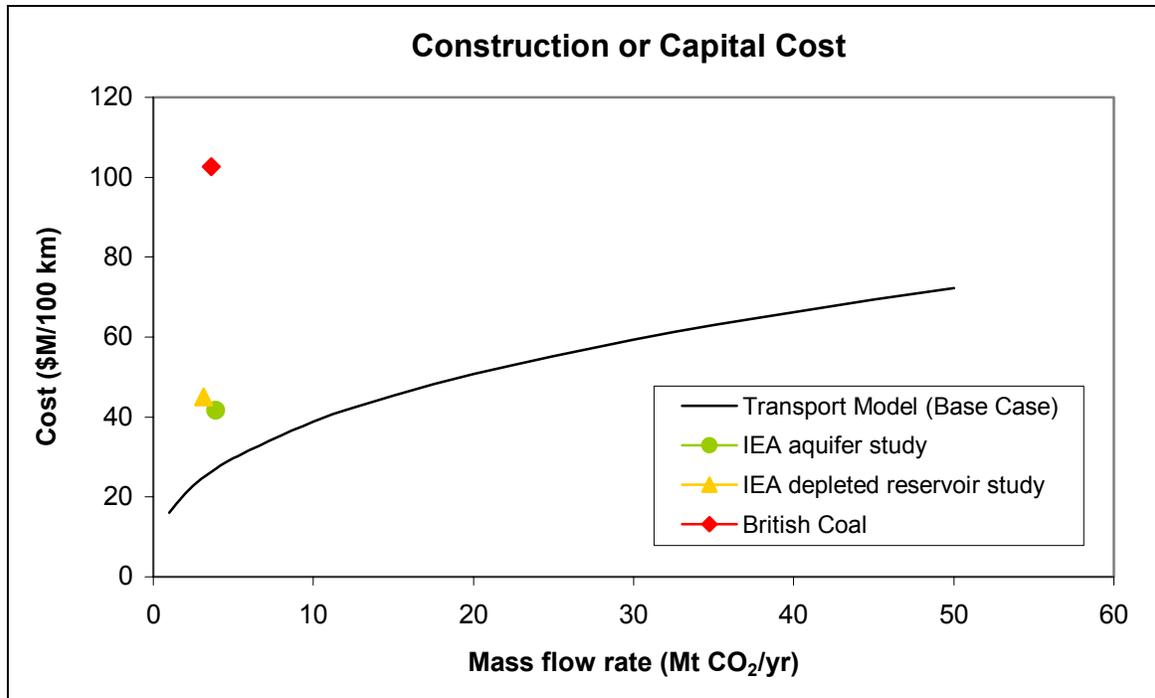
Figure 4-8
Comparison of pipeline capital cost values

The O&M cost used in the 'IEA aquifer' study is compared to the estimate provided by Fox in Figure 4-9. There was no O&M cost specified for the 'IEA depleted reservoir' or 'British Coal' pipeline. It is not possible to undertake a comparison for total annual cost per tonne of CO_2 due to uncertainties regarding the capital charge factors used in the studies.
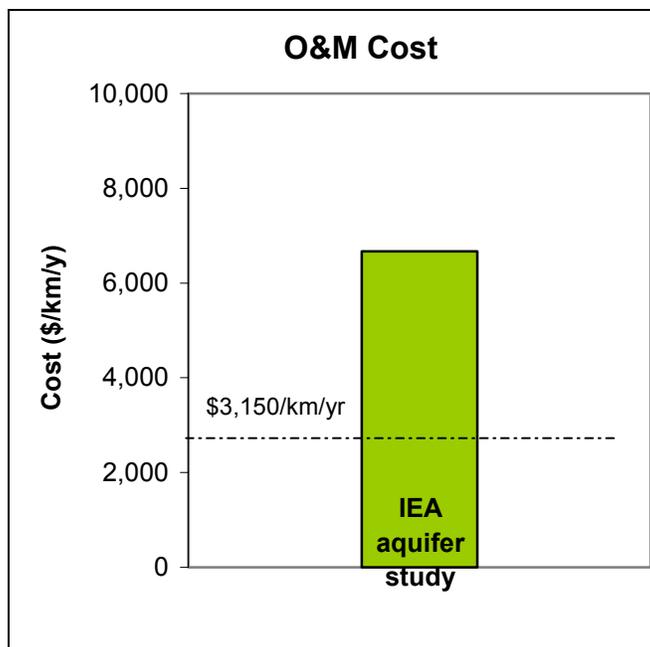
O&M Cost

Figure 4-9
Comparison of O&M cost values

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5
ENHANCED OIL RECOVERY

5.1 Introduction

This chapter deals with the storage of CO_2 in depleted oil reservoirs where enhanced oil production results in a value-added product. The use of depleted oil reservoirs for CO_2 storage without enhanced production is treated separately in Chapter 7.

5.2 State of the Art

5.2.1 Applications

There were a total of 84 commercial or research-level applications of enhanced oil recovery using CO_2 floods (CO_2-EOR) worldwide in 2000. The amount of enhanced oil production from these CO_2-EOR projects during that year averaged 200,772 barrels (bbl) of oil per day[a], which is only a very small amount (0.3 percent) of that year's total worldwide oil production of 67.2 million bbl of oil per day. The United States account for 72 of the 84 projects, or 96 percent of worldwide enhanced oil production from CO_2 floods, and is as such the world leader in the use of CO_2-EOR technology. Currently, Turkey is the only other country with a commercial-scale application of CO_2-EOR, with Canada and Trinidad having only pilot-scale projects.[1,2]

Enhanced oil production from the 72 CO_2 floods in the United States in 2000 was 192,209 bbl of oil per day, which is equivalent to 5 percent of total U.S. oil production during the same period. Most of these CO_2 floods (53) are located in the southwestern United States within the Permian basin of western Texas and eastern New Mexico. The next largest concentrations of CO_2 floods in the United States are in the Rocky Mountain and Mid-continent regions. The details of the six largest CO_2-EOR projects in 2000 are given in Table 5-1. It should be noted that these six projects are all situated in the United States and that together they accounted in 2000 for 47 percent of worldwide enhanced oil production from CO_2 floods.[1,2]

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[a] Only the oil recovered due to the CO_2 flood is included here as enhanced oil production. Quoted enhanced oil production figures may thus account for only a fraction of the total amount of oil produced during the tertiary recovery process.

Enhanced Oil Recovery

Table 5-1
Six largest CO_2-EOR projects[1]

Operator	Field	Basin/Region	Area (km^2)	Production Wells	Injection Wells	EOR Production (bbl/d)
Altura	Wasson (Denver)	Permian	113	735	385	29,000
Amerada Hess	Seminole (Main)	Permian	64	408	160	25,900
Chevron	Rangely Weber Sand	Rocky Mountain	61	341	209	11,208
ExxonMobil	Salt Creek	Permian	49	137	100	9,300
Devon Energy	SACROC	Permian	202	325	57	9,000
Altura	Wasson (ODC)	Permian	32	293	290	9,000

Currently, there is no commercial-scale CO_2-EOR project that utilizes CO_2 from a power plant. In the 1980s, there were three small-scale CO_2-EOR projects that utilized CO_2 from gas boiler power plants. These plants were shut down when the price of oil dropped in the mid-1980s, making this source of CO_2 too expensive.[3] The main obstacle to the utilization of this source of CO_2 for EOR is its significant cost of capture. Most of the CO_2-EOR projects, particularly those located in the Permian basin, are dependent upon naturally occurring CO_2, which is obtained from high-pressure, high-purity underground deposits. The most important of these natural CO_2 deposits, in decreasing order of size, are the McElmo Dome, the Bravo Dome, and the Sheep Mountain Field.[4] A small fraction of the Permian basin CO_2 supply has also come from anthropogenic sources, namely the Mitchell, Gray Ranch, Pucket, and Terrell gas processing facilities in the southern Permian basin. In contrast, the Rocky Mountain and Mid-continent regions are almost wholly supplied by anthropogenic CO_2 from gas processing and fertilizer production facilities. The Rangely Weber Sand CO_2-EOR project, for example, is supplied by the La Barge gas processing plant in southwestern Wyoming and is as such the world's largest single sequestration site of anthropogenic CO_2.[5]

5.2.2 Storage Potential

The Weyburn Field in southeastern Saskatchewan, Canada, is the only CO_2-EOR project to date that has been monitored specifically to understand CO_2 sequestration. In the case of most CO_2-EOR projects, much of the CO_2 injected into the oil reservoir should be considered as being only temporarily stored. This is because the decommissioning of an EOR project usually involves the "blowing down" of the reservoir pressure to maximize oil recovery. This "blowing down" results in CO_2 being released[b], with a small but significant amount of the injected CO_2 remaining

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[b] The CO_2 from 'blow down' may be either vented or reused in other EOR fields.

dissolved in the immobile oil. In the case of the Weyburn Field, no "blow-down" phase is planned, thereby allowing for permanent CO_2 sequestration. Over the anticipated 25-year life of the project, it is expected that the injection of some 18 million tonnes of CO_2 from the Dakota Gasification Facility in North Dakota will produce around 130 million bbl of enhanced oil. This has been calculated to be equivalent to, taking into account the CO_2 emitted by the generation of electricity required, approximately 14 million tonnes of CO_2 being prevented from reaching the atmosphere.[5,6]

5.2.3 Storage Mechanics

Most CO_2 floods achieve enhanced oil production through miscible, as opposed to immiscible, displacement. The six largest CO_2-EOR projects described above, for example, are all miscible CO_2 floods. Miscible displacement involves the injected CO_2 mixing thoroughly with the oil in the reservoir whereas, in the case of immiscible displacement, the CO_2 remains physically distinct from the oil. The type of displacement that occurs is dependent on the reservoir pressure and crude oil composition, with a reservoir depth greater than 1,200 m and an oil density less than 22° API typically leading to miscible conditions. Miscible displacement leads to an ultimate recovery of about 7 to 15 percent of the original oil in place (OOIP). Immiscible displacement yields lower recoveries compared to miscible conditions, but can still achieve a high recovery rate due to oil swelling and viscosity reduction. Currently, only one large CO_2-EOR project, located in Turkey, utilizes immiscible processes. However, it is expected that the number of immiscible CO_2 floods will increase as the use of CO_2-EOR becomes increasingly widespread.[1,5,7,8,9]

In CO_2-EOR projects, it is most common for the CO_2 to not be injected as a continuous gas stream, but for it to be alternated with water injection in a water-alternating-gas (WAG) process. This WAG process is carried out to help overcome the problem of high CO_2 mobility that greatly reduces the effectiveness of CO_2 flooding. This high CO_2 mobility problem, caused by the CO_2 having a lower density and viscosity than the reservoir oil, is responsible for the phenomena of gravity tonguing and viscous fingering. These phenomena are undesirable as they lead to injected CO_2 flowing through areas that have already been swept. Taking advantage of the fact that water is less mobile than CO_2, the WAG process is able to significantly improve the sweep efficiency through reducing CO_2 mobility. This, in turn, results in improved oil recovery while also preventing early CO_2 breakthrough in producing wells. The world's largest CO_2-EOR project, Wasson (Denver), is an example of a WAG flood.[5,9,10]

5.2.4 Feasibility of Storage Option

The use of CO_2 floods for EOR presents a very attractive CO_2 storage option. Even without CO_2 sequestration credits, most of the active CO_2-EOR projects are profitable. In addition to a value-added product, CO_2-EOR has the advantage that it has been widely applied and is a proven technology. Furthermore, significant advances continue to be made in the computer simulation of CO_2 flood performance. This CO_2 storage option also has the added bonus that most oil fields have already undergone primary and secondary recovery prior to CO_2 flooding. This means that certain components of the existing infrastructure, such as the wells, are able to be simply adapted

for CO_2 storage purposes. There is the downside that CO_2 floods require significant additional infrastructure to handle the processing and recycling of CO_2. On a positive note, however, the cost of anticorrosive equipment to deal with the problem of CO_2 reacting with water to form carbonic acid has recently been reduced.[5,7]

5.3 Process Description

The CO_2 for the EOR case is taken from Case 3a of the DOE/EPRI Report on CO_2 removal from fossil fuel power plants.[11] This case is used for the design basis since potential CO_2 sources from a coal-based power plant would most probably be associated with an IGCC plant. CO_2 recovery from IGCC is most economical because of the CO_2 concentration in syngas at a high partial pressure, enabling the use of conventional recovery processes. The storage system is to be designed to handle 3.76 million scm (7,389 tonnes) of new CO_2 per day. It is important to note that, since the capacity factor of the IGCC power plant is assumed to be 80 percent, this new CO_2 is not available 20 percent of the time. Consideration of this issue is beyond the scope of the current project.

Figure 5-1 is a block flow diagram, indicating the overall flow and distribution of CO_2 from the IGCC power plant to the EOR field. First, the CO_2 leaving the plant is fed to an additional stage of compression to bring it up to the required pipeline inlet pressure. Second, the pipeline transports the CO_2 a distance of 100 km to the EOR field, where it is mixed with recycled CO_2 and injected into the EOR CO_2 injection wells. Third, the oil produced at the EOR wells is separated from water and CO_2 at the surface. Finally, the CO_2 is dehydrated, compressed, and mixed with fresh incoming CO_2.

The CO_2 injection wells are an important component of the EOR field. These wells function as conduits for moving supercritical CO_2 fluid from the surface down into the reservoir. The wells are regulated under the provisions of the Underground Injection Control (UIC) Program under the Federal Safe Drinking Water Act (SDWA) as either Class I or Class V wells.[12]

The EOR field also consists of a distribution system, which serves the following functions:

- Receives CO_2 from the pipeline terminal and distributes it to the EOR CO_2 injection wells.

- Gathers oil from the EOR production wells and delivers it to the tank battery.

- Compresses separated CO_2 and mixes it with pipeline CO_2 for injection into EOR CO_2 injection wells.

The oil from the EOR production wells is carried by small pipelines called flow lines to a part of the production site known as the tank battery. In addition to storage tanks, the tank battery contains equipment for preparing the oil before further distribution. The fluid coming out of nearly all wells is actually a mixture of oil, gas (in this case CO_2), salt water, and sediment. First, most of the CO_2 present is separated from the oil and water at 7 bar, recompressed and recycled, then re-injected to help maintain reservoir pressure, and thereby, production. Separation of the remaining mixture is accomplished in special tanks where the settling process

separates water and oil, or it may be assisted by special equipment such as a heater treater. Vapor recovery units recover the remaining CO_2, which is also recompressed and recycled.

Testing of the oil to determine its properties is conducted at the well site by taking samples of oil from the storage tanks. Today, oil volumes are measured with Lease Automatic Custody Transfer facilities (LACTs), which do most of the measuring, sampling, and testing without human intervention. Oil that has been completely prepared is stored in tanks at the well site until it is transported to the refinery.

Most CO_2-EOR projects take place at fields that have already undergone secondary recovery, i.e. waterflooding. The modification of water-flooded fields for CO_2 flooding involves:

- Makeover and equipping of injection wells

- Installation of CO_2 distribution and recycle systems

- Provision of high-pressure injection equipment and related piping

- Replacement of selected production facilities

The production phase of the Weyburn field is expected to be more than 25 years. The Millennium Energy CO_2 flood in West Texas has been going on since 1983. It is assumed that this flood has, like the power plant, a lifetime of 20 years. As a final note, the design/construction time is taken to be the same as the power plant, 4 years.
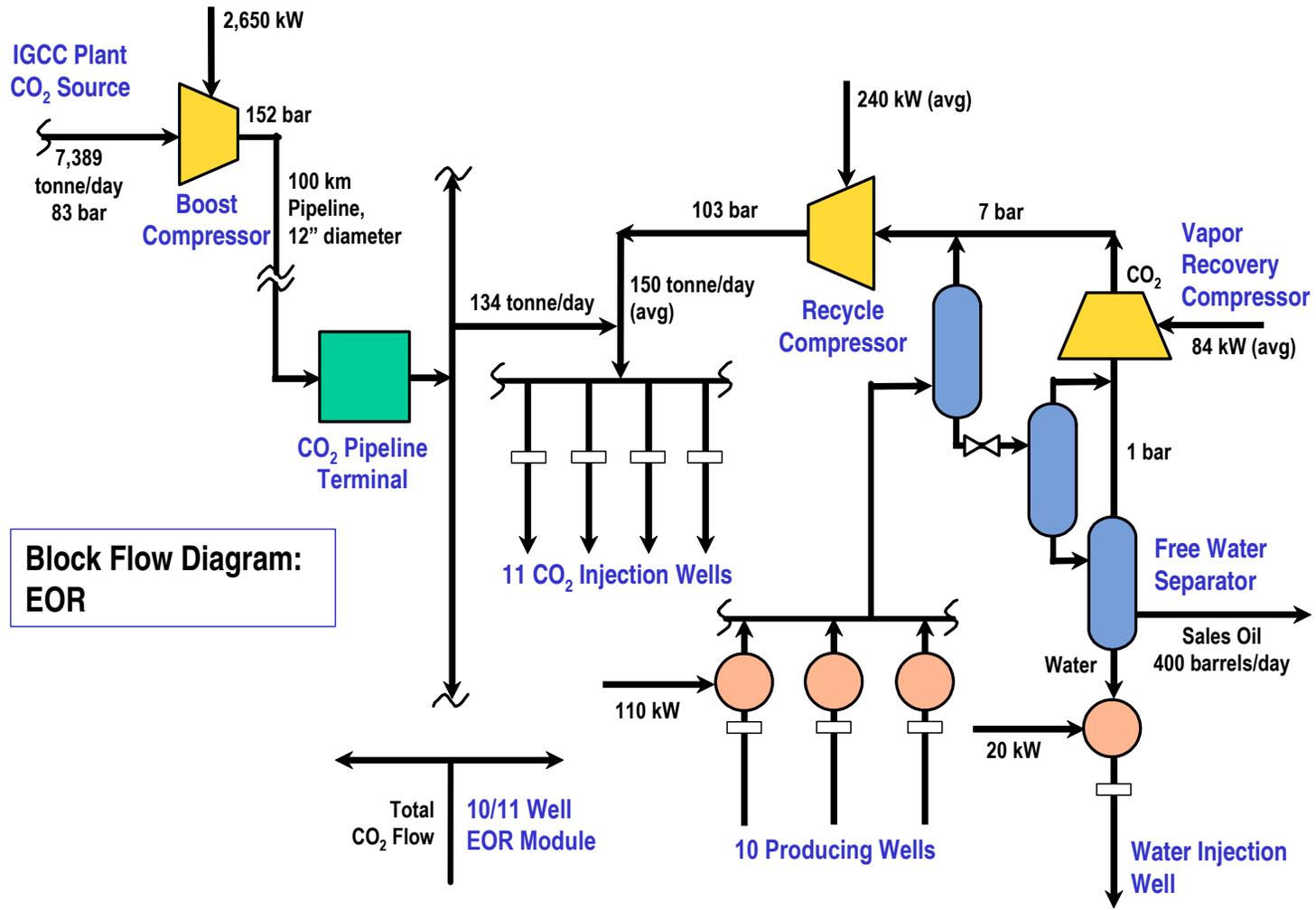
Figure 5-1
EOR block flow diagram

5.4 Methodology Used

For specific projects, the complex interactions between the injected CO_2 and reservoir oil would be modeled to assess the likely performance of a proposed CO_2-EOR project. Based on the output of this modeling, the cost of the proposed CO_2 flood is calculated. However, for our purposes of developing general costing algorithms, 'rules of thumb' are used to define the engineering parameters needed to estimate the cost of a CO_2-EOR project. These 'rules of thumb' have been derived based on information from experts in the field and the literature.

The method used for costing the EOR process can be split up into a number of steps. First, the average amount of enhanced oil produced per day for the given CO_2 mass flow rate is determined using a CO_2 effectiveness factor of 170 standard cubic meters (6,000 standard cubic feet) of new CO_2 per bbl of enhanced oil. Second, the number of production wells is found by dividing this total amount of enhanced oil produced per day by an assumed average of 40 bbl of enhanced oil per day being produced at each well. Third, a ratio of producers to injectors of 1 to 1.1 is used to calculate the number of injection wells from the number of production wells. Fourth, the capital cost of the CO_2 recycle plant is determined based on a maximum CO_2 recycle ratio of 3, with an average recycle ratio of 1.1 being used for the plant's O&M costs. Finally, the capital and O&M costs associated with the wells and the field equipment are calculated. Figure 5-2 provides an overview of the cost model, with the assumptions made in each of these steps being discussed below in more detail.

5.4.1 CO_2 Effectiveness

For the EOR-design basis, an average of 170 scm (6,000 scf) of CO_2 is taken to remain in the ground for each bbl of enhanced oil production. It is important to note, however, that the effectiveness of CO_2-EOR varies both from one basin to another and within a basin itself. In the case of the Permian basin, Malcolm Wilson from the Petroleum Technology Research Center indicated that around 170 to 227 scm (6,000 to 8,000 scf) of CO_2 per bbl of enhanced oil would remain in the ground.[13] In contrast, the CO_2 effectiveness in the Weyburn Field, according to Ray Hattenbach from the Dakota Gasification Company, is closer to 85 scm (3,000 scf) per bbl of enhanced oil.[14] Given this, it was deemed necessary that the sensitivity of the cost of EOR to a range of CO_2 effectiveness values be determined. Based on the rough estimates given above, and the values given in the literature (see Table 5-2), a range of 85 to 227 scm (3,000 to 8,000 scf) of CO_2 per bbl of enhanced oil was chosen for the sensitivity calculation.

The CO_2-EOR projects in Table 5-2 have illustrate the range of CO_2 effectiveness. The projects chosen include two of the largest CO_2 floods in the Permian basin. In addition, two other smaller CO_2-EOR projects in this basin, namely Dollarhide (Devonian) and Vacuum, are provided as examples of CO_2 floods displaying relatively high and low CO_2 effectiveness, respectively. CO_2-EOR projects located in the other two main CO_2-flood regions are also included. These projects comprise the two largest CO_2 floods in the Rocky Mountain region while, for the Mid-continent region, data was only available for two medium-sized floods. Finally, a last case study is made of the highly efficient CO_2 flood at the Weyburn Field.

Rule of thumb:
CO_2 effectiveness

Rule of thumb:
Rate of enhanced oil
production at producer

Rule of thumb:
Ratio of producers to injectors

Rule of thumb:
CO_2 recycle ratio

**ENHANCED OIL
PRODUCTION
CALCULATION**

**PRODUCTION
WELL NUMBER
CALCULATION**

**INJECTION
WELL NUMBER
CALCULATION**

**QUANTITY CO_2
RECYCLED
CALCULATION**

Input:
CO_2 mass
flow rate

Input:
CO_2 mass
flow rate

Total enhanced oil production

Number of production wells

Number of 10/11 well modules

Compressor size and power requirement

COST MODEL
Internal Calcs:
Capital costs:
*Site screening & evaluation, injection
equipment, injection wells*
O&M costs:
*Normal daily expenses, surface
maintenance, subsurface maintenance*

Inputs:
Well depth
Capital charge rate

Outputs:
Total capital cost
Total O&M cost
Total annual cost
Total cost per tonne CO_2

Figure 5-2
EOR cost model overview diagram

Table 5-2
Estimated CO_2 effectiveness for selected CO_2-EOR projects[5,6]

Operator	Field	Basin/Region	Est. Ultimate EOR (million bbl)	Est. Ultimate CO_2 Sequestered (giga scm)	Est. CO_2 Effectiveness (scm/bbl)
Altura	Wasson (Denver)	Permian	348	47	136
Devon Energy	SACROC	Permian	169	26	153
Texaco	Vacuum	Permian	33	3	94
Spirit Energy	Dollarhide (Devonian)	Permian	28	5	177
Chevron	Rangely Weber Sand	Rocky Mountain	136	17	127
Merit Energy	Lost Soldier (Tensleep)	Rocky Mountain	24	3	117
Anadarko	Northeast Purdy	Mid-continent	17	2	117
Henry Petroleum	Sho-Vel-Tum	Mid-continent	10	3	292
PanCanadian	Weyburn	Saskatchewan	130	9	70

The CO_2 effectiveness has been calculated for the above CO_2-EOR projects by dividing the estimated total amount of CO_2 to be sequestered, taken as being equal to 90 percent of the CO_2 purchased,[5] by the estimated total amount of enhanced oil to be recovered over the lifetime of the project. The resulting estimates of CO_2 effectiveness are all, except for those for the Sho-Vel-Tum and Weyburn Field CO_2 floods, within the selected range of 85 to 227 scm (3,000 to 8,000 scf) of CO_2 per bbl of enhanced oil. In the case of the Sho-Vel-Tum flood, the use of the less-efficient immiscible displacement process to recover enhanced oil is the likely cause of the exceedingly high CO_2 effectiveness value.[1]

5.4.2 Rate of Enhanced Oil Production at Producer

The average amount of enhanced oil produced per day per well over the 20-year life of the field is taken to be 40 bbl. Unfortunately, there is no industry 'rule of thumb' for the amount of enhanced oil production that should be allowed at each production well on a daily basis. This is primarily because, as explained below, such a value is not used in practice as a basis for determining the number of production wells required. Given this, a value equal to the average amount of enhanced oil produced per day per well at the Weyburn Field has been adopted. Based on the calculated values of average daily enhanced oil production per well for the six largest CO_2-EOR projects, given in Table 5-3, this assumed base-case value of 40 bbl would seem adequate and a sensitivity range of 20 to 70 bbl appropriate.

There is no evidence to suggest that the amount of enhanced oil produced per day per well is dependent on the basin in which the CO_2 flood is located. The values of average daily enhanced oil production per well for the six largest CO_2-EOR projects, all but one of which are located in the Permian basin, can therefore be considered typical. The fact that the average of these enhanced oil production per well values is 44 bbl, which is very close to the assumed base-case value of 40 bbl, is reassuring.

Table 5-3
Average enhanced oil production per day per well for six largest CO_2-EOR projects[1]

Operator	Field	Basin/Region	Production Wells	EOR Production (bbl/day)	EOR Production (bbl/day/well)
Altura	Wasson (Denver)	Permian	735	29,000	40
Amerada Hess	Seminole (Main)	Permian	408	25,900	64
Chevron	Rangely Weber Sand	Rocky Mountain	341	11,208	33
ExxonMobil	Salt Creek	Permian	137	9,300	68
Devon Energy	SACROC	Permian	325	9,000	28
Altura	Wasson (ODC)	Permian	293	9,000	31

It should be noted that the EOR industry determines the number of production wells based, not on an optimal level of enhanced oil production per day per well, but rather, on a required well spacing. This required spacing of wells, set by a state's gas and oil commission, can vary significantly. The required spacing in one state might be one well per 0.08 km^2 (20 acres), while in another it might be one well per 1.30 km^2 (320 acres). It has not been possible here to calculate the well numbers using this method, as doing so would require that the typical amount of enhanced oil produced per acre be known.[14]

5.4.3 Ratio of Producers to Injectors

A ratio of producers to injectors of 1 to 1.1 is used in the EOR concept design. Since this ratio depends largely on the injection strategy used, it is important to note here that use of WAG injection is assumed. For WAG injection, the 'rule of thumb' is that there be a rough balance between producers and injectors. The specific choice of a 1 to 1.1 ratio can be attributed to the fact that modules comprising 10 production and 11 injection wells are used as the basis for costing in the EIA's 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report and this report is used here for cost data.[13,14]

Table 5-4 gives the ratio of producers to injectors for each of the six largest CO_2-EOR projects. It can be seen that, for those projects using the WAG process, the number of production and injection wells is roughly equal. However, this is not the case for the Seminole (Main) and SACROC projects for which CO_2 is injected continuously. The Lost Soldier (Tensleep) CO_2-EOR project, the second largest in the Rocky Mountain region, is also included in the table as it provides an example of a CO_2 flood having a producer to injector ratio of 1 to 1.1.

Table 5-4
Ratio of producers to injectors for selected CO_2-EOR projects[5,6]

Operator	Field	Basin/Region	Injection Strategy	Production Wells	Injection Wells	Producers: Injectors
Altura	Wasson (Denver)	Permian	WAG	735	385	1.9:1
Amerada Hess	Seminole (Main)	Permian	Continuous	408	160	2.6:1
Chevron	Rangely Weber Sand	Rocky Mountain	WAG	341	209	1.6:1
ExxonMobil	Salt Creek	Permian	WAG	137	100	1.4:1
Devon Energy	SACROC	Permian	Continuous	325	57	5.7:1
Altura	Wasson (ODC)	Permian	WAG	293	290	1:1
Merit Energy	Lost Soldier (Tensleep)	Rocky Mountain	WAG	54	60	1:1.1

5.4.4 CO_2 Recycle Ratio

The CO_2 recycle ratio is taken to have an average value of 1.1.[15] This value is used to calculate the power requirements of the CO_2 recycle plant. The CO_2 recycle ratio increases over the lifetime of the CO_2 flood, from effectively zero to its maximum value, as the amount of CO_2 produced with the oil at the production wells increases while the amount of oil produced decreases. This increase in the recycle ratio is well illustrated in the case of the Rangely Weber Sand CO_2-EOR project. During the first 10 years of CO_2 flooding, 9 giga scm of net CO_2 purchases and 10 giga scm of recycled CO_2 were injected, giving an average recycle ratio of 1.1. In contrast, the recycle ratio in 1998 was close to 2.8, with an average of 1.2 million scm per day of net CO_2 purchases and 3.3 million scm per day of recycled CO_2 being injected.[5]

5.4.5 Reworking of Existing Wells

It is assumed that only the reworking of existing wells, as opposed to the drilling of new wells, is required. The maturity of the field and the choice of injection strategy together determine whether or not extra wells are needed. For the purpose of the EOR-concept design, the assumptions are made that the field has undergone primary and secondary flooding and that the CO_2 flood uses WAG injection. A field that has been subject to secondary flooding, i.e., waterflooding, has both production and injection wells. For WAG injection, it is adequate to assume that no additional injection wells are required. While the concept design as such requires that no extra wells be drilled, it is important to note that the existing production and injection wells and production surface facilities need to be reworked for the changed reservoir conditions. Also, it is necessary to provide the appropriate injection surface facilities.[13,14]

5.4.6 Cost Calculations

The total capital cost comprises the injection and production equipment costs, and the cost of refurbishing the existing wells. The O&M costs include normal daily expenses, and surface and subsurface maintenance costs.

The EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report[16] includes a scenario for secondary oil recovery using water flooding. Costs and indices for additional secondary oil recovery equipment and its operation are provided for a representative lease, located in west Texas. This lease, or module, comprises 10 production wells, 11 water injection wells and 1 disposal well, and the wells are nominally 4,000 feet, or 1,219 m, deep. This scenario was modified for CO_2 flooding, and used as the basis for field equipment and production operations costs. The capital and O&M costs on a per module basis, as well as the cost of power on a per kilowatt-hour basis, are given in Table 5-5.

Table 5-5
Capital and O&M cost estimation factors

Parameter	Unit	Value
CAPITAL COSTS		
Injection Equipment:		
Recycle & Vapor Compressors	$/module	1,773,000
Plant	$/module	113,600
Distribution Lines	$/module	77,200
Header	$/module	61,100
Electrical Service	$/module	97,400
Producing Equipment:		
Tubing Replacement	$/module	90,800
Rods & Pumps	$/module	41,000
Equipment	$/module	405,000
Makeover of Existing Wells	$/module	605,000
O&M COSTS		
Normal Daily Expenses:		
Supervision & Overhead	$/module	53,100
Labor	$/module	62,600
Consumables	$/module	7,500
Operative Supplies	$/module	7,700
Pumping & Field Power	$/kWh	0.044
Recycle Compressor Power	$/kWh	0.044
Surface Maintenance (Repair & Services):		
Labor (roustabout)	$/module	32,200
Supplies & Services	$/module	44,300
Equipment Usage	$/module	16,300
Other	$/module	2,300
Subsurface Maintenance (Repair & Services):		
Workover Rig Services	$/module	46,400
Remedial Services	$/module	15,100
Equipment Repair	$/module	11,200
Other	$/module	9,900

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5.5 Design Basis

5.5.1 Module design

The EOR design is tied as closely as possible to the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report[16] in order to make use of the cost data. This report is a continuation of the EIA series on equipment and operating costs, and cost indices for oil and gas leases. In addition to cost comparisons within the petroleum industry, the reported data are often used to assess the economic effects of specific plans and policies relating to the industry. Standardization of this data has occurred over the past 23 years.

The costs and cost indices provided in this report are for representative 10-well lease operations, with equipment and operating procedures designed by EIA staff engineers. As previously mentioned, each EOR lease has 10 producing wells, 11 injection wells, and 1 disposal well, and the wells are nominally 4,000 feet, or 1,219 m, deep. The design criteria have taken into account the predominant methods of operation in each region. Individual items of equipment have been priced by using price lists and by communication with the manufacturer or supplier of the item in each region. Freight and installation costs have been determined based on regional rates. All costs presented in the report are current to their year and are not adjusted for inflation.

The base case design is based on a CO_2 effectiveness factor of 170 scm (6,000 scf) per bbl of enhanced oil and an enhanced oil production rate of 40 bbl per day per well. From the design flow rate of 3.76 million scm (7,389 tonnes) of CO_2 per day, the total enhanced oil production is calculated using the CO_2 effectiveness factor to be 22,142 bbl. Dividing this total enhanced oil production by the enhanced oil production rate per well, the required number of production wells is found to be 554. Given a producer to injector ratio of 1 to 1.1, 609 injection wells are required. In keeping the design consistent with the EIA modular approach, the EOR field for the base case therefore consists of 56 10/11 well modules. Finally, the quantities of new CO_2 and CO_2 to be recycled, assuming a maximum recycle ratio of 3, per module are 68,000 and 204,000 scm per day, respectively. Table 5-6 summarizes the base case for EOR.

Table 5-6
Design basis for the EOR base case

Parameter	Unit	EOR Base Case
CO$_2$ Effectiveness	scf/bbl enhanced oil	6,000
	scm/bbl enhanced oil	170
Oil Production per Well	bbl enhanced oil/day/well	40
Total Oil Production*	bbl enhanced oil/day	22,142
Number of Production Wells*		554
Number of Injection Wells*		609
Number of 10/11 Well Modules*		56
New CO$_2$*	scm/d/module	68,000
Maximum Recycled CO$_2$*	scm/d/module	204,000
Well Depth	m	1,219

* calculated

A key component of the EOR field is the recycle compressor as it requires a large amount of energy, and capital investment. The compressor use is initially minimal but, after 20 years of operation, it is assumed that the ratio of CO_2 produced with the enhanced oil production to the new CO_2 will reach the maximum value of 3.

The compressor is sized to handle all of the CO_2 that is recycled in the 10/11 well module. The actual compressor is a Superior Model WG74, sized by Cooper Energy Services and priced by Gas Packagers, Inc. To meet the CO_2 recycle requirements of the 10/11 well module, two compressors, each delivering 71 scm per minute are required. The base cost for each compressor was adjusted by Parsons to include shipping, foundations, installation and a cooling system. Table 5-7 gives the recycle compressor's parameters and cost.

Enhanced Oil Recovery

Table 5-7
Recycle compressor's parameters and cost

Parameter	Unit	Individual Compressor	Total for 10/11 Module
Maximum CO_2 to be Compressed	scm/d	102,000	204,000
Compressor Type		Reciprocating	Reciprocating
Suction Pressure	bar	7	7
	psia	100	100
Discharge Pressure	bar	103	103
	psia	1,500	1,500
Compressor Displacement	scm/min	71	142
Overall Compression Ratio		14.7	14.7
Number of Stages		2	2
Horsepower		4.2	4.2
Connected Horsepower		500	1,000
Maximum Power Consumption	kW	319	638
Average Power Consumption	kW	120	240
Power Consumption	kW/thousand scm/d	3.1	3.1
Capital Cost per Compressor	$/compressor	737,000	1,473,000
Total Compressor Cost	$		82,500,000

A summary of the lease equipment required for the EOR design is given in Table 5-8.

Table 5-8
Lease equipment

Equipment Description	Specification	Quantity
Tubing	2.375 inch, Grade J-55	40,000 ft
Sucker Rod	API Class K	40,000 ft
Pump Rod	API Type RWBC	10
Pumping Unit	API Size M160D 173-74, 12 hp	10
Oil Flowline	2.375 inch, PVC	16,000 ft
Manifold	10 valves, 2 inch 3-way	1
Production Separator	Vertical, 30 inch x 10 feet, 2,700 barrels per day of fluid, 5.7 million scf/day gas	1
Vapor Compressor	500 scf/min, 0-100 psig, 115 hp	1
Test Separator	1.0 bbl/d	1
Oil Storage Tank	2,000 bbls	2
Water Disposal Pump	Quintuplex, 1,000 psi, 20 hp	1
Water Disposal Line	2.375 in, 2,500 psi yield	2,000 ft
LACT Unit	2,000 bbl/d	1

1 in = 0.0254m, 1 hp = 746 J/s, 1 ft = 0.305 m, 1 cf = 0.028 cm, 1 psig = 0.069 bar,

5.5.2 Capital and O&M Cost Inputs

All of the capital and O&M costs, except for the power costs, are found by multiplying the per module costs, given in Table 5-5, by the required number of modules, as detailed in Section 5.5.1. In the case of the pumping and field, and recycle compressor, power costs, the costs per kilowatt-hour are multiplied by 8,760, the total hours of operation per year, and the respective power requirement. Table 5-10 summarizes the model inputs for the capital and O&M costs for the base case EOR design.

Table 5-9
Capital and O&M cost inputs for the EOR base case

Parameter	Input
Number of Modules	56
CAPITAL COSTS	
Injection Equipment:	
Recycle & Vapor Compressors	$99,300,000
Injection Plant Confines	$6,360,000
Distribution Lines	$4,320,000
Header	$3,420,000
Electrical Service	$5,450,000
Makeover of Existing Injection Wells	$33,900,000
Producing Equipment:	
Tubing Replacement	$5,080,000
Rods & Pumps	$2,300,000
Equipment	$22,700,000
Subtotal	$182,800,000
O&M COSTS	
Normal Daily Expenses:	
Supervision & Overhead	$2,970,000
Labor	$3,510,000
Consumables	$420,000
Operative Supplies	$431,000
Pumping & Field Power (7,196 kW)	$2,770,000
Recycle Compressor Power (17,946 kW)	$6,910,000
Surface Maintenance (Repair & Services):	
Labor (roustabout)	$1,800,000
Supplies & Services	$2,480,000
Equipment Usage	$913,000
Other	$129,000
Subsurface Maintenance (Repair & Services):	
Workover Rig Services	$2,600,000
Remedial Services	$846,000
Equipment Repair	$627,000
Other	$554,000
Subtotal	$27,000,000

5.6 Model Results

This section presents costs for CO_2 capture and storage for EOR for the base case, described in Section 5.5.1. The storage costs comprise transaction, transportation (from Chapter 4), injection and monitoring costs. These costs are combined with capture costs from the IGCC power plant referred to earlier. The results, which include the revenue generated from the sale of the enhanced oil produced, are given on several bases as described in Chapter 2. Appendix B provides a detailed description of these spreadsheets.

The **Process Input** sheet for the base case is presented in Table 5-10.

Table 5-10
Process input sheet for base case EOR

Enhanced Oil Recovery Input Variables

Design Basis		Economic	
IGCC Plant		*IGCC Plant* (Case 3a)	
Capacity Factor	80%	CO_2 Capture Cost ($/tonne captured)	$14.55
Pipeline Distance	100 km	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*CO_2 Storage*	
		Wellhead Oil Price ($/bbl)	$15.00
CO_2 Storage		Oil Royalty	12.5%
Well Depth (m)	1,219	Oil Credit ($/bbl)	$13.13
Well Depth (ft)	4,000	Break Even Oil Price to Offset CO_2 Storage Costs ($/bbl)	
CO_2 Effectiveness (scm/bbl)	170	Years 1-20	$10.6360
CO_2 Effectiveness (scf/bbl)	6,000	Years 1-100, NPV Basis	$10.6527
Oil Production (bbl/day/well)	40		
Maximum Recycle Ratio	3.0		
		IGCC Plant & CO_2 Storage	
Previous Waterflooding	☑	After-Tax Discount Rate	6.09%
		Levelized Carrying Charge Factor	15.0%

1 inch = 0.0254m

The **Summary** sheet for the base case is presented in Table 5-11. This summary assumes a Wellhead Oil Price of $15.00/bbl and an Oil Royalty of 12.5 percent.

**Table 5-11
Summary sheet for base case EOR**

════════════ **Enhanced Oil Recovery Summary** ════════════

Process Description

Previous Waterflooding	Yes	CO_2 Stored (M tonne/yr)	2.158
EOR Well Modules	56	CO_2 Avoided (M tonne/yr)	1.694
Pileline Distance	100 km	LC Avoided GHG (M tonne/yr)	2.022
Well Depth (m)	1,219	LC Avoided GHG (M tonne/yr)	1.672

Economic Description

Oil Credit ($/bbl) $13.13   Oil Price ($/bbl) $15.00
Break Even Oil Price to Offset CO_2 Storage Costs ($/bbl)
    Years 1-20 $10.64
    Years 1-100, NPV Basis $10.65

Capital & O&M Cost

	Capital	*O&M*
Transaction	$2,160,000	$0
Transport	$26,800,000	$1,333,000
Sequestration	$182,800,000	$27,000,000
Monitoring	$0	$216,000
Total	**$211,800,000**	**$28,500,000**

Cost of CO_2 Capture & Storage

1. Levelized Annual CO_2 Storage Costs *(years 1-20)*

	CO_2 Captured Basis	LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	60.17	60.17
Enhanced Oil Revenues, M $/yr	84.86	84.86
Net CO_2 Storage Cost, M $/yr	(24.69)	(24.69)
CO_2 Stored or Avoided, M tonne/yr	2.16	2.02
Net Storage Cost, $/tonne CO_2	(11.44)	(12.21)

2. Levelized Annual CO_2 Capture and Net Storage Costs *(years 1-20)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	31.39	31.39	31.39
Net CO_2 Storage Cost, M $/yr	(24.69)	(24.69)	(24.69)
Capture + Net Storage Cost, M$/yr	6.70	6.70	6.70
CO_2 Stored or Avoided, M tonne/yr	2.16	1.69	1.67
Capture + Net Storage Cost, $/tonne CO_2	3.11	3.96	4.01

3. CO_2 Capture and Net Storage Costs, NPV Basis *(years 1-100)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	357.42	357.42	357.42
NPV of Net CO_2 Storage Costs, M$	(280.04)	(280.04)	(280.04)
NPV of Capture + Net Storage Costs, M$	77.38	77.38	77.38
NPV of CO_2 Stored or Avoided, M tonne	24.57	19.29	19.04
Capture + Net Storage Cost (NPV Basis), $/tonne CO_2	3.15	4.01	4.06

4. Cost of Electricity, $/MWh

Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Net Storage Costs (years 1-20)	(8.73)
Storage Costs, Monitoring, etc. (years 21-100)	0.03
Total Cost of Electricity	46.39

5.7 Sensitivity Analysis

The sensitivity of the CO_2 storage cost for EOR is determined for six key parameters as well as for the case of no previous waterflooding. It can be seen in Figure 5-3 that increases in well depth, CO_2 effectiveness, recycle ratio and pipeline distance cause an increase in the cost of storage, while increases in oil production rate and oil price decrease the storage cost.   More noteworthy, the figure shows that changes in oil price have the greatest effect on storage cost, followed closely by changes in CO_2 effectiveness. As is to be expected, the case of no previous waterflooding results in an upward shift in the cost.
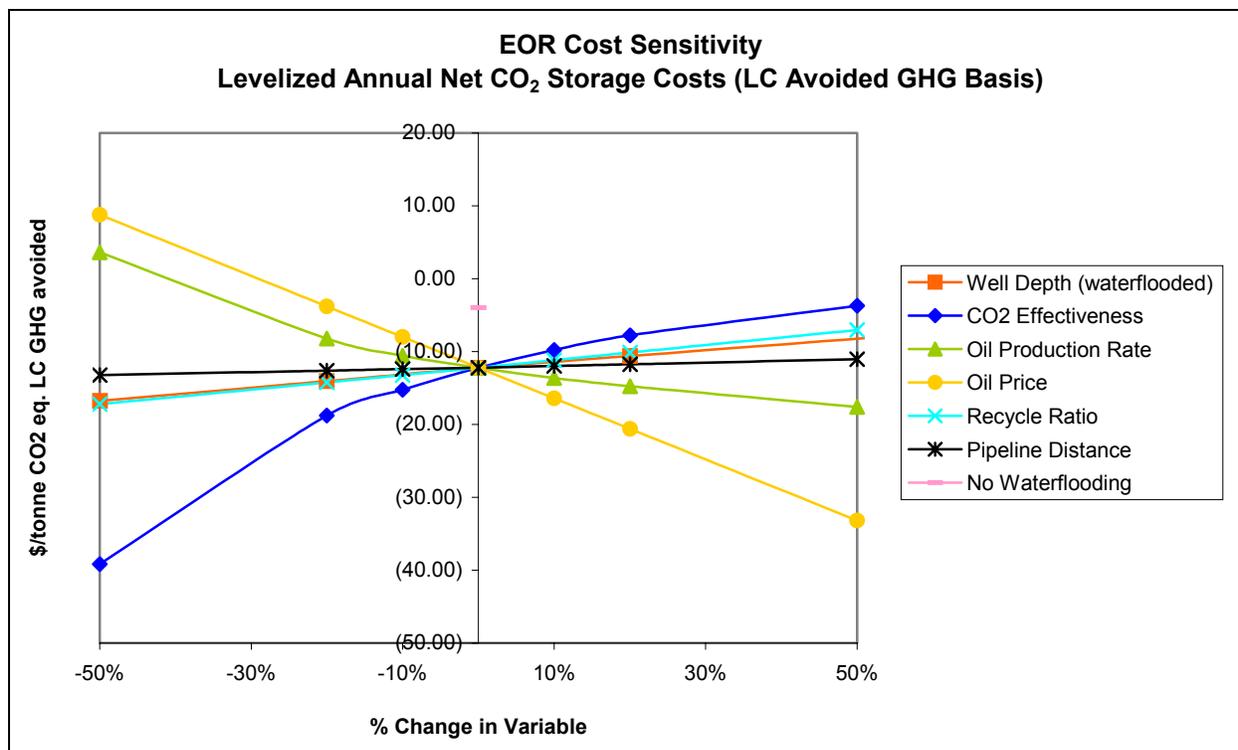
Figure 5-3
Sensitivity analysis for EOR

High and low cost cases have been chosen for EOR, and are presented together with the base case in Table 5-12. The price of oil at the wellhead is taken to have a low-end value of $12 per bbl and a ceiling price of $20 per bbl. For the high and low cost values for each of the six key parameters, the percentage change in the value from the base case is shown. This is done to illustrate the fact that the range in the values of some parameters is expected to be greater than for others. The table also shows that the high cost case assumes no previous waterflooding, while the low cost case assumes the field has been waterflooded as for the base case.

Table 5-12
EOR base, high cost and low cost cases

Parameter	Units	EOR Base Case	EOR High Cost Case		EOR Low Cost Case	
CO_2 Effectiveness	scm/bbl enhanced oil	170	227	+34%	85	-50%
Oil Production per Well	bbl enhanced oil/d/well	40	20	-50%	70	+75%
Maximum Recycle Ratio		3	4	+33%	1	-67%
Oil Price	$/bbl	15	12	-20%	20	+33%
Depth	m	1,219	2,438	+100%	610	-50%
Pipeline Distance	km	100	300	+200%	0	-100%
Previous Waterflooding		Yes	No	-	Yes	-

Enhanced Oil Recovery

The results for the high and low cost cases as well as the base case are given in Table 5-13. The CO_2 storage cost for EOR can be seen to be widely different for the high and low cost cases. In reality, a CO_2-EOR project with parameter values approaching those of the high cost case would not be carried out.

Table 5-13
Results for EOR base, high cost and low cost cases

Parameter	Units	EOR Base Case	EOR High Cost Case	EOR Low Cost Case
Total Oil Production	bbl enhanced oil/d	22,142	16,582	44,285
Number of 10/11 Well Modules		56	83	64
New CO_2	scm/d/module	68,000	45,000	59,000
Maximum Recycled CO_2	scm/d/module	204,000	182,000	59,000
Levelized Annual Net CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG Avoided	(12.21)	73.84	(91.26)

5.8 Comparison to Literature

A comparison is made between the costs obtained for the EOR base-case design using the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report and those calculated using cost estimation functions provided by Reference 15. The relevant cost functions are shown in Table 5-14.

Table 5-14
EOR cost estimation functions[15]

Item	Unit	Value
CAPITAL COSTS		
Workover of existing injector	$	5 * depth(ft) + 35,000
Workover of existing producer	$	40,000
Provision of injection surface facilities	$/well	22,000
Workover of production surface facilities	$/well	10,000
CO_2 recycle plant	$	457,000 * CO_2 recycled (million scf per day)
O&M COSTS		
CO_2 recycle compression operating costs	$/y	200 * CO_2 recycled (million scf per day) * 365

Using these cost functions, the capital and O&M costs of EOR for the base-case design were calculated. Table 5-15 shows the results of these calculations together with the previously determined base-case EOR costs.

Table 5-15
Comparison of EOR cost results[15,16]

Item	Unit	This Study	Using Cost Functions
CAPITAL COSTS			
Workover of injectors	$	33,900,000	33,495,000
Provision of injection surface facilities	$	13,190,000	13,398,000
Total cost injection equipment	$	**47,090,000**	**46,893,000**
Workover of producers	$	27,780,000	22,160,000
Workover of production surface facilities	$	2,300,000	5,540,000
Total cost production equipment	$	**30,080,000**	**27,700,000**
CO_2 recycle plant	$	105,660,000	182,354,000
Total Capital Cost	$	**182,800,000**	**256,947,000**
O&M COSTS			
CO_2 recycle compression operating costs	$/yr	12,232,000	14,540,000
TOTAL O&M COSTS	$/yr	**27,000,000**	**-**

Except for the CO_2 recycle plant, it can be seen from the table that the cost of the EOR base-case design is very similar for the two sets of cost data. The CO_2 recycle plant costs were not included in the EIA report and were developed from vendor quotations and in-house data. It is concluded that using the EIA report for costs was reliable, given the uncertainties and variation in the data.

5.9 References

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6
ENHANCED COALBED METHANE

6.1 Introduction

This chapter looks at the injection of CO_2 into deep coal seams as a means of enhancing coalbed methane production while simultaneously sequestering CO_2.

6.2 State of the Art

6.2.1 Applications

The injection of CO_2 into deep, unmineable coal seams to enhance coal-bed methane production (CO_2-ECBMR) is a relatively recent technology. It was not until 1996 that the world's first, and to date only, pilot-scale application of CO_2-ECBMR began operation. In contrast, EOR using CO_2 floods (CO_2-EOR) is a mature technology with over three decades of commercial-scale application. The one CO_2-ECBMR project, comprising nine coal-bed methane (CBM) production and four CO_2 injection wells, is located in the southwestern United States within the Allison production unit of the San Juan basin and is operated by Burlington Resources, the United States' largest producer of coal-bed methane. Analysis of operations at the Allison unit has shown the CO_2-ECBMR process to be technically and economically feasible.[1,2,3]

6.2.2 Storage Potential

CBM production has become an increasingly important component of natural gas supply in the United States during the last decade. In 2000, approximately 40 billion standard cubic meters (scm) of CBM was produced, accounting for about 7 percent of the nation's total natural gas production. The most significant CBM production, some 85 percent of the total, occurs in the San Juan basin of southern Colorado and northern New Mexico. Another 10 percent is produced in the Black Warrior basin of Alabama and the remaining 5 percent comes from rapidly developing Rocky Mountain coal basins, namely the Uinta basin in Utah, the Raton basin in Colorado and New Mexico, and the Powder River basin in Wyoming.[1,4]

Essentially all current CBM production utilizes primary recovery methods. Primary recovery involves pumping off large volumes of formation water to lower reservoir pressure and cause methane desorption from the coal. Primary production of CBM recovers only 20 to 60 percent of original gas-in-place (OGIP), where this varies depending on reservoir properties such as coal seam permeability and gas saturation, and operational practices such as well spacing. In comparison, over 90 percent of the OGIP can theoretically be recovered using CO_2-ECBMR.

Furthermore, CO_2-ECBMR can accelerate CBM recovery, providing greater real value for a given reserve.[1,2]

Significant potential for CO_2-ECBMR exists worldwide. In order for CO_2-ECBMR to be successfully applied, reservoirs must have laterally continuous and permeable coal seams, concentrated seam geometry, and minimal faulting and reservoir compartmentalization. In the United States, the geologically most favorable reservoirs are located within the San Juan, Uinta, and Raton basins, while additional potential exists in the Greater Green River and Appalachian basins. A number of coal basins in Australia, Russia, China, India, Indonesia, and other countries have also been identified as having large CO_2-ECBMR potential. Indeed, the total worldwide potential for CO_2-ECBMR, taking into consideration only those reservoirs where CO_2-ECBMR could be profitably developed without CO_2 sequestration credits or free or reduced-cost CO_2 supplies, is estimated at around two trillion scm of CBM, with about 7.1 billion tonnes of associated CO_2 sequestration potential.[5]

6.2.3 Storage Mechanics

Four patents have been issued over the past two decades relating to the CO_2-ECBMR process. Each of these patents is based on the principle that CO_2 is adsorbed more readily onto the coal matrix than methane. Specifically, CO_2-ECBMR involves injected CO_2 being adsorbed at the expense of methane, which having been displaced can be recovered as a free gas at production wells. Sorption isotherm measurements in the laboratory indicate that two unit volumes of CO_2 are required to displace one unit volume of methane. This ratio of CO_2 effectiveness is however expected to vary in the field according to the thermal maturity of the coal.[1,2,5,6]

A successful demonstration of CO_2-ECBMR technology has been provided by the Allison unit pilot project. Prior to CO_2 injection, CBM was produced within the unit using conventional pressure-depletion methods. Since the start of CO_2 injection, enhanced CBM production has been observed. A marked increase in water production was also observed initially, signaling improved sweep of bypassed reservoir areas that should lead to higher ultimate gas recovery. Finally, there has been negligible CO_2 breakthrough, despite around one billion scf of CO_2 being injected each year since the project began in 1996. The injected CO_2 comes from the McElmo Dome, which is a natural CO_2 deposit in southwestern Colorado.[1,2,3]

6.2.4 Feasibility of Storage Option

CO_2-ECBMR presents an attractive option for the sequestering of CO_2. Like CO_2-EOR, it has the distinct advantage over other CO_2 storage options that it sequesters CO_2 while also generating a value-added product. While CO_2-ECBMR as a technology is still in the development stage and has not been widely applied, it has been successfully demonstrated in a pilot-scale application. Also, given the broad similarities between the two, the technology required to implement CO_2-ECBMR in the field can be largely based on that used for CO_2-EOR operations. The fact that CO_2 is adsorbed onto the coal surface means that there should be little risk of leakage of CO_2 from the reservoir. Also on a positive note, coal, and so CBM, typically

lies at relatively shallow depths so that well drilling and completion costs are generally lower than for other geologic options.

On the downside, CO_2-ECBMR is a very energy intensive process, requiring significant electricity both for pumping large volumes of formation water to the surface and for compressing the produced methane to a suitable pressure for pipeline transport and sale. Another disadvantage is that the large volumes of formation water produced by CO_2-ECBMR are most often saline and need to be disposed of in an environmentally acceptable manner.

6.3 Process Description

Figure 6-1 is a block flow diagram, indicating the overall flow and distribution of CO_2 from the IGCC plant to the ECBMR field. First, the CO_2 leaving the plant is fed to an additional stage of compression to bring it up to the required pipeline inlet pressure. Second, the pipeline transports the CO_2 a distance of 100 km to the ECBMR field, where it is injected into the ECBMR CO_2 wells. Third, the ECBMR product is dewatered, and dry gas from the ECBMR wells is compressed to the gathering line pressure. Finally, the gas from the gathering line is then further compressed for sale to a nearby pipeline.

The source and quantity of CO_2 supplied to the ECBMR field is the same as for the EOR storage option. It should also be noted that the pipeline outlet pressure of 103 bar is assumed to be at or above the required surface injection pressure.

Very simple vertical wells from 300 to 1,200 m in total depth are common to this type of production. These wells produce gas at very low pressures; wellhead pressures of between 2 to 3 bar are common.[7] Because these wells are generally operated at low backpressures (assuming 1.7 bar), compression is required to increase the wellhead pressure to the gas gathering line pressure of 4.5 bar. The gathered gas is then further compressed to 25.1 bar for delivery to a nearby pipeline.

Developing an ECBMR lease for production involves:

- Lease acquisition activities

- Drilling and equipping production/injection wells

- Installation of high-pressure injection equipment and related piping

- Installation of ECBMR production equipment and facilities

- Installation of product gas compressors

The ECBMR field is a grass-roots facility, which has not produced CBM in the past. The ECBMR field therefore requires a new distribution and injection/ECBMR production system, which serves the following purposes:

- Receives CO_2 from the pipeline terminal and distributes it to the ECBMR CO_2 injection wells.

- Gathers gas from the ECBMR production wells and delivers it to a central gas/liquid separator.

- Dewaters the ECBMR production wells and conveys water to a central disposal well.

- Compresses the separated gas to 4.5 bar for distribution to a regional gathering line.

- Compresses the gathered gas to 25.1 bar for sale to a nearby pipeline.

Most coal-bed methane reservoirs are low-pressure water-bearing gas reservoirs. Under conditions of high water saturation, the water volume and the hydrostatic pressure must be reduced by artificial lift to initiate gas desorption and flow to the wellbore.[8] This dewatering process produces large quantities of saline water that must be disposed of carefully. In the Warrior Basin, water is usually piped to a central treatment facility and disposed into a surface stream. In the San Juan Basin, because of the higher total dissolved solids in the water, disposal wells are used.[9] For this study, the use of disposal wells is assumed.

A productive life span of 20 to 30 years is typical for coal-bed methane fields.[10] The life of this field is assumed to be the same as that of the power plant, 20 years. As a final note, the design/construction time is taken to be the same as the power plant, 4 years.
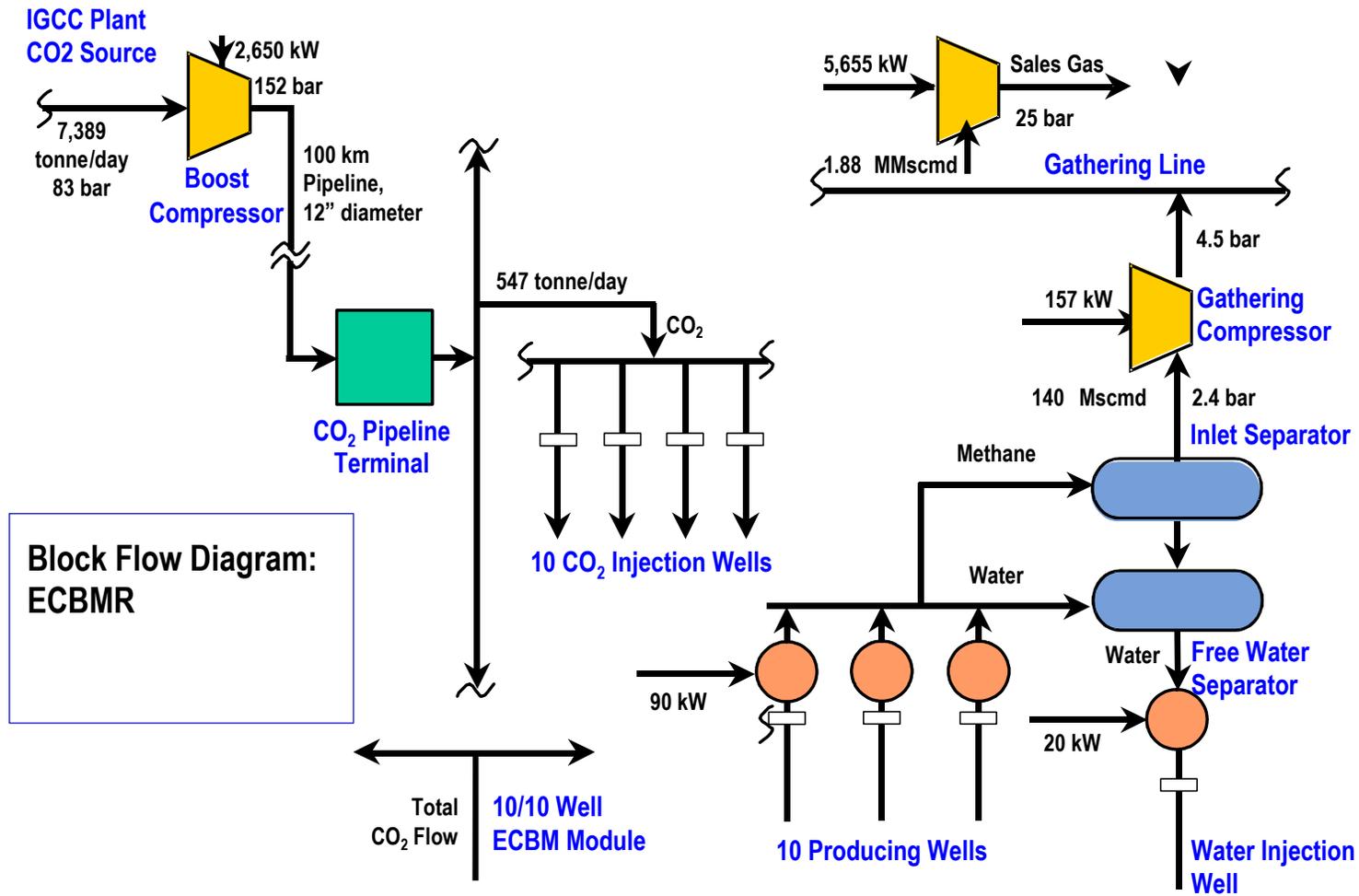
Figure 6-1
ECBMR block flow diagram

6.4 Methodology Used

As in the case of the CO_2-EOR concept design, 'rules of thumb' are used to define the engineering parameters needed to estimate the cost of a CO_2-ECBMR project. As for CO_2-EOR, the method for costing the CO_2-ECBMR process is also split up into a number of steps. First, the total amount of enhanced CBM produced per day for the given CO_2 mass flow rate is determined using a CO_2 effectiveness factor of two scm CO_2 per scm of enhanced CBM. Second, the number of production wells is found by dividing this total amount of enhanced CBM produced per day by an assumed 14,000 scm of enhanced CBM per day being produced at each well. Third, a ratio of producers to injectors of 1 to 1 is used to calculate the number of injection wells from the number of production wells. Fourth, it is assumed that no recycling of CO_2 is required. Finally, the cost of drilling and equipping the required production and injection wells is calculated. An overview of the cost model is provided in Figure 6-2.

6.4.1 CO_2 Effectiveness

For the design basis, it is assumed that 2 scm of CO_2 needs to be injected to produce 1 scm of enhanced CBM. This CO_2 effectiveness ratio is based on the results of sorption isotherm measurements carried out on bituminous coals in the laboratory. These measurements indicate that coal can adsorb roughly twice as much CO_2 by volume as methane. This may vary, however, as a result of other physical processes active within a coal reservoir. Based on data collected in the field, one source[11] has reported the amount of CO_2 injected to CBM produced as being between 1.5 and 2 while another[12] has reported it as being closer to 3 than 2. It is important to note that the ratio is also dependent on the thermal maturity of the coal and that it can be as high as 10 to 1 for sub-bituminous coals. Based on these values, a range of 1.5 to 10 scm of CO_2 per scm of enhanced CBM was chosen for the sensitivity analysis.[1,2,5]

6.4.2 Rate of Enhanced CBM Production

The amount of enhanced CBM produced per day at each well is taken to be 14,000 scm.   As in the case of EOR, there is no industry 'rule of thumb' for the production at each well on a daily basis. Instead, the CBM production rate depends on reservoir parameters such as coal seam permeability, gas saturation and thickness, and operational practices such as the recovery method used and well spacing.[13]

The variation in the CBM production rate that results from different values of reservoir parameters can be seen from a comparison of values for the San Juan and Black Warrior basins. Average production in the San Juan basin exceeds 23,000 scm per day per well, with many wells in the most productive area averaging over 85,000 scm per day. In contrast, the Black Warrior basin wells average 3,400 scm per day, reflecting the fact that this basin has lower permeability, thinner coal seams.

Rule of thumb:
CO_2 effectiveness

Rule of thumb:
Rate of enhanced CBM
production at producer

Rule of thumb:
Ratio of producers to injectors

Input:
CO_2 mass
flow rate

**ENHANCED CBM
PRODUCTION
CALCULATION**

**PRODUCTION
WELL NUMBER
CALCULATION**

**INJECTION
WELL NUMBER
CALCULATION**

Total enhanced CBM production

Number of production wells

Number of 10/10 well modules

COST MODEL
Internal Calcs:
Capital costs:
*Front end, lease acquisition, injection
equipment, producing equipment, production &
injection wells, gathering system*
O&M costs:
Normal daily expenses, surface maintenance,

Inputs:
Well depth
Capital charge rate

Outputs:
Total capital cost
Total O&M cost
Total annual cost
Total cost per tonne CO_2

Figure 6-2
ECBMR cost model overview diagram

The effect of the recovery method on the CBM production rate is evident from a look at the production history of the #115 well within the Allison unit of the San Juan basin. Prior to CO_2 injection, the #115 well had been a sub-average performer, with a CBM production rate of 14,000 scm per day. However, following CO_2 injection, the daily CBM production rate rose sharply to 37,000 scm.[2,13]

Based on the values given above for projects without CO_2 injection as well as the Allison unit CO_2-ECBMR pilot project, and advice from experts in the field[11,12], the assumed base-case value of 14,000 scm of enhanced CBM per day per well was chosen. A sensitivity analysis range of 3,000 to 30,000 scm of enhanced CBM per day per well was also chosen. It is important to note that the values for the base-case and sensitivity range were chosen to be somewhat lower than those values quoted for the San Juan basin. This is simply because the San Juan basin, being the world's most prolific basin for CBM, is expected to have higher CBM production rates than other coal basins with CO_2-ECBMR potential.

6.4.3 Ratio of Producers to Injectors

A ratio of producers to injectors of 1 to 1 is assumed for the CO_2-ECBMR concept design. It is an industry standard for production and injection wells to be arranged in a five-spot configuration, where this entails each injector being surrounded by four producers. This well configuration is used in the case of the Allison unit CO_2-ECBMR pilot project, which comprises nine CBM production and four CO_2 injection wells. The ratio of producers to injectors resulting from the five-spot configuration for this small number of wells is just over 2 to 1. However, as the number of production and injection wells increases, a repeating five-spot configuration results and the ratio of producers to injectors steadily approaches 1 to 1. For the CO_2-ECBMR concept design, which comprises a relatively large number of wells, a ratio of producers to injectors of 1 to 1 is therefore used.

6.4.4 CO_2 Recycle Ratio

The CO_2-ECBMR concept design assumes that CO_2 breakthrough at the production wells is negligible and that there is, therefore, no need for CO_2 recycling. At the Allison unit, breakthrough of CO_2 has been minimal during the life of the project. Following almost five years of injection, the CO_2 concentration in the produced gas was about 0.6 percent, which is only slightly above pre-injection levels of 0.4 percent.[3]

6.4.5 Drilling and Equipping of Production and Injection Wells

The cost of the CO_2-ECBMR process is calculated based on both production and injection wells needing to be drilled and equipped. If a coal bed is viewed primarily as a source of CBM, it makes more economic sense to partially deplete the reservoir of CBM before injecting CO_2. However, in the case that the primary role of the coal bed is as a repository for CO_2, early use of CO_2-ECBMR is favored. Given that the concern here is CO_2 sequestration, it is assumed for the

purpose of the concept design that no CBM production has taken place at the coal bed prior to CO_2 injection. This assumption implies that production and injection wells need to be provided.[5]

6.4.6 Cost Calculations

The total capital cost comprises front end and lease acquisition, injection and production equipment, well drilling and gathering system costs. The O&M costs include normal daily expenses, and surface and subsurface maintenance costs.

Prior to acquiring a lease position, geological expenditures, geophysical expenditures, and engineering-based feasibility studies are often conducted. In addition, outlays are generally required for obtaining the lease and its associated permits. These front-end transaction costs will vary greatly but may range from \$20,000 to \$30,000 per well for a commercial project.[9] For this study, a cost of \$25,000 per well is assumed.

All of the other field costs, except for the well drilling cost, are based on data contained in the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report.[14] A representative ECBMR lease, or module, comprising 10 CO_2 injection wells and 10 producing wells with dewatering facilities is used for the design basis. The 10 CO_2 injection wells are drilled to a depth of 610 m and equipped with a battery of lease equipment, which includes distribution lines, headers, electrical service, and controls. The 10 producing wells, also drilled to a depth of 610 m, are equipped with beam balanced/sucker rod dewatering.

The well drilling cost is calculated based on a relationship derived from data contained in the '1998 Joint Association Survey (JAS) on Drilling Costs' report.[15] This relationship between well depth and drilling cost is shown in Figure 6-3.

Well Drilling Cost as a Function of Depth
1998 Onshore Gas & Oil Well Data

$y = 0.0888e^{0.0008x}$
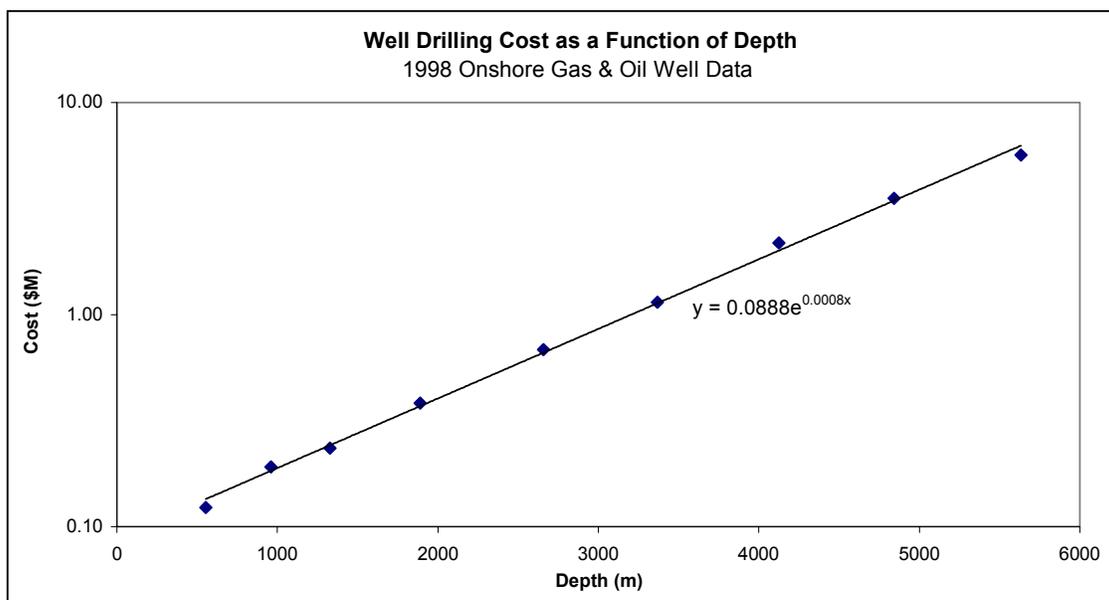
Figure 6-3
Well drilling cost as a function of depth

The field equipment and well drilling capital costs, and the associated O&M costs, are shown on a per module basis in Table 6-1. This table also gives the power costs associated with the gathering and sales gas compressors on a per kilowatt-hour basis.

Table 6-1
Capital and O&M cost estimation factors

Parameter	Unit	Value
CAPITAL COSTS		
Injection Equipment:		
Plant	$/module	104,455
Distribution Lines	$/module	70,182
Header	$/module	55,545
Electrical Service	$/module	87,818
Producing Equipment:		
Tubing	$/module	40,800
Rods & Pumps	$/module	39,200
Pumping Equipment	$/module	340,000
Gathering System:		
Flowlines	$/module	42,500
Manifold	$/module	42,600
Gathering Compressor	$/module	105,000
Sales Gas Compressor	$/module	3,970,000
Lease Equipment:		
Producing Separator	$/module	12,400
Storage Tanks	$/module	76,600
Accessory Equipment	$/module	35,800
Disposal System	$/module	96,700
Production & Injection Wells	$/module	1,446,601
O&M COSTS		
Normal Daily Expenses:		
Supervision & Overhead	$/module	50,245
Labor	$/module	39,936
Consumables	$/module	7,664
Operative Supplies	$/module	4,518
Auto Usage	$/module	7,900
Pumping & Field Power	$/kWh	0.044
Gathering Compressor	$/kWh	0.044

Table 6-1 (continued)
Capital and O&M cost estimation factors

Parameter	Unit	Value
Sales Gas Compressor	$/kWh	0.044
Surface Maintenance (Repair & Services):		
Labor (roustabout)	$/module	18,282
Supplies & Services	$/module	27,182
Equipment Usage	$/module	7,064
Other	$/module	2,782
Subsurface Maintenance (Repair & Services):		
Workover Rig Services	$/module	30,518
Remedial Services	$/module	8,145
Equipment Repair	$/module	7,400
Other	$/module	6,764

6.5 Design Basis

6.5.1 Module Design

The ECBMR design is tied as closely as possible to the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report[14] in order to make use of the cost data. This report is described in detail in Section 5.5.1.

The base case design is based on a CO_2 effectiveness factor of 2 scm per scm of enhanced CBM and an enhanced CBM production rate of 14,000 scm per day per well. From the design flow rate of 3.76 million scm (7,389 tonnes) of CO_2 per day, the total enhanced CBM production is calculated using the CO_2 effectiveness factor to be 1.88 million scm. Dividing this total enhanced CBM production by the enhanced CBM production rate per well, the required number of production wells is found to be 135. Given a producer to injector ratio of 1 to 1, 135 injection wells are required. In keeping the design consistent with the EIA modular approach, the ECBMR field for the base case therefore consists of 14 10/10 well modules. Finally, a well depth of 610 m, which is slightly more than the average depth of the CBM wells reported in the '1998 JAS on Drilling Costs' report, is selected as typical. Table 6-2 summarizes the base case for ECBMR.

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Table 6-2
Design basis for ECBMR base case

Parameter	Unit	ECBMR Base Case
CO_2 Effectiveness	scm/scm enhanced CBM	2.0
CBM Production per Well	scm enhanced CBM/d/well	14,000
Total CBM Production*	million scm enhanced CBM/d	1.88
Number of CBM Wells*		135
Number of CO_2 Wells*		135
New CO_2*	scm/d/well	28,000
Well Depth	m	610

Each ECBMR field requires a gathering line compressor to transfer dewatered methane from the 10 producing wells to a connecting pipeline. The methane from the wells is fed to a common pipe at 1.7 bar and compressed to 4.5 bar. Table 6-3 indicates the basis for the gathering compressor design and the compressor requirements.

Table 6-3
ECBMR gathering compressor design basis

Parameter	Unit	Value
Maximum Methane Rate	thousand scm/d	140
Suction Pressure	bar	2.4
	psia	24.7
Discharge Pressure	bar	4.5
	psia	64.7
Compressor Displacement	cmm	41
Compression Ratio		1.875
Compressor Configuration		Motor Driven Reciprocating
Maximum Horsepower		210
Maximum Connected Power	kW	157
Compressor Cost	$	105,000

A second compressor is required for sending the gathered gas from all the modules though a common sales gas line to a nearby pipeline. The gas must be compressed to 25.1 bar for transfer to the pipeline. Table 6-4 indicates the basis for the sales gas compressor design and the compressor requirements.

Table 6-4
ECBMR sales gas compressor design basis

Parameter	Unit	Value
Maximum Methane Rate	million scm/d	1.88
Suction Pressure	bar	4.5
	psia	64.7
Discharge Pressure	bar	25.1
	psia	364.7
Compressor Displacement	cmm	291
Compression Ratio		5.637
Compressor Configuration		Motor Driven Reciprocating
Maximum Horsepower		7,580
Maximum Connected Power	kW	5,655
Sales Gas Compressor Cost	$	3,970,000

A summary of lease equipment required for the ECBMR design is given in Table 6-5.

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Table 6-5
Lease equipment

Equipment Description	Specification	Quantity
Tubing	2.375 inch, Grade J-55	20,000 ft
Sucker Rod	API Class K	20,000 ft
Pump Rod	API Type RWBC	10
Pumping Unit	API Size M160D 173-74, 20 hp	10
Flowline	4 inch, Schedule 40 Steel	16,000 ft
Manifold	10 valves, 2 inch 3-way	1
Production Separator	Vertical, 30 inch x 10 feet, 5.0 million scf/d gas	1
Storage Tank	50,000 gallon	2
Water Disposal Pump	Quintuplex, 1,000 psi, 20 hp	1
Water Disposal Line	3 inch, Schedule 40 Steel	2,000 ft
Gas Meter	million scf/d	1

1 in = 0.0254m, 1 hp = 746 J/s, 1 ft = 0.305 m, 1 cf = 0.028 cm, 1 psig = 0.069 bar,

6.5.2 Capital and O&M Cost Inputs

All of the capital and O&M costs, except for the power costs, are found by multiplying the per module costs, given in Table 6-1, by the required number of modules, as detailed in Section 6.5.1. In the case of the gathering compressor and sales gas compressor power costs, the costs per kilowatt-hour are multiplied by 8,760, the total hours of operation per year, and the respective power requirement. Table 6-6 summarizes the model inputs for the capital and O&M costs for the base case EOR design.

Table 6-6
Capital and O&M cost inputs for the ECBMR base case

Parameter	Input
Number of Modules	
CAPITAL COSTS	
Front End & Lease Acquisition Costs	$6,750,000
Injection Equipment:	
Plant	$1,410,000
Distribution Lines	$947,000
Header	$750,000
Electrical Service	$1,190,000
Producing Equipment:	
Tubing	$551,000
Rods & Pumps	$529,000
Pumping Equipment	$4,590,000
Gathering System:	
Flowlines	$574,000
Manifold	$575,000
Gathering Compressor	$1,420,000
Sales Gas Compressor	$3,970,000
Lease Equipment:	
Producing Separator	$167,000
Storage Tanks	$1,030,000
Accessory Equipment	$483,000
Disposal System	$1,310,000
Production & Injection Wells	$39,100,000
Subtotal	$65,300,000
O&M COSTS	
Normal Daily Expenses:	
Supervision & Overhead	$678,000
Labor	$539,000
Consumables	$103,000
Operative Supplies	$61,000
Auto Usage	$107,000
Pumping & Field Power (1,485 kW)	$572,000

Table 6-6 (continued)
Capital and O&M cost inputs for the ECBMR base case

Parameter	Input
Gathering Compressor (2,120 kW)	$817,000
Sales Gas Compressor Power (6,654 kW)	$2,180,000
Surface Maintenance (Repair & Services):	
Labor (roustabout)	$247,000
Supplies & Services	$367,000
Equipment Usage	$95,400
Other	$37,600
Subsurface Maintenance (Repair & Services):	
Workover Rig Services	$412,000
Remedial Services	$110,000
Equipment Repair	$100,000
Other	$91,300
Subtotal	$6,520,000

6.6 Model Results

This section presents costs for CO_2 capture and storage for ECBMR for the base case, described in Section 6.5. The storage costs comprise transaction, transportation, injection and monitoring costs. These costs are combined with capture costs from an IGCC power plant. The results, which include the revenue generated from the sale of the enhanced CBM produced, are given on several bases as described in Chapter 2. Appendix B provides a detailed description of these spreadsheets.

The **Process Input** sheet for the base case is presented in Table 6-7.

Table 6-7
Process input sheet for base case ECBMR

Enhanced Coal Bed Methane Input Variables

Design Basis			Economic		
IGCC Plant			**IGCC Plant** *(Case 3a)*		
Capacity Factor		80%	CO_2 Capture Cost ($/tonne captured)		$14.55
Pipeline Distance		100 km	COE Including CO_2 Capture Cost ($/MWh)		$55.08
Pipeline Distance		62 miles			
Nominal pipe size (in)		12	**CO_2 Storage**		
			Gas Royalty		12.5%
CO_2 Storage			Gas Price ($/$10^6$ BTU)		$2.00
Well Depth (m)		610	Gas Credit ($/$10^6$ BTU)		$1.75
Well Depth (ft)		2,000	Break Even Gas Price to Offset CO_2 Storage Costs ($/$10^6$ BTU)		
CO_2 Effectiveness (scm CO2/scm CBM)		2.0	*Years 1-20*		$1.3073
CBM Production (scm/day/well)		14,000	*Years 1-100, NPV Basis*		$1.3129
			IGCC Plant & CO_2 Storage		
			After-Tax Discount Rate		6.09%
			Levelized Carrying Charge Factor		15.0%

10^6Btu = 1.06 GJ, 1 inch = 0.0254m

The **Summary** sheet for the base case is presented in Table 6-8. This summary assumes a Gas Price of $1.90/giga joule ($2.00/million Btu) and a Gas Royalty of 12.5 percent.

Enhanced CoalBed Methane

Table 6-8
Summary sheet for base case ECBMR

<div align="center">══ Enhanced Coal Bed Methane Summary ══</div>

Process Description

Pileline Distance	100 km	CO_2 Stored (M tonne/yr)	2.158
Well Depth (m)	610	CO_2 Avoided (M tonne/yr)	1.775
CBM Production (million scm/day)	1.88	LC Avoided GHG (M tonne/yr)	2.106
		LC Avoided GHG (M tonne/yr)	1.756

Economic Description

After-Tax Discount Rate	6.09%	
Gas Price ($/10^6 BTU)	$2.00 Gas Credit ($/10^6 BTU)	$1.75
Break Even Gas Price to Offset CO_2 Storage Costs ($/10^6 BTU)		
Years 1-20		$1.31
Years 1-100, NPV Basis		$1.31

Capital & O&M Cost

	Capital	*O&M*
Transaction	$2,160,000	$0
Transport	$26,800,000	$1,333,000
Sequestration	$65,300,000	$6,520,000
Monitoring	$0	$216,000
Total	**$94,300,000**	**$8,100,000**

<div align="center">Cost of CO₂ Capture & Storage</div>

1. Levelized Annual CO_2 Storage Costs *(years 1-20)*

	CO_2 Captured Basis	LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	22.20	22.20
Gas Revenues, M $/yr	33.96	33.96
Net CO_2 Storage Cost, M $/yr	(11.76)	(11.76)
CO_2 Stored or Avoided, M tonne/yr	2.16	2.11
Net Storage Cost, $/tonne CO_2	(5.45)	(5.59)

2. Levelized Annual CO_2 Capture and Net Storage Costs *(years 1-20)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	31.39	31.39	31.39
Net CO_2 Storage Cost, M $/yr	(11.76)	(11.76)	(11.76)
Capture + Net Storage Cost, M$/yr	19.63	19.63	19.63
CO_2 Stored or Avoided, M tonne/yr	2.16	1.78	1.76
Capture + Net Storage Cost, $/tonne CO_2	9.10	11.06	11.18

3. CO_2 Capture and Net Storage Costs, NPV Basis *(years 1-100)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	357.42	357.42	357.42
NPV of Net CO_2 Storage Costs, M$	(132.86)	(132.86)	(132.86)
NPV of Capture + Net Storage Costs, M$	224.56	224.56	224.56
NPV of CO_2 Stored or Avoided, M tonne	24.57	20.21	19.99
Capture + Net Storage Cost (NPV Basis), $/tonne CO_2	9.14	11.11	11.23

4. Cost of Electricity, $/MWh

Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Net Storage Costs (years 1-20)	(4.16)
Storage Costs, Monitoring, etc. (years 21-100)	0.03
Total Cost of Electricity	50.96

6.7 Sensitivity Analysis

The sensitivity of the CO_2 storage cost for ECBMR is determined for five key parameters: well depth, CO_2 effectiveness, CBM production rate, gas price and pipeline distance. It can be seen in Figure 6-4 that increases in well depth, CO_2 effectiveness and pipeline distance cause an increase in the cost of storage, while increases in CBM production rate and gas price decrease the storage cost. More noteworthy, the figure shows that changes in gas price have the greatest effect on storage cost, followed closely by changes in CO_2 effectiveness.
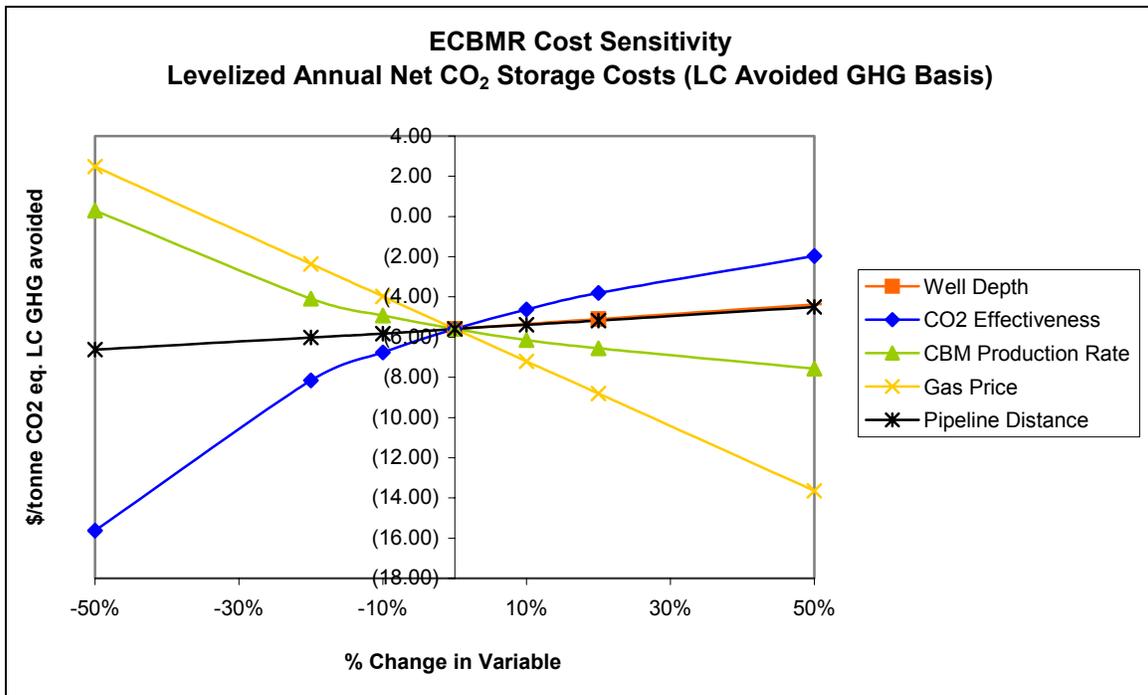
Figure 6-4
Sensitivity analysis for ECBMR

High and low cost cases have been chosen for ECBMR, and are presented together with the base case in Table 6-9. The price of gas at the wellhead is taken to have a low-end value of $1.80 per giga joule and a ceiling price of $3 per giga joule. For the high and low cost values for each of the five key parameters, the percentage change in the value from the base case is shown. This is done to illustrate the fact that the range in the values of some parameters is expected to be greater than for others.

Enhanced CoalBed Methane

Table 6-9
ECBMR base, high cost and low cost cases

Parameter	Units	ECBMR Base Case	ECBMR High Cost Case		ECBMR Low Cost Case	
CO_2 Effectiveness	scm/scm enhanced CBM	2	10	+400%	1.5	-33%
CBM Production per Well	scm enhanced CBM/d/well	14,000	3,000	-79%	30,000	+114%
Gas Price	$/giga joule	2	1.80	-10%	3	+50%
Depth	m	610	1,219	+100%	610	0%
Pipeline Distance	km	100	300	+200%	0	-100%

The results for the high and low cost cases as well as the base case are given in Table 6-10. The CO_2 storage cost for ECBMR can be seen to be widely different for the high and low cost cases. In reality, a CO_2-ECBMR project with parameter values approaching those of the high cost case would not be carried out.

Table 6-10
Results for ECBMR base, high cost and low cost cases

Parameter	Units	ECBMR Base Case	ECBMR High Cost Case	ECBMR Low Cost Case
Total CBM Production	(million scm enhanced CBM/d)	1.88	0.38	2.51
Number of CBM Wells		135	126	84
Number of CO_2 Wells		135	126	84
New CO_2	scm/d/well	28,000	30,000	45,000
Levelized Annual Net CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG Avoided	(5.59)	18.88	(25.72)

6.8 Comparison to Literature

A comparison is made between the costs obtained in this study for the CO_2-ECBMR base case design and those calculated using cost estimates from a paper by Wong, et al.[5] The costs for this study were based on the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and

Production Operations' report[14] and the API 'Joint Association Survey on Drilling Costs' report[15]. Wong, et al., cost estimates are given for a conceptual 50-well pair CO_2-ECBMR field development in the Alberta Plains region and are shown in Table 6-11. It is to be noted that the well drilling and completion cost estimates are based on a reservoir depth of 1,280 m.

Table 6-11
CO_2-ECBMR cost estimates from Wong, et al.[5]

Item	Unit	Value
CAPITAL COSTS		
Wells:		
Drilling	$/well pair	346,840
Completion	$/well pair	113,390
Equipment:		
Tie-in	$/well pair	113,390
Stimulation	$/well pair	6,670
O&M COSTS		
Well maintenance	$/well pair/yr	21,344

Using these cost estimates, the capital, the well surface, and subsurface maintenance, costs of CO_2-ECBMR were calculated for the 1,219 m case design. Table 6-12 shows the results of these calculations together with the previously determined CO_2-ECBMR costs from this study. It should be noted that the latter, in order to make the results comparable, have been given for a reservoir depth of 1,219 m and do not include the front end lease expense of the sales gas compressor.

Table 6-12
Comparison of CO_2-ECBMR cost results[5,14]

Item	Unit	This Study	Using Cost Estimates
CAPITAL COSTS			
Total cost of wells	$	63,600,000	62,131,000
Total cost of equipment	$	17,980,000	16,208,000
Subtotal	$	81,580,000	78,339,000
O&M COSTS			
Well maintenance	$/y	2,204,000	2,881,000
Subtotal	$/y	7,660,000	not reported

This comparison shows that the cost of the CO_2-ECBMR design is very similar for the two sets of cost data.

Enhanced CoalBed Methane

6.9 References

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7
DEPLETED GAS AND OIL RESERVOIR/AQUIFER STORAGE

7.1 Introduction

The CO_2 sequestration options considered here include CO_2 storage in depleted natural gas and oil reservoirs, and deep saline aquifers. Geologic CO_2 storage options with value-added products, specifically EOR and ECBMR, are treated separately.

7.2 State of the Art

7.2.1 Applications

The first, and to date only, commercial-scale project dedicated to geologic CO_2 storage is in operation at the Sleipner West field. Sleipner West is a natural gas/condensate field operated by Statoil and located in the North Sea about 250 km off the coast of Norway. The natural gas produced at the field has a CO_2 content of about 9 percent which, to meet commercial specifications, must be reduced to 2.5 percent. It is standard practice in natural gas production for the byproduct CO_2 to be vented to the atmosphere. At Sleipner, however, the CO_2 is compressed and injected via a single well into the Utsira Formation, a 250-m-thick aquifer located at a depth of 800 m below the seabed. About one million tonnes of CO_2 have been sequestered annually at Sleipner since October 1996, with a total of 20 million tonnes of CO_2 expected to be sequestered over the lifetime of the project. A second scheme, which would involve about 0.7 million tonnes per year of CO_2 produced at the Snohvit gas field in the Barents Sea off northern Norway being injected into a deep sub-sea formation, is planned.[1,2,3,4,5]

7.2.2 Storage Potential

Depleted Natural Gas Reservoirs

One type of geologic reservoir with significant potential for CO_2 sequestration is the abandoned natural gas field. Nearly all of the volume of abandoned gas fields should be available for CO_2 storage. The first reason for this is that the exploitation of a gas field normally extracts up to 95 percent of the available gas. The second is that only a very small fraction of the abandoned reservoir's pore space is likely to be invaded by formation water because water is more viscous than low-pressure methane. In the unlikely case that an abandoned reservoir does become water saturated, due to the reservoir being highly permeable and/or having been abandoned for many

Depleted Gas and Oil Reservoir/Aquifer Storage

years prior to CO_2 injection, the reservoir will be similar to an aquifer. It should be noted here that abandoned gas fields are quite widespread, with an estimated 98 to 133 giga tonnes of total carbon sequestration potential.[1,2,6,7,8]

In active natural gas fields, it has been proposed that CO_2 injection could prolong the economic life of a field by maintaining reservoir pressure longer than would otherwise be possible. It is important to note that, to date, there have been no demonstrations of CO_2-enhanced gas production. Furthermore, this technology is unlikely to be implemented in the future due to the fact that it risks contaminating the hydrocarbon reserve. For these reasons, CO_2 injection into active gas fields is not considered here as a geologic CO_2 storage option.[1,6,7]

Depleted Oil Reservoirs

The other type of hydrocarbon reservoir in which CO_2 could possibly be sequestered is the depleted oil field. In the case of the depleted oil field, it is important to note that production ceases not because all the oil has been recovered but rather because the field is no longer economic to produce. It is typical for primary production to result in only about 30 percent of the original oil in place (OOIP) being recovered. Even in fields in which secondary recovery by waterflooding has taken place, around 50 percent of the OOIP may remain in the reservoir.

Deep Saline Aquifers

Deep saline aquifers have the greatest CO_2 sequestration potential, with these reservoirs being the most widespread and having the largest volumes. The latter is very important given that, unlike exhausted hydrocarbon reservoirs where the reservoir pressure has been very substantially reduced by the production of reservoir fluids, the pressure in aquifers is hydrostatic or greater. In order to ensure that the fracture pressure of an aquifer is not exceeded, it is necessary that CO_2 injection wells be located in regions of high permeability and that the total amount of CO_2 injected be limited. Modeling suggests that an average of around only two percent of the pore volume of an aquifer can be safely occupied by CO_2, but this number is highly uncertain.[1]

To give an illustration of the aquifer volumes needed to store the CO_2 emissions from power plants, the aquifer volume required for the CO_2 captured at the base-case IGCC plant was determined. Calculating the total quantity of CO_2 to be supplied by the base-case plant over its 20-year lifetime to be 43 Mt and assuming a supercritical CO_2 density of 0.7 kg/m^3, it is found that an aquifer with an effective pore volume of approximately 0.0617 km^3 is needed. Given a realistic effective porosity of 30 percent and a storage efficiency of two percent, this is equivalent to a total aquifer volume of about 10.28 km^3. This can be visualized as a circular-shaped aquifer with a diameter of 11.4 km and a thickness of 100 m.[1,8]

CO_2 can be sequestered in either of two types of deep saline aquifer. The first type of aquifer is directly analogous to a hydrocarbon field, where the reservoir acts as a geologic trap. It should also be possible to inject the CO_2 into aquifers that do not have lateral seals. An impermeable caprock to prevent the buoyant CO_2 from escaping vertically and a down-directed flow regime to transport the CO_2 away from the surface should theoretically be sufficient to provide secure CO_2

storage.[9,10] This possibility vastly increases the total potential CO_2 sequestration capacity of aquifers. A lack of information about aquifers that are not located near where oil and gas exploration has taken place has led to greatly varying estimates of global CO_2 storage potential. An assessment of the varying estimates has, however, suggested that the global storage potential lies somewhere between 100 and 3,000 giga tonnes of carbon.[1,8,11]

7.2.3 Storage Mechanics

CO_2 is stored in geologic formations by a number of different trapping mechanisms, with the exact mechanisms depending on the formation type. To make full use of storage capacity, the CO_2 should be stored in a dense or supercritical phase, i.e., above the critical pressure of 7.4 MPa. For a hydrostatic pressure gradient of 10.5 MPa/km, this condition is met at depths below about 700 m. At 800-m depth, the density of supercritical CO_2 is 740 kg/m^3. Since the CO_2 under these pressure and temperature conditions will still be less dense than formation water, the CO_2 will naturally rise to the top of the reservoir and a trap is needed to ensure that it does not reach the surface. In oil and gas reservoirs, as well as aquifers directly analogous to hydrocarbon fields, geologic traps immobilize the CO_2. In the case of aquifers with no distinct geologic traps, however, an impermeable caprock above the underground reservoir is needed. This forces the CO_2 to be entrained in the groundwater flow and is known as hydrodynamic trapping.[1,7,8,10]

Two other very important trapping mechanisms are solubility and mineral trapping. Solubility and mineral trapping involve the dissolution of CO_2 into fluids, and the reaction of CO_2 with minerals present in the host formation to form stable, solid compounds like carbonates, respectively. These latter two mechanisms are particularly important in the case of the aquifer with no lateral seals. As the CO_2 moves through the reservoir along the flowpath, it comes into contact with uncarbonated formation water and reactive minerals. A proportion of the CO_2 dissolves in the formation water and some of this dissolved CO_2 becomes permanently fixed by reactions with minerals in the host rock. If the flowpath is long enough, the CO_2 might all dissolve or become fixed by mineral reactions before it reaches the basin margin, essentially becoming permanently trapped in the reservoir.[1,3,9,10]

7.2.4 Storage Option Feasibility

The injection of CO_2 into geologic formations is a promising CO_2 sequestration option. First, the technology for injecting CO_2 into exhausted hydrocarbon reservoirs and deep saline aquifers already exists. Oil producers in the Permian Basin of western Texas and eastern New Mexico, and in the Rocky Mountain and Mid-continent regions have been injecting CO_2 for EOR for more than 25 years. Underground natural gas storage projects also provide a considerable base of relevant geologic and engineering experience. Second, even though no direct economic benefits are derived, it should be noted that the CO_2 sequestration potential associated with the injection of CO_2 into exhausted oil and natural gas reservoirs and deep saline aquifers greatly exceeds that of EOR and ECBMR using CO_2 floods.[7]

Exhausted hydrocarbon reservoirs have the advantage over aquifers that these fields are proven long-term traps, their geology is well characterized, and their existing surface and subsurface

infrastructures could readily be converted for CO_2 distribution and injection. On the downside, the locating and sealing of abandoned wells could present an ongoing challenge. Aquifers, however, have a larger CO_2 capacity, are more widespread and are generally located closer to CO_2 emission sources.[6,7,8,11]

7.3 Process Description

Figure 7-1 is a block flow diagram, indicating the overall flow and distribution of CO_2 from the IGCC plant to the depleted gas and oil fields, and aquifer. Developing a depleted reservoir or aquifer for CO_2 storage involves:

- Screening and evaluation of sites

- Drilling and equipping injection wells

- Installation of high-pressure injection equipment and related piping

Equipment must be available at the injection site to accept pressurized CO_2 from the pipeline, and transfer it to the injection well at the flow rate and pressure required for injection. The primary components include piping to distribute CO_2 to the injection wells, CO_2 flow controls equipment, and equipment to monitor well condition.

The source and quantity of CO_2 supplied to the field is the same as for the EOR storage option, i.e. the system must be able to handle 3.76 million scm (7,389 tonnes) of CO_2 per day. Determining the required CO_2 pressure at the top of the well requires consideration of the pressure required at the bottom of the well to force CO_2 into the injection zone, the pressure increase in the pipe due to the height of the CO_2 column, and the pressure loss due to flow in the pipe. Moving the CO_2 into the reservoir requires raising the CO_2 sufficiently above the in situ pressure to provide a driving force, but not so high as to risk hydrofracturing the injection interval.[12] It was decided that the pipeline delivery pressure, 103 bar, is adequate for injection.

The CO_2 injection wells are as described in Section 5.3. For geologic CO_2 storage, these wells are equipped with a battery of lease equipment that includes distribution lines, headers, electrical service and controls. This equipment enables the CO_2 to be taken from the pipeline terminal and injected at a pressure that maintains the downhole injection point pressure.

As a final note, it is assumed that this facility, like the power plant, has a lifetime and design/construction time of 20 and 4 years, respectively.
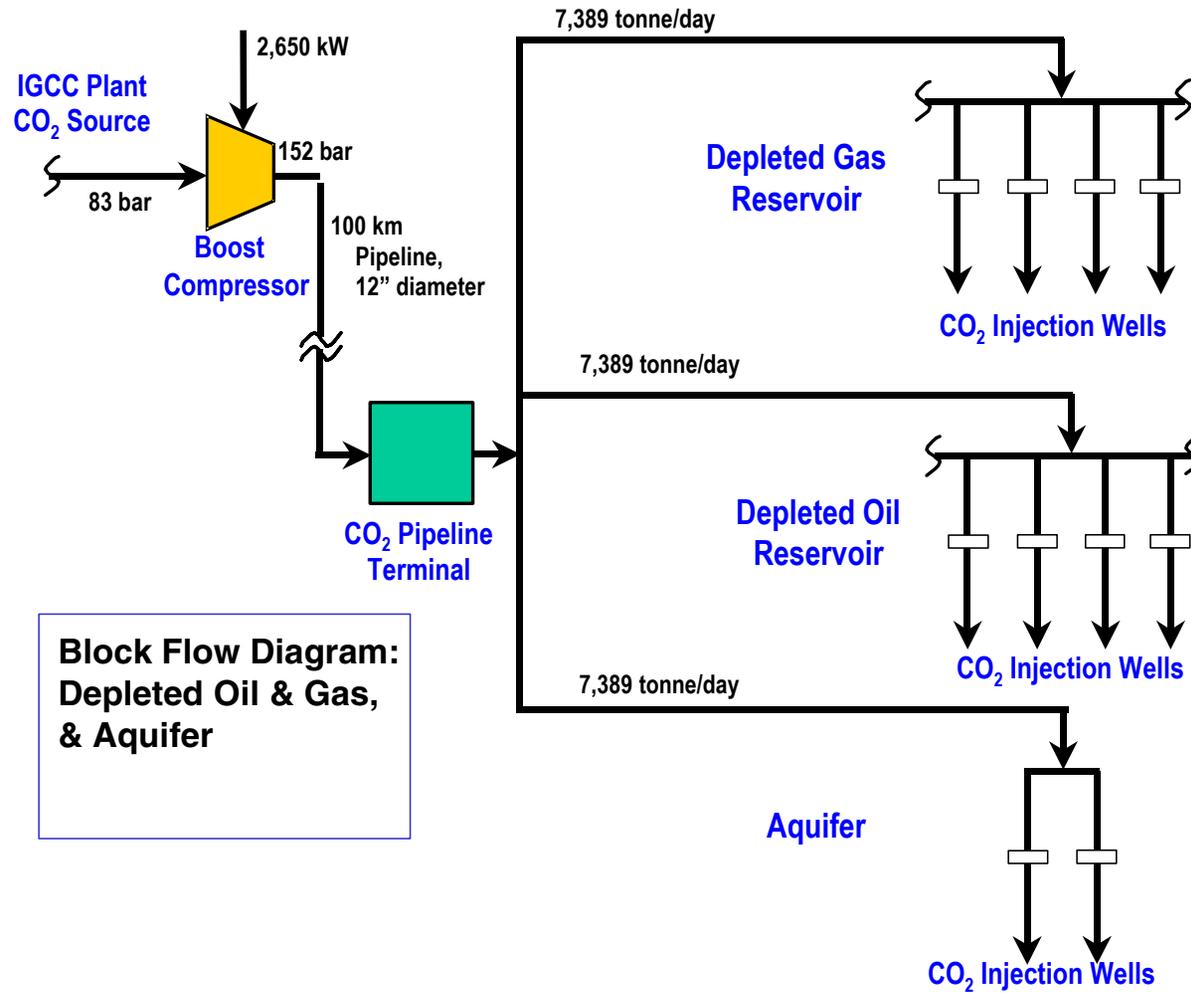
Figure 7-1
Depleted oil, gas, and aquifer block flow diagram

7.4 Methodology Used

Depleted natural gas and oil reservoirs, and deep saline aquifers, differ quite substantially from one another in terms of typical values of reservoir parameters such as pressure, thickness, depth, and permeability. The processes that govern the rate at which CO_2 can be injected at a well, and thus the number of wells required, are however essentially identical for the three types of reservoir. Given this, the same costing method is applied to each of the three geologic CO_2 storage options.

The cost model for the geologic CO_2 storage options can be broken down into a number of components. First, there is a relationship for calculating the number of wells required for a given CO_2 flow rate, CO_2 downhole injection pressure, and set of reservoir parameters. Second, an iterative procedure is used to take into account the interdependent relationship between CO_2 downhole injection pressure and well number. Third, a set of capital and O&M cost factors are used to determine cost based on well number. Each of these components, illustrated in the overview diagram in Figure 7-2 is described below in greater detail.
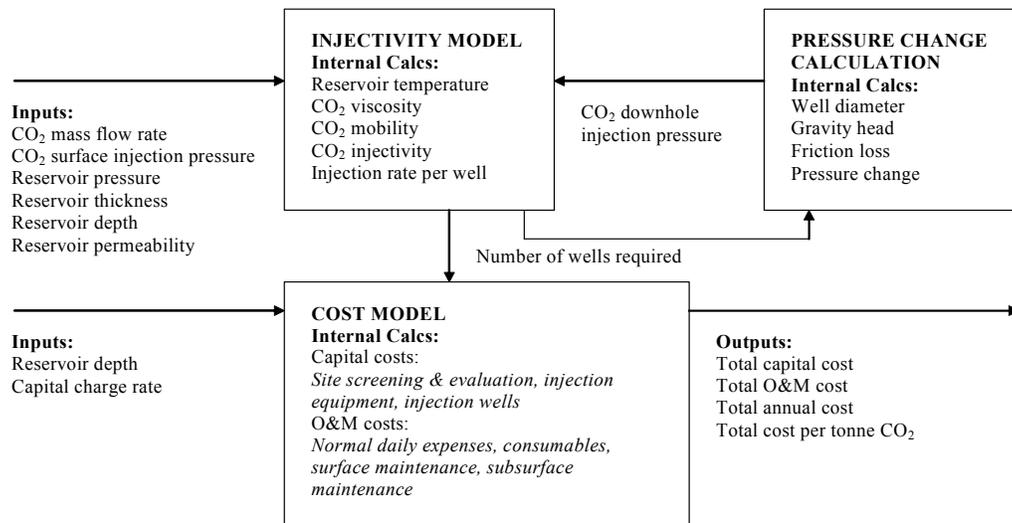
Figure 7-2
Geologic storage cost model overview diagram

The value of a particular reservoir parameter, where the same type of geological reservoir is being considered, can vary significantly. This variation is important because it has the potential to greatly affect the cost estimate of the geologic CO_2 storage option. In order to take account of this variation, base and sensitivity cases are run for each of the three storage options. These design bases, which comprise different sets of reservoir parameters, are detailed in Section 7.5.1.

7.4.1 Well Number Calculation

The well number calculation requires inputs for CO_2 mass flow rate, CO_2 downhole injection pressure, and reservoir pressure, thickness, depth, and permeability. Given the depth of the reservoir, reservoir temperature is calculated assuming a surface temperature of 15°C and a geothermal gradient of 25°C/km. The viscosity of the CO_2 (μ_{CO2}) is then calculated based on a correlation published by McHugh and Krukonis.[13] Next, the absolute permeability (k_a) is found from

$$k_a = (k_h \times k_v)^{0.5}$$

where k_v = the vertical permeability and is equal to 0.3 times the horizontal permeability and k_h = the given horizontal permeability.[14]

A relationship, derived by Law and Bachu,[14] is used to determine CO_2 injectivity from CO_2 mobility. This relationship is shown in Figure 7-3. The equation for CO_2 injectivity is

$$CO_2 \text{ injectivity} = 0.0208 \times CO_2 \text{ mobility}$$

where CO_2 injectivity is equal to the mass flow rate of CO_2 (m) that can be injected per unit of reservoir thickness (h) and per unit of downhole pressure difference ($P_{inj} - P_{res}$), and CO_2 mobility equals the CO_2 absolute permeability (k_a) divided by the CO_2 viscosity (μ_{CO2}). Given the CO_2 injectivity, the CO_2 injection rate per well ($Q_{CO2/well}$) can be found from

$$Q_{CO2/well} = CO_2 \text{ injectivity} \times h \times (P_{inj} - P_{res})$$

Finally, the number of wells required (n) is given by

$$n = m/Q_{CO2/well}$$

Depleted Gas and Oil Reservoir/Aquifer Storage
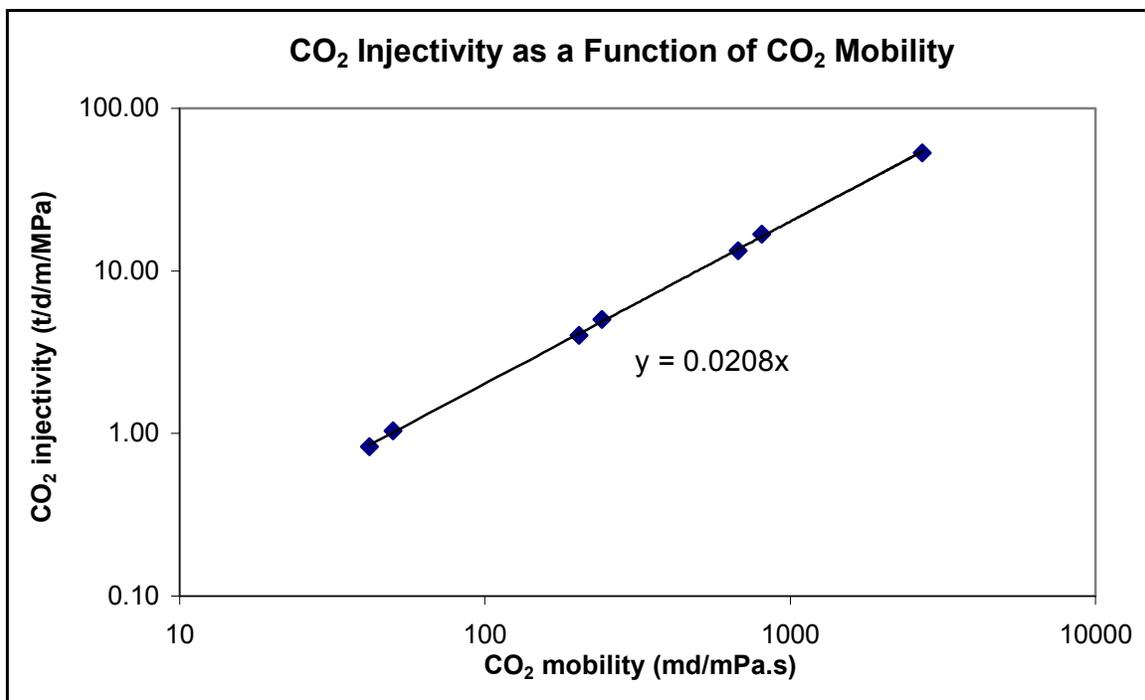
Figure 7-3
CO_2 injectivity as a function of CO_2 mobility

7.4.2 CO_2 Downhole Injection Pressure Calculation

The surface CO_2 injection pressure is equal to the 10.3 MPa minimum CO_2 pipeline outlet pressure used in the design of the pipeline for CO_2 transport. Based on this value, no additional recompression of CO_2 is required at the wellhead. A typical well diameter of 0.059 m is used for the injection pipe.

An iterative procedure is used to calculate the CO_2 downhole injection pressure and the required number of wells. This is because downhole injection pressure and well number are mutually dependent. Downhole injection pressure is found by adding the pressure increase due to the gravity head to the surface pressure and then subtracting from this the pressure decrease due to friction loss, which depends on the velocity of CO_2 in each well. Well number, on the other hand, is determined by CO_2 injectivity, which is dependent on the difference between the downhole injection and reservoir pressures.

It is important to note that, for the aquifer base and low-cost cases, it is necessary to increase the pipe diameter to 0.1 and 0.5 m, respectively. This is because smaller diameters in these cases result in unacceptable friction losses.

7.4.3 Cost Calculations

The total capital cost comprises site screening and evaluation, injection equipment and well drilling costs, while the total O&M cost includes the costs of normal daily operations, consumables, and surface and subsurface maintenance.

The capital cost for site screening and evaluation is based on an estimate given in a recent study by the Battelle Memorial Institute.[15] This study estimated the costs for preliminary site screening and candidate evaluation at $1,685,000.

All of the other costs, except for the well drilling cost, are calculated based on values given in the EIA 'Costs and Indices for Domestic Oil and Gas Field Equipment and Production Operations' report.[12] Average lease equipment costs and O&M costs were developed on a per well basis. In the case of the injection equipment and surface maintenance, the average cost values are factored by 0.5 to take into account the number of wells and thus the size/complexity of the surface equipment. Similarly, the average cost value for subsurface maintenance is adjusted to take into account the well depth. These capital and O&M cost factors/functions are given in Table 7-1.

Table 7-1
Capital and O&M cost estimation factors/functions

Parameter	Unit	Value
CAPITAL COSTS		
Injection Equipment (Flowlines & Connections)	$/well	43,600*(7,389/(280*Number_of_wells))^0.5
O&M COSTS		
Normal Daily Expenses	$/well	6,700
Consumables	$/well	17,900
Surface Maintenance (Repair & Services)	$/well	13,600*(7,389/(280*Number_of_wells))^0.5
Subsurface Maintenance (Repair & Services)	$/well	5,000*Well_depth/1219

The well drilling cost is calculated based on a relationship derived from data contained in the '1998 Joint Association Survey (JAS) on Drilling Costs' report.[16] This relationship between well depth and drilling cost is shown in Figure 7-4. To determine the relationship, regression analysis was performed on drilling cost data for onshore gas and oil wells. The total well drilling cost is found by multiplying the cost of drilling a single well for the given reservoir depth, taken from the graph, by the required number of wells.

Depleted Gas and Oil Reservoir/Aquifer Storage

Well Drilling Cost as a Function of Depth
1998 Onshore Gas & Oil Well Data

$y = 0.0888e^{0.0008x}$
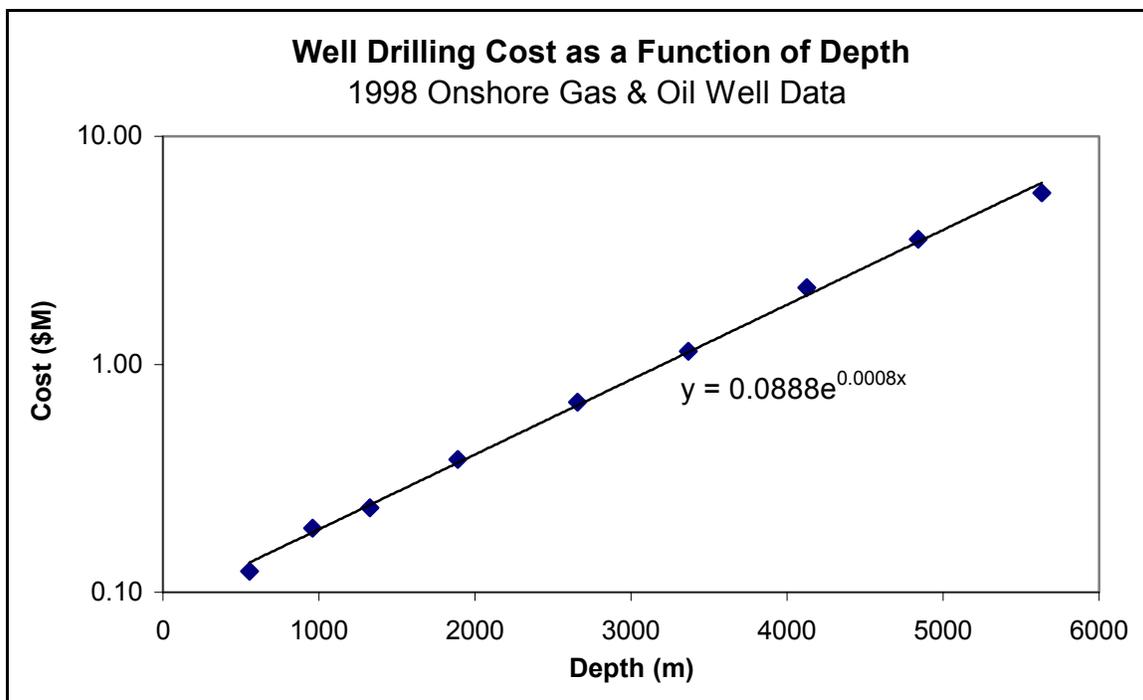
Figure 7-4
Well drilling cost as a function of depth

7.5 Design Basis

7.5.1 Reservoir Parameters and Well Numbers for Base and Sensitivity Cases

Typical, as well as a range of values for, reservoir properties of exhausted natural gas and oil fields, as suggested by Vello Kuuskraa of Advanced Resources International,[17] are given in Table 7-2. It should be noted that these values are representative of the properties of gas and oil reservoirs found in the Permian Basin.

Table 7-2
Natural gas and oil reservoir property data

Parameter	Units	Gas Reservoir Typical	Gas Reservoir Range	Oil Reservoir Typical	Oil Reservoir Range
Pressure	MPa	3.45	2.07 – 6.89	13.78	3.45 – 20.7
Thickness	m	30.5	15.24 – 61.0	42.7	21.3 – 61.0
Depth	m	1524	610 - 3048	1554	1524 – 2134
Permeability	md	1	0.01 - 100	5	5 - 19

Based on these reservoir parameter values, a base case as well as high-cost and low-cost cases were selected for both the depleted gas and oil reservoir options. It should be noted that, in the case of the gas reservoir, the range of permeability values considered was limited to give a practical number of wells. The parameter values for each of the base, high-cost and low-cost cases, as well as the corresponding number of wells required, are given for the gas and oil reservoir storage options in Table 7-3 and Table 7-4, respectively.

Table 7-3
Design bases for natural gas reservoir storage option

Parameter	Units	Gas Reservoir Base Case	Gas Reservoir High Cost Case	Gas Reservoir Low Cost Case
Pressure	MPa	3.5	6.9	2.1
Thickness	m	31	15	61
Depth	m	1,524	3,048	610
Permeability	md	1	0.8	10
Injection Rate per Well*	t/d	154	58	2,985
Number of Wells*		48	127	3

* calculated

Table 7-4
Design bases for oil reservoir storage option

Parameter	Units	Oil Reservoir Base Case	Oil Reservoir High Cost Case	Oil Reservoir Low Cost Case
Pressure	MPa	13.8	20.7	3.5
Thickness	m	43	21	61
Depth	m	1,554	2,134	1,524
Permeability	md	5	5	19
Injection Rate per Well*	t/d	358	116	5,720
Number of Wells*		21	64	2

* calculated

The aquifer base and sensitivity cases are based on aquifer property data given in the literature,[8,14] including data obtained from the Bureau of Economic Geology's website.[18] This property data is presented in Table 7-5. In addition, the calculated values of well number are shown. It can be seen from this table that aquifer properties, and thus the number of wells that would be required and the cost, can vary considerably.

Depleted Gas and Oil Reservoir/Aquifer Storage

Table 7-5
Aquifer property data

Aquifer	Pressure (MPa)	Thickness (m)	Depth (m)	Permeability (md)	Number of wells
Sleipner West	9.0	184	1,020	10	2
IEA Study Aquifer	11.3	55	1,459	13	6
Glauconitic Sandstone, Albert Basin	12.4	13	1,480	30	11
Repetto Formation, Los Angeles Basin	6.9	800	2,400	250	1
Arbuckle Group, Oklahoma	2.1	600	2,400	0.005	418
Paluxy Sandstone, East Texas Basin	10.3	75	1,000	400	1
Jasper Interval, East Texas Gulf Coast	8.4	1,500	800	100	1
Pottsville Formation, Black Warrior Basin	6.9	1,100	500	15	1
Cedar Key Dolomite, Central Florida Region	1.0	325	1,000	15	1

Incomplete sets of data for 13 aquifers were also available from the Bureau of Economic Geology. This data is shown in Table 7-6.

Table 7-6
Incomplete sets of aquifer property data

Aquifer	Pressure (MPa)	Thickness (m)	Depth (m)	Permeability (md)
Glen Canyon Group, Sevier/Kaiparowitz Basin		175	2,000	
Morrison Formation, San Juan Basin		250	1,600	
Fox Hills Sandstone, Power River Basin		175	800	
Madison Group, Williston Basin		250	1,400	
Lyons Sandstone, Denver Basin		300	2,000	
Granite Wash, Palo Duro Basin	9.1	800	1,000	
Woodbine Formation, East Texas Basin	12.4	100	1,000	
Frio Formation, Texas Gulf Coast		500	800	500
St. Peter Sandstone, Illinois Basin	5.3	50	50	
Mt. Simon Formation, Michigan Basin	11.4	100	100	
Tuscaloosa Group, Alabama Gulf Coastal Plain	10.9	40	40	
Oriskany Formation, Appalachian Basin	10.0	5	5	
Lower Potomac Group, Eastern Coastal Plain	6.9	225	225	

The data given in these two tables were used in a statistical analysis to determine suitable base, high-cost and low-cost cases for the aquifer storage option. The calculation of the values of aquifer pressure and depth for the base, high-cost and low-cost cases used standard statistical functions. In the case of aquifer thickness and permeability, however, a logarithmic regression was necessary. This was due to the fact that the values of these two latter variables varied by more than two orders of magnitude.

The base values for aquifer pressure and depth were based on the arithmetic mean. The high-cost values of each of these parameters were then taken as the mean plus the standard deviation and the low-cost values as the mean minus the standard deviation. This corresponds to an increase in pressure and depth causing an increase in cost, and a decrease in these parameters causing a reduction in cost. The values for thickness and permeability were calculated in a similar manner, but taking into account that a reduction in these parameters increases the cost and an increase reduces the cost. The final value for each parameter for each of the base, high-cost and low-cost cases is given Table 7-7. The number of wells required for each of these cases is also shown.

Depleted Gas and Oil Reservoir/Aquifer Storage

Table 7-7
Design bases for aquifer storage option

Parameter	Units	Aquifer Base Case	Aquifer High Cost Case	Aquifer Low Cost Case
Pressure	MPa	8.4	11.8	5.0
Thickness	m	171	42	703
Depth	m	1,239	1,784	694
Permeability	md	22	0.8	585
Injection Rate per Well*	t/d	9,363	82	889,495
Number of Wells*		1	91	1

* calculated

Reservoirs that are thick, shallow, and have high permeability require a smaller number of wells and, therefore, have a lower storage cost. A higher reservoir pressure results in lower injectivity (not desired), but higher CO_2 densities (desired). Therefore, a moderate pressure is optimal. In general, the permeability is the most critical parameter in determining costs.

7.5.2 Capital and O&M Cost Inputs

The capital cost of site screening and evaluation is assumed equal ($1,685,000) for each of the three geologic storage options. The other capital and O&M costs are calculated using the cost estimation factors/functions given in Section 7.4.3. Based on the respective values of well depth and required number of wells, as detailed in Section 7.5.1, it is possible to determine the costs on a per well basis for each of the storage options. These per well costs are then multiplied by the total number of wells. The model inputs for the capital and O&M costs for the base cases are given in Table 7-8.

Table 7-8
Capital and O&M cost inputs for gas and oil reservoir, and aquifer base cases

Parameter	Gas Reservoir	Oil Reservoir	Aquifer
Number of Wells	48	21	1
CAPITAL COSTS			
Screening and Evaluation of Sites	$1,685,000	$1,685,00	$1,685,000
Injection Equipment (Flowlines & Connections)	$1,552,000	$1,026,000	$224,000
Injection Wells	$14,426,000	$6,465,000	$239,000
Subtotal	$17,700,000	$9,180,000	$2,150,000
O&M COSTS			
Normal Daily Expenses	$322,000	$141,000	$7,000
Consumables	$859,000	$376,000	$18,000
Surface Maintenance (Repair & Services)	$484,000	$320,000	$70,000
Subsurface Maintenance (Repair & Services)	$300,000	$134,000	$5,000
Subtotal	$1,970,000	$970,000	$100,000

7.6 Model Results

This section presents costs for CO_2 capture and storage for the base cases described in Section 7.5. The storage costs comprise transaction, transportation, injection and monitoring costs. These costs are combined with capture costs from an IGCC power plant. The results are given on several bases as described in Chapter 2. Appendix B provides a detailed description of these spreadsheets.

7.6.1 Depleted Gas Reservoir: Spreadsheet Orientation and Typical Costs

The Process Input sheet for the depleted gas reservoir base case is presented in Table 7-9.

Depleted Gas and Oil Reservoir/Aquifer Storage

Table 7-9
Process input sheet for base case depleted gas reservoir

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━━━━━━━━━━ **Depleted Gas Reservoir Input Variables** ━━━━━━━━━━

</div>

Design Basis		**Economic**	
IGCC Plant		*IGCC Plant* (Case 3a)	
Capacity Factor	80%	CO_2 Capture Cost ($/tonne captured)	$14.55
Pipeline Distance	100 km	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*IGCC Plant & CO_2 Storage*	
		After-Tax Discount Rate	6.09%
CO_2 Storage		Levelized Carrying Charge Factor	15.0%
Design Basis	Base Cost Case		
Well Depth (m)	1,524		
Reservoir Pressure (MPa)	3.5		
Thickness (m)	31		
Permeability (md)	1.0		
Injection Rate Per Well (tonne/day)	156		

The Summary sheet for the depleted gas reservoir base case is presented in Table 7-10.

Table 7-10
Summary sheet for base case depleted gas reservoir

━━━━━ **Depleted Gas Reservoir Summary** ━━━━━

Process Description						**Capital & O&M Cost**		
							Capital	*O&M*
Pileline Distance	100 km		CO_2 Stored (M tonne/yr)	2.158		Transaction	$2,160,000	$0
Design Basis:	*Base Cost Case*		CO_2 Avoided (M tonne/yr)	1.822		Transport	$26,800,000	$1,333,000
			LC Avoided GHG (M tonne/yr)	2.154		Sequestration	$17,700,000	$1,970,000
			LC Avoided GHG (M tonne/yr)	1.804		Monitoring	$0	$216,000
Economic Description								
After-Tax Discount Rate	6.09%					Total	**$46,700,000**	**$3,500,000**

Cost of CO_2 Capture & Storage

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
1. Levelized Annual CO_2 Storage Costs *(years 1-20)*			*(storage only)*
CO_2 Storage Cost, M $/yr	10.48		10.48
CO_2 Stored or Avoided, M tonne/yr	2.16		2.15
Storage Cost, $/tonne CO_2	4.86		4.87
2. Levelized Annual CO_2 Capture and Storage Costs *(years 1-20)*			
CO_2 Capture Cost, M $/yr	31.39	31.39	31.39
CO_2 Storage Cost, M $/yr	10.48	10.48	10.48
Capture + Storage Cost, M$/yr	41.87	41.87	41.87
CO_2 Stored or Avoided, M tonne/yr	2.16	1.82	1.80
Capture + Storage Cost, $/tonne CO_2	19.41	22.98	23.21
3. CO_2 Capture and Net Storage Costs, NPV Basis *(years 1-100)*			
NPV of CO_2 Capture Costs, M$	357.42	357.42	357.42
NPV of CO_2 Storage Costs, M$	120.45	120.45	120.45
NPV of Capture + Storage Costs, M$	477.87	477.87	477.87
NPV of CO_2 Stored or Avoided, M tonne	24.57	20.75	20.55
Capture + Storage Cost (NPV Basis), $/tonne CO_2	19.45	23.03	23.26
4. Cost of Electricity, $/MWh			
Reference Plant (no capture)	43.98		
Capture Costs (years 1-20)	11.10		
Storage Costs (years 1-20)	3.71		
Storage Costs, Monitoring, etc. (years 21-100)	0.03		
Total Cost of Electricity	58.82		

7.6.2 Depleted Oil Reservoir: Spreadsheet Orientation and Typical Costs

The Process Input sheet for the depleted oil reservoir base case is presented in Table 7-11.

Depleted Gas and Oil Reservoir/Aquifer Storage

Table 7-11
Process input sheet for depleted oil reservoir base case

Depleted Oil Reservoir Input Variables

Design Basis		Economic	
IGCC Plant		*IGCC Plant (Case 3a)*	
Capacity Factor	80%	CO_2 Capture Cost ($/tonne captured)	$14.55
Pipeline Distance	100 km	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*IGCC Plant & CO_2 Storage*	
		After-Tax Discount Rate	6.09%
CO_2 Storage		Levelized Carrying Charge Factor	15.0%
Design Basis	Base Cost Case		
Well Depth (m)	1,554		
Reservoir Pressure (MPa)	13.8		
Thickness (m)	43		
Permeability (md)	5.0		
Injection Rate Per Well (tonne/day)	360		

The Summary sheet for the depleted oil reservoir base case is presented in Table 7-12.

Table 7-12
Summary sheet for depleted oil reservoir base case

━━━━━━━━━━━━━━ **Depleted Oil Reservoir Summary** ━━━━━━━━━━━━━━

Process Description

Pileline Distance	100 km	CO_2 Stored (M tonne/yr)	2.158
Design Basis:	*Base Cost Case*	CO_2 Avoided (M tonne/yr)	1.822
		LC Avoided GHG (M tonne/yr)	2.154
		LC Avoided GHG (M tonne/yr)	1.804

Economic Description

After-Tax Discount Rate	6.09%

Capital & O&M Cost

	Capital	*O&M*
Transaction	$2,160,000	$0
Transport	$26,800,000	$1,333,000
Sequestration	$9,180,000	$970,000
Monitoring	$0	$216,000
Total	**$38,140,000**	**$2,520,000**

Cost of CO_2 Capture & Storage

1. Levelized Annual CO_2 Storage Costs *(years 1-20)*

	CO_2 Captured Basis	LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	8.22	8.22
CO_2 Stored or Avoided, M tonne/yr	2.16	2.15
Storage Cost, $/tonne CO_2	3.81	3.82

2. Levelized Annual CO_2 Capture and Storage Costs *(years 1-20)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	31.39	31.39	31.39
CO_2 Storage Cost, M $/yr	8.22	8.22	8.22
Capture + Storage Cost, M$/yr	39.61	39.61	39.61
CO_2 Stored or Avoided, M tonne/yr	2.16	1.82	1.80
Capture + Storage Cost, $/tonne CO_2	18.36	21.74	21.95

3. CO_2 Capture and Storage Costs, NPV Basis *(years 1-100)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	357.42	357.42	357.42
NPV of CO_2 Storage Costs, M$	94.71	94.71	94.71
NPV of Capture + Storage Costs, M$	452.14	452.14	452.14
NPV of CO_2 Stored or Avoided, M tonne	24.57	20.75	20.55
Capture + Storage Cost (NPV Basis), $/tonne CO_2	18.40	21.79	22.01

4. Cost of Electricity, $/MWh

Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Storage Costs (years 1-20)	2.91
Storage Costs, Monitoring, etc. (years 21-100)	0.03
Total Cost of Electricity	58.02

7.6.3 Aquifer Storage: Spreadsheet Orientation and Typical Costs

The Process Input sheet for the aquifer storage base case is presented in Table 7-13.

Table 7-13
Process input sheet for aquifer storage base

Aquifer Storage Input Variables

Design Basis		**Economic**	
IGCC Plant		*IGCC Plant (Case 3a)*	
Capacity Factor	80%	CO_2 Capture Cost ($/tonne captured)	$14.55
Pipeline Distance	100 km	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*IGCC Plant & CO_2 Storage*	
		After-Tax Discount Rate	6.09%
CO_2 Storage		Levelized Carrying Charge Factor	15.0%
Design Basis	Base Cost Case		
Well Depth (m)	1,239		
Reservoir Pressure (MPa)	8.4		
Thickness (m)	171		
Permeability (md)	22.0		
Injection Rate Per Well (tonne/day)	6,452		

The Summary sheet for the aquifer storage base case is presented in Table 7-14.

Table 7-14
Summary sheet for the aquifer storage base case

══════════════════════ **Aquifer Storage Summary** ══════════════════════

Process Description

Pileline Distance	100 km	CO_2 Stored (M tonne/yr)	2.158
Design Basis:	*Base Cost Case*	CO_2 Avoided (M tonne/yr)	1.822
		LC Avoided GHG (M tonne/yr)	2.155
		LC Avoided GHG (M tonne/yr)	1.804

Economic Description

After-Tax Discount Rate	6.09%

Capital & O&M Cost

	Capital	O&M
Transaction	$2,160,000	$0
Transport	$26,800,000	$1,333,000
Sequestration	$2,480,000	$158,000
Monitoring	$0	$216,000
Total	**$31,440,000**	**$1,710,000**

Cost of CO_2 Capture & Storage

1. Levelized Annual CO_2 Storage Costs *(years 1-20)*

	CO_2 Captured Basis	LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	6.41	6.41
CO_2 Stored or Avoided, M tonne/yr	2.16	2.15
Storage Cost, $/tonne CO_2	2.97	2.98

2. Levelized Annual CO_2 Capture and Storage Costs *(years 1-20)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	31.39	31.39	31.39
CO_2 Storage Cost, M $/yr	6.41	6.41	6.41
Capture + Storage Cost, M$/yr	37.80	37.80	37.80
CO_2 Stored or Avoided, M tonne/yr	2.16	1.82	1.80
Capture + Storage Cost, $/tonne CO_2	17.52	20.74	20.95

3. CO_2 Capture and Net Storage Costs, NPV Basis *(years 1-100)*

	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	357.42	357.42	357.42
NPV of CO_2 Storage Costs, M$	74.08	74.08	74.08
NPV of Capture + Storage Costs, M$	431.50	431.50	431.50
NPV of CO_2 Stored or Avoided, M tonne	24.57	20.75	20.55
Capture + Storage Cost (NPV Basis), $/tonne CO_2	17.56	20.80	21.00

4. Cost of Electricity, $/MWh

Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Storage Costs (years 1-20)	2.27
Storage Costs, Monitoring, etc. (years 21-100)	0.03
Total Cost of Electricity	57.38

7.7 Sensitivity Analyses

7.7.1 Depleted Gas Reservoir

The sensitivity of the CO_2 storage cost for the depleted gas reservoir option is determined for five key parameters: well depth, pressure, thickness, permeability and pipeline distance. It can be seen in Figure 7-5 that increases in well depth, reservoir pressure and pipeline distance cause an increase in the cost of storage, while increases in reservoir thickness and permeability decrease the storage cost. More noteworthy, the figure shows that, for the chosen base case values, changes in thickness and permeability have the greatest effect on storage cost.

Depleted Gas and Oil Reservoir/Aquifer Storage
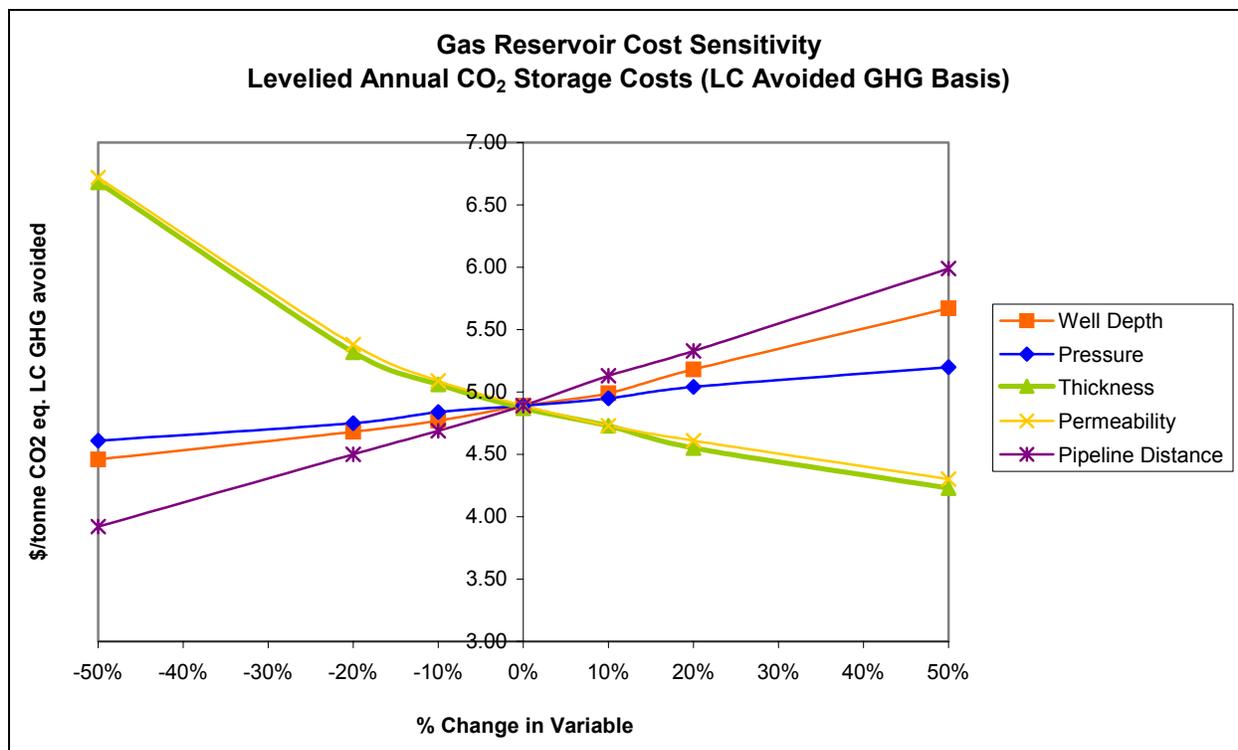
Figure 7-5
Sensitivity analysis for depleted gas reservoir

High and low cost cases have been chosen for the depleted gas reservoir option, and are presented together with the base case in Table 7-15. For the high and low cost values for each of the five key parameters, the percentage change in the value from the base case is shown. This is done to illustrate the fact that the range in the values of some parameters is expected to be greater than for others.

Table 7-15
Depleted gas reservoir base, high cost and low cost cases

Parameter	Units	Gas Reservoir Base Case	Gas Reservoir High Cost Case		Gas Reservoir Low Cost Case	
Pressure	MPa	3.5	6.9	+97%	2.1	-40%
Thickness	m	31	15	-52%	61	+97%
Depth	m	1,524	3,048	+100%	610	-60%
Permeability	md	1	0.8	-20%	10	+900%
Pipeline Distance	km	100	300	+200%	0	-100%

The results for the high and low cost cases as well as the base case are given in Table 7-16. The range of CO_2 storage cost for the depleted gas reservoir option varies by about a factor of 20 for the high and low cost cases.

Table 7-16
Results for depleted gas reservoir base, high cost and low cost cases

Parameter	Units	Gas Reservoir Base Case	Gas Reservoir High Cost Case	Gas Reservoir Low Cost Case
Injection Rate per Well	t/d	156	57	2,975
Number of Wells		48	129	3
Levelized Annual CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG avoided	4.87	19.43	1.20

7.7.2 Depleted Oil Reservoir

The sensitivity of the CO_2 storage cost for the depleted gas reservoir option is determined for the same five key parameters as used in the case of the depleted oil reservoir. It can be seen in Figure 7-6 that increases in reservoir pressure and pipeline distance cause an increase in the cost of storage, while increases in well depth, reservoir thickness and permeability decrease the storage cost.   In contrast to the depleted gas reservoir option, increased well depth results in a decrease in the number of wells required, the resulting decrease in cost of which outweighs the increase in well drilling cost. The figure shows that, for the chosen base case values, changes in pressure have the greatest effect on storage cost.
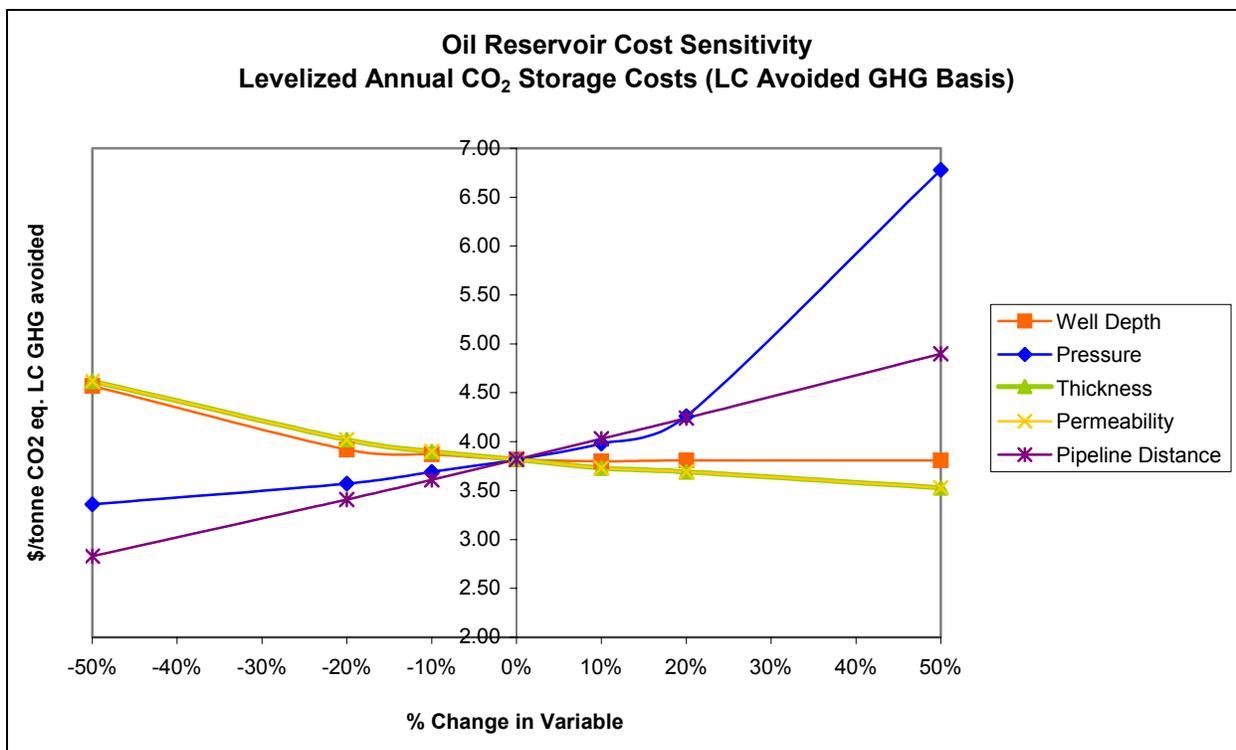
Figure 7-6
Sensitivity analysis for depleted oil reservoir

High and low cost cases have been chosen for the depleted oil reservoir option, and are presented together with the base case in Table 7-17. For the high and low cost values for each of the five key parameters, the percentage change in the value from the base case is shown.

Table 7-17
Depleted oil reservoir base, high cost and low cost cases

Parameter	Units	Oil Reservoir Base Case	Oil Reservoir High Cost Case		Oil Reservoir Low Cost Case	
Pressure	MPa	13.8	20.7	+50%	3.5	-75%
Thickness	m	43	21	-51%	61	+42%
Depth	m	1,554	2,134	+37%	1,524	-29%
Permeability	md	5	5	0%	19	+280%
Pipeline Distance	km	100	300	+200%	0	-100%

The results for the high and low cost cases as well as the base case are given in Table 7-18. The range of the CO_2 storage cost for the depleted oil reservoir option differ by about a factor of 10 for the high and low cost cases.

Table 7-18
Results for depleted oil reservoir base, high cost and low cost cases

Parameter	Units	Oil Reservoir Base Case	Oil Reservoir High Cost Case	Oil Reservoir Low Cost Case
Injection Rate per Well	t/d	360	115	5,690
Number of Wells		21	65	2
Levelized Annual CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG avoided	3.82	11.16	1.21

7.7.3 Aquifer

The sensitivity of the CO_2 storage cost for the aquifer option is determined for the same five key parameters as for the other geologic storage options. It can be seen in Figure 7-7 that, for the range of values considered, the storage cost is only sensitive to pipeline distance. This is because, for the base case values chosen, the value of CO_2 injectivity is very high. This in turn results in only one well being required, where this is relatively insensitive to changes in reservoir properties.
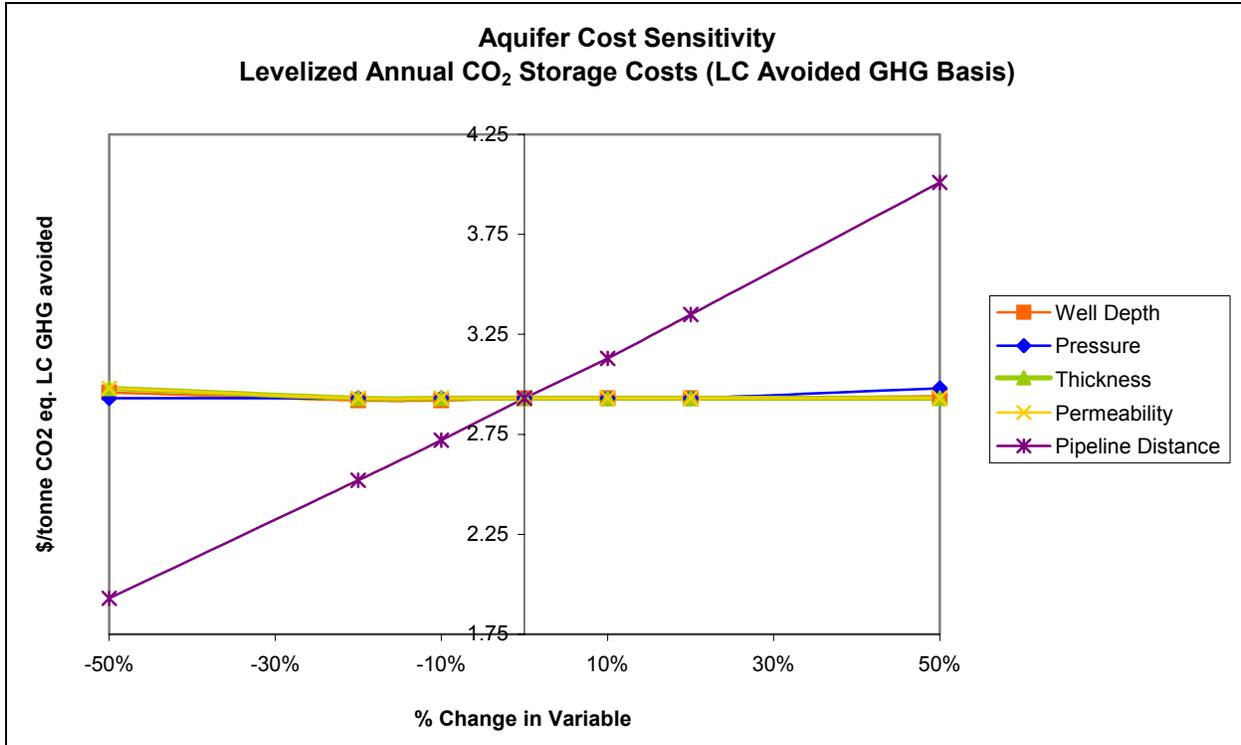
Figure 7-7
Sensitivity analysis for aquifer

Depleted Gas and Oil Reservoir/Aquifer Storage

High and low cost cases have been chosen for the aquifer option, and are presented together with the base case in Table 7-19. For the high and low cost values for each of the five key parameters, the percentage change in the value from the base case is shown. As compared to the depleted gas and oil reservoir options, thickness and permeability can vary to a far greater degree.

Table 7-19
Aquifer base, high cost and low cost cases

Parameter	Units	Aquifer Base Case	Aquifer High Cost Case		Aquifer Low Cost Case	
Pressure	MPa	8.4	11.8	+40%	5.0	-40%
Thickness	m	171	42	-75%	703	+311%
Depth	m	1,239	1,784	+44%	694	-44%
Permeability	md	22	0.8	-96%	585	+2559%
Pipeline Distance	km	100	300	+200%	0	-100%

The results for the high and low cost cases as well as the base case are given in Table 7-20. The range of CO_2 storage cost for the aquifer option differ by about a factor of 10 for the high and low cost cases.

Table 7-20
Results for aquifer base, high cost and low cost cases

Parameter	Units	Aquifer Base Case	Aquifer High Cost Case	Aquifer Low Cost Case
Injection Rate per Well	t/d	9,363	82	889,495
Number of Wells		1	91	1
Levelized Annual CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG avoided	2.93	11.71	1.14

It is important to note that an aquifer could have a value of permeability equal to or 2 or 3 orders of magnitude less than the base case value. A reduction in the permeability of this magnitude would in turn cause a dramatic increase in the CO_2 storage cost. For example, for the base case, reducing the base case permeability value from 22 to 0.22 md gives a storage cost of $5.37, while a permeability of 0.022 md gives a cost of $25.23. Similarly, as the thickness of the reservoir approaches zero, the storage cost skyrockets.

7.8 Comparison To Literature

7.8.1 Studies Used in Model Evaluation

Injection scheme details and reservoir properties as well as cost data were collected from the studies listed in Table 7-21. All of the studies are concerned with the injection of CO_2 into a saline aquifer, except for the 'IEA depleted reservoir' study that looks at storing CO_2 in an exhausted gas reservoir.

Table 7-21
Injection schemes' characteristics

Study	CO₂ Flow Rate (t/d)	Downhole Injection Pressure (MPa)	Reservoir Pressure (MPa)	Thickness (m)	Depth (m)	Permeability (md)	Number of Wells	Location
IEA aquifer[8]	10,685	28.0	11.3	55	1,459	13	6	Onshore
IEA depleted reservoir[8]	8,560	10.4	3.0	-	2,500	100	4	Onshore
Elsamprojekt[19]	3,770	-	-	-	1,100	-	12	Onshore
GEODISC[20]	15,780	17.4	17.2	400	1,600	300	4	Offshore
Sleipner West[21]	2,740	11.0	9.0	184	1,020	10	1	Offshore

The aquifer in both the 'GEODISC' and 'Sleipner West' studies is located offshore, in a depth of water of 100 and 80 m respectively. Due to certain reservoir properties not being specified, a benchmark for CO_2 injectivity cannot be obtained from either of the 'IEA depleted reservoir' or the 'Elsamprojekt' studies. It should also be noted that cost data are not available for the 'Sleipner West' project.

7.8.2 Comparison of Values from Model and Studies

Figure 7-8 shows that, for CO_2 injectivity, the value calculated by the model generally agrees with the value used in each of the studies. Indeed, the same relationship between CO_2 mobility and injectivity, as is used in the model, has been used in the 'GEODISC' study[22] and possibly also the 'IEA aquifer' study. In the case of the 'Sleipner West' study, it should be noted the model at least underestimates, rather than overestimates, the injectivity.

Depleted Gas and Oil Reservoir/Aquifer Storage
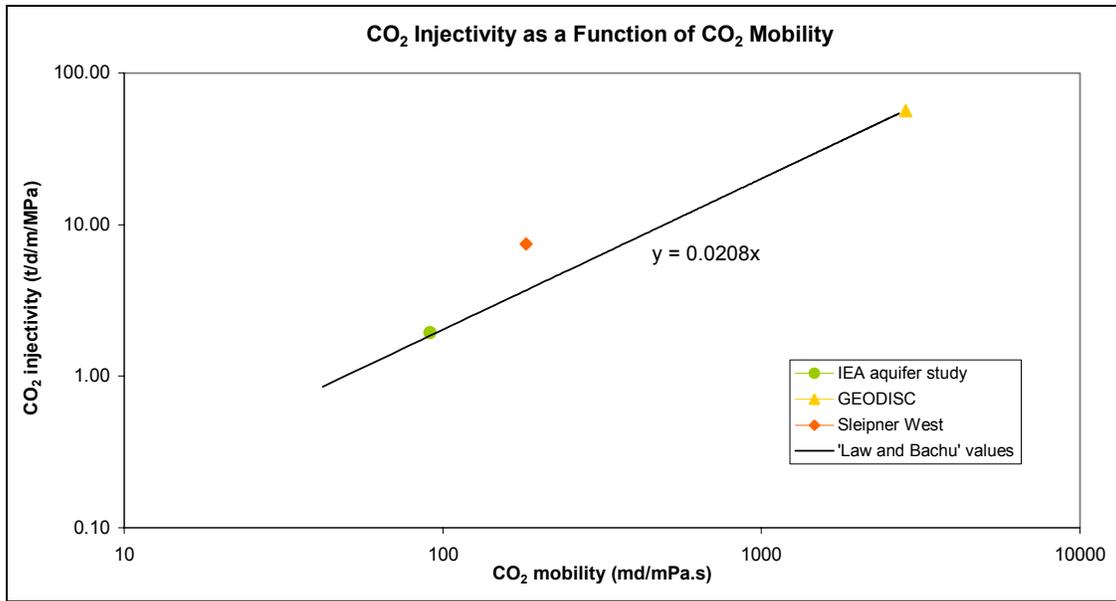
Figure 7-8
Comparison of CO_2 injectivity values

A comparison of well drilling cost as calculated by the model and given in various studies is shown in Figure 7-9. The drilling cost in three of the studies can be seen to be about four times that calculated by the model, with the value in the 'GEODISC' study being exceedingly higher. The significant difference between the model's and the 'GEODISC' study's drilling cost can be attributed in part to the aquifer in the latter being located offshore. The drilling costs in the other three studies, one of which is based on conditions in Europe and the other two on those in Canada, are likely higher due to less drilling activity in these regions.
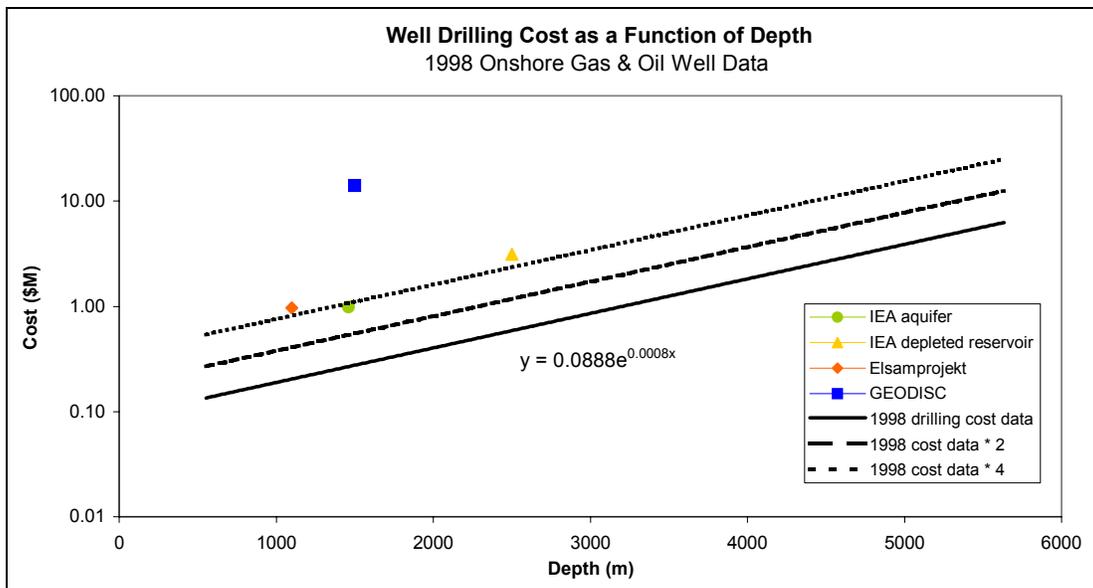
Figure 7-9
Comparison of onshore well drilling cost values

Injecting CO_2 into an offshore reservoir can be expected to be significantly more expensive than for a reservoir in an onshore location. Firstly, offshore drilling costs are higher. This can be seen from a comparison of Figure 7-10, which gives the cost of offshore well drilling based on 1998 JAS data for offshore gas and oil wells, with Figure 7-9. From Figure 7-10 it can also be seen that the offshore well drilling cost given in the 'GEODISC' study is about four times the JAS value. Secondly, CO_2 injection into an offshore reservoir requires that a platform be installed. The cost of a platform depends primarily on the water depth and the number of wells it accommodates, with an unmanned platform with ten wells in a water depth of around 100 and 200 m costing around $4 million and $6.5 million per meter water depth, respectively[20]. If CO_2 injection into offshore reservoirs were to be considered, these factors would need to be taken into account.

Well Drilling Cost as a Function of Depth
1998 Offshore Gas and Oil Well Data

$y = 1.3555e^{0.0004x}$

Legend:
GEODISC
1998 drilling cost data
1998 cost data * 2
1998 cost data * 4
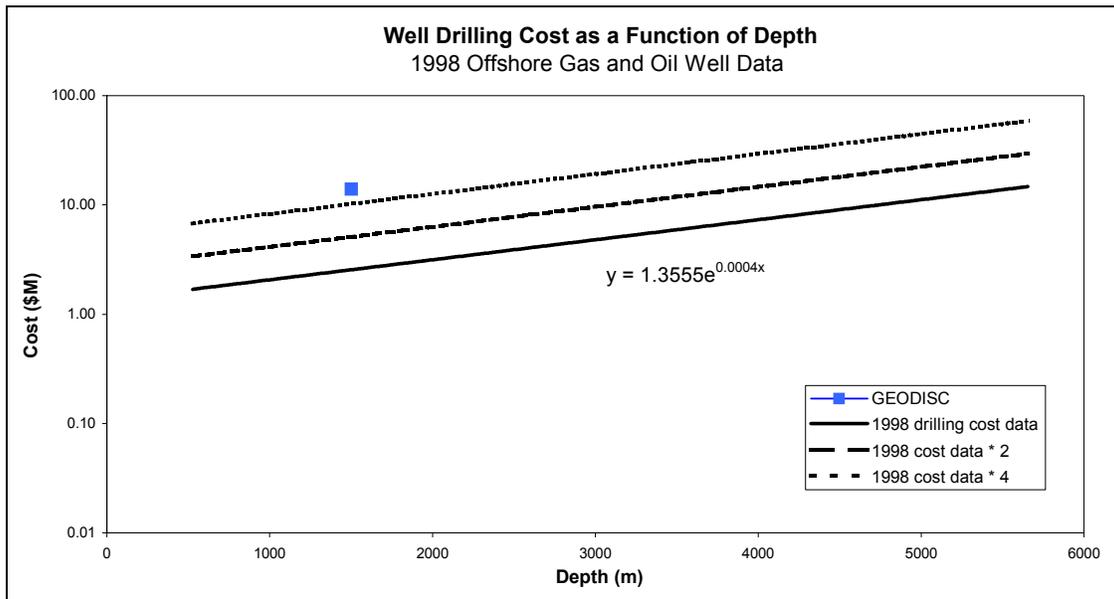
Figure 7-10
Comparison of offshore well drilling cost values

Depleted Gas and Oil Reservoir/Aquifer Storage

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8
OCEAN VIA PIPELINE

8.1 Introduction

This chapter looks at the injection of CO_2 into the deep ocean via a pipeline laid on the seabed.

8.2 State of the Art

The direct injection of CO_2 into the ocean requires starting with a fairly concentrated stream of CO_2 and delivering it to locations in the ocean where it will be effectively sequestered for hundreds of years, if not longer. To accomplish this, the CO_2 needs to be injected below the thermocline at depths greater than 1000 meters.[1] The CO_2 may be injected at moderate depths of 1,000 to 2,000 m or at depths greater than 3,000 m. The CO_2 can be sequestered either by dissolution in the water column or by the formation of CO_2 hydrates, which are solid, ice-like compounds.

Led by offshore exploration and production activities of the oil and gas industry, great strides have been made in the development of undersea offshore technology. It is becoming routine for work to be done at depths approaching 2,000 m (6,600 feet). Work at much greater depths, even approaching 10,000 m, is possible at reduced scales and/or time horizons, as has been shown in deep drilling and other scientific programs. However, there are still many technical challenges in going deep at large scales for extended times. Therefore, as a first step, it appears that the best strategy is to discharge the CO_2 below the thermocline at moderate depths of 1,000 to 2,000 m.[2]

The technology to proceed with this option is available. There is however a lack of information regarding how to adequately optimize the costs, determine the effectiveness of the sequestration and understand the resulting changes in the biogeochemical cycles of the oceans. This storage option is also limited by the fact that it is best suited to large, stationary CO_2 sources with access to deep-sea sequestration sites — sources that may account for only about 15 to 20 percent of our anthropogenic CO_2 emissions.

Figure 8-1 illustrates that for a total CO_2 pipeline distance of 400 km from the power plant to the injection site, considered here as a sensitivity case for ocean storage, around 35 percent of U. S. power plant CO_2 emissions could be considered for storage. Given that U. S. power plant CO_2 emissions account for slightly less than 35 percent of total U. S. CO_2 emissions, this is equivalent to about 12 percent of the U. S. anthropogenic CO_2 emissions.

Cumulative Distribution of Population and CO$_2$ Emissions
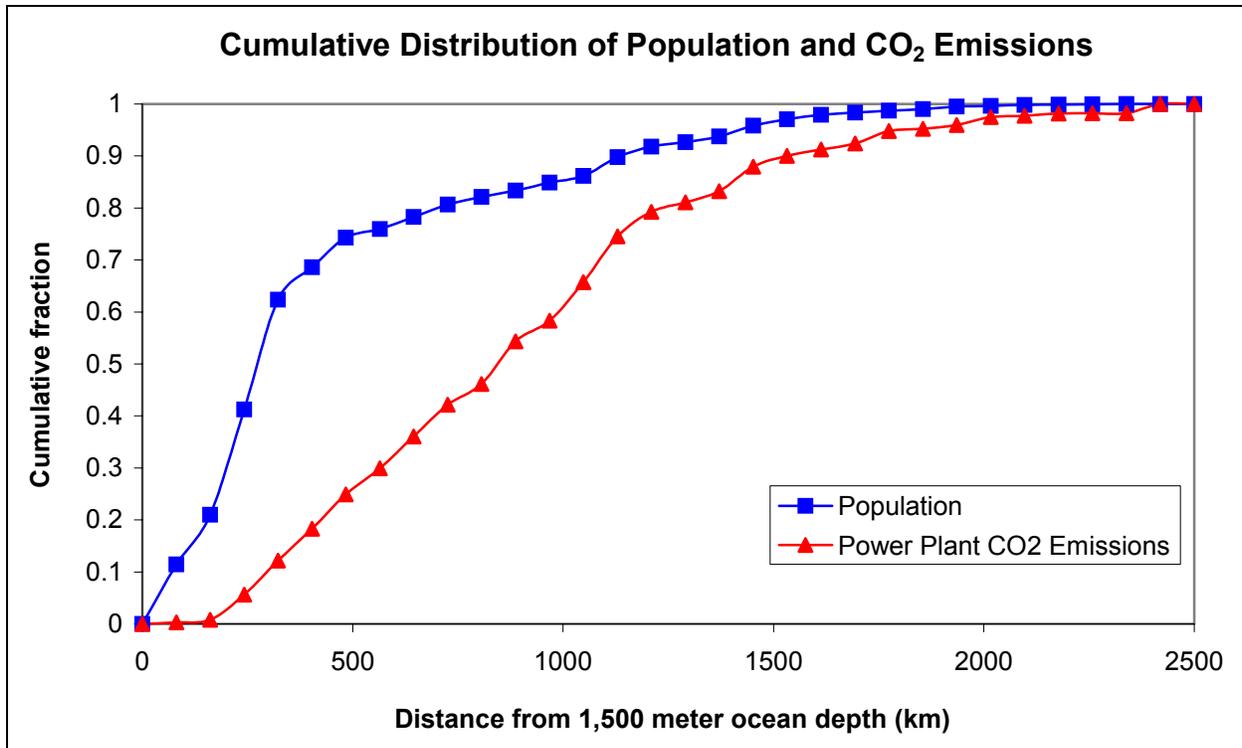
Figure 8-1
Cumulative distribution of population and power plant CO$_2$ emissions

8.3 Process Description

To make a more realistic case, it is assumed that three IGCC power plants supply CO$_2$ to a single ocean pipeline. Based on this, the ocean pipeline system needs to be designed to handle three times the quantity of CO$_2$, i.e. 11.29 million scm (22,167 tonnes), as opposed to 3.76 million scm (7,389 tonnes) of CO$_2$ per day. At the shoreline collection point, additional compression is needed to bring the CO$_2$ up to the ocean pipeline's required inlet pressure of 152 bar. As a final note, it is assumed that this facility, like the power plant, has a lifetime and design/construction time of 20 and 4 years, respectively.

8.4 Methodology Used

The ocean pipeline storage option involves transporting the CO$_2$ via a subsea pipeline from the shoreline to a depth of 2,000 m, at which depth the CO$_2$ is discharged into the deep ocean via a diffuser unit. An offshore distance of 100 km, for the base case, is considered.   The method used for calculating the cost of this process can be broken down into a couple of steps. First, the diameter of the subsea pipeline is determined. It is then possible, as a second step, to calculate the capital and O&M costs as well as the cost per tonne of CO$_2$. These two steps are explained in greater detail below. Figure 8-2 gives an overview of the ocean pipeline cost model.

OCEAN PIPELINE MODEL
Internal Calcs:
CO_2 outlet pressure
Gravity head
Pressure drop per unit length
Pipe diameter
Capital costs:
Pipeline, injector unit, boost compressor
O&M costs:
Subsea maintenance, boost compressor power & maintenance

Inputs:
CO_2 mass flow rate
Pipeline length
Injection depth
CO_2 inlet pressure
Diffuser head loss
Capital charge rate

Outputs:
Total capital cost
Total O&M cost
Total annual cost
Total cost per tonne CO_2

Figure 8-2
Ocean pipeline cost model overview diagram

8.4.1 Diameter Calculation

The pipeline diameter is calculated using the same method, described in Section 4.4.1, as is used in the CO_2 overland pipeline transport model. The only difference is the means by which the maximum allowable pressure drop per unit length ($\bullet P/\bullet L$) is determined. In the case of CO_2 overland pipeline transport, the pressure drop per unit length is simply found as the difference between the pipeline CO_2 inlet and outlet pressures divided by the pipeline length. The pipeline ocean CO_2 storage model however requires that the pressure drop per unit length calculation also take into account the gravity head gain and diffuser head loss. In addition, it is necessary that the CO_2 be discharged at a pressure equal to the hydrostatic pressure.

The pipeline CO_2 inlet pressure for the subsea pipeline is set at 152 bar, the same as the outlet value in the land-based cases. Given that the CO_2 outlet pressure for the overland pipelines is set at 103 bar, this requires the use of booster pumps. The required pipeline outlet pressure, taken to be equal to the hydrostatic pressure of water at a depth of 2,000 m, is calculated to be approximately 200 bar. A diffuser head loss of 20 bar is then assumed. Next, calculating the average value of CO_2 specific gravity over both the 0 to 1,000 m-depth and 1,000 to 2,000 m-depth intervals, and adding the respective CO_2 pressure head gains, gives a gravity head of 194 bar. Based on the set inlet pressure, assumed diffuser head loss and the calculated values of outlet pressure and gravity head, maximum allowable pressure drops per unit length for the base and sensitivity cases are found. Finally, the equations for pressure drop and head loss due to frictional resistance in a pipe, assuming turbulent flow, are used to determine the respective diameters. Figure 8-3 gives the calculated pipe diameter, for the base case, as a function of CO_2 mass flow rate.

Ocean Via Pipeline
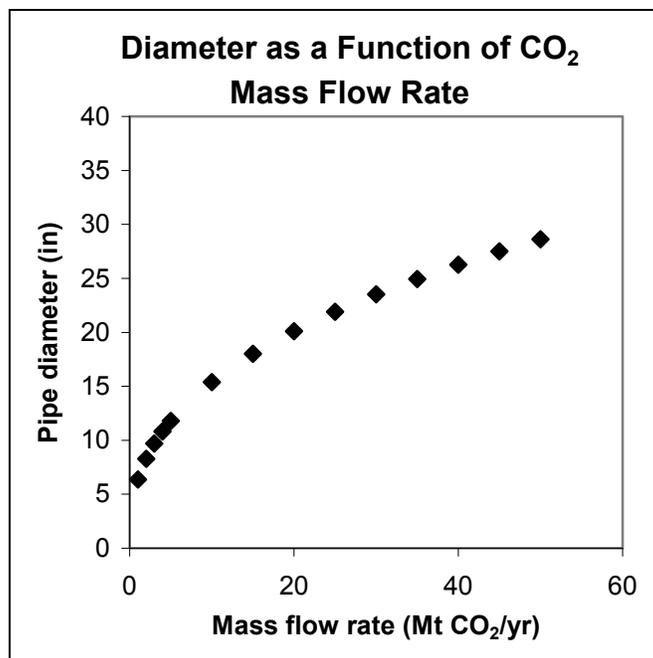
Figure 8-3
Diameter for the base case as a function of CO$_2$ mass flow rate

8.4.2 Cost Calculations

The cost of the subsea pipeline has been determined based on cost information contained in McDermott's phase II final report on 'Large-scale CO$_2$ Transportation and Deep Ocean Sequestration.[3] Based on McDermott's total capital cost of $3,224.5 million for six 30-inch, 500-km long pipelines, a capital cost factor of $35,749/in/km ($57,659/in/mi) is calculated. The total annual O&M cost for the six pipelines was found by McDermott to be $75,400,000, where this excludes the cost of pump operation.[4] Based on this figure, an O&M cost factor of $25,078/yr/km ($40,448/yr/mi) is calculated. The capital cost of an injector unit, based on an estimate given in an IEA report,[5] is taken to be $14.5 million.

The capital and yearly maintenance costs of the boost compressor are estimated at $9,355,000 and $432,000, respectively. The cost of the power used by the compressor is taken to be $0.055 per kilowatt-hour. These costs together with the costs associated with the subsea pipeline and injector unit are summarized in Table 8-1.

Table 8-1
Capital and O&M cost estimation factors

Parameter	Unit	Value
CAPITAL COSTS		
Subsea Pipeline	$/in/km	35,749
Injector Unit	$	14,500,000
Boost Compressor	$	9,355,000
O&M COSTS		
Subsea Maintenance	$/y/km	25,078
Boost Compressor Power	$/kWh	0.055
Boost Compressor Maintenance	$	432,000

8.5 Design Basis

8.5.1 Pipeline Design

The methodology described in Section 8.4.1 was used to determine pressure drop per unit length and pipeline diameter for the base case. The design basis for ocean storage via pipeline is summarized in Table 8-2.

Table 8-2
Design basis for ocean storage via pipeline

Parameter	Unit	Ocean Pipeline Base Case
Subsea Pipeline Length	km	100
Injection Depth	m	2,000
CO_2 Inlet Pressure	MPa	15.2
CO_2 Outlet Pressure*	MPa	20.0
Gravity Head*	MPa	19.4
Diffuser Head Loss*	MPa	2.0
Pressure Drop per Unit Length*	Pa/m	126
Pipe Diameter*	inches	14.2
Nominal Pipe Size*	inches	16

* calculated
1 inch = 0.0254 meters

The calculated nominal pipe size for the base case is 16 inches (0.41 meters). This pipe diameter is larger than the 12-inch diameter (0.30 meters) for the case of CO_2 overland pipeline transport. This is despite the value of maximum allowable pressure drop per unit length also being larger. This can be explained by the fact that the design CO_2 mass flow rate used here is 11.29 million scm (22,167 tonnes) per day as opposed to 3.76 million scm (7,389 tonnes) per day.

8.5.2 Capital and O&M Cost Inputs

The capital and O&M costs of ocean storage via pipeline for the base case are calculated using the methodology described in Section 8.4.2. The results are shown in Table 8-3.

Table 8-3
Capital and O&M cost inputs for the ocean pipeline base case

Parameter	Unit	Ocean Pipeline Base Case
Subsea Pipe Diameter	inches	14.2
Subsea Pipeline	$	50,900,000
Injector Unit	$	14,500,000
Boost Compressor	$	9,355,000
Subtotal	$	74,755,000
Subsea Maintenance	$	2,507,776
Boost Compressor Power (5,650 kW)	$	2,726,000
Boost Compressor Maintenance	$	432,000
Subtotal	$	5,665,776

1 inch = 0.0254 meters

8.6 Model Results

This section presents costs for CO_2 capture and storage for the base case described in Section 8.5. The storage costs comprise transaction, transportation, injection and monitoring costs. These costs are combined with capture costs from an IGCC power plant. The results are given on several bases as described in Chapter 2. Appendix B provides a detailed description of each of the spreadsheets.

The Process Input sheet for the ocean pipeline base case is presented in Table 8-4.

Table 8-4
Process input sheet for the ocean pipeline base case

═══════════ **Ocean Pipeline Storage Input Variables** ═══════════

Design Basis		**Economic**	
IGCC Plant		*IGCC Plant* (Case 3a)	
Capacity Factor	**80%**	CO_2 Capture Cost ($/tonne captured)	$14.55
Land Pipeline Distance	**100 km**	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Land Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*IGCC Plant & CO_2 Storage*	
		After-Tax Discount Rate	**6.09%**
CO_2 Storage		Levelized Carrying Charge Factor	15.0%
Injection Depth (m)	2000		
Ocean Pipeline Distance	**100 km**		
Ocean Pipeline Distance	62 miles		
Nominal ocean pipe size (in)	16		

1 inch = 0.0254 meters

Ocean Via Pipeline

The Summary sheet for the ocean pipeline base case is presented in Table 8-5.

Table 8-5
Summary sheet for the ocean pipeline base case

───── **Ocean Pipeline Storage Summary** ─────

Process Description					**Capital & O&M Cost**		
						Capital	*O&M*
Land Pileline Distance	100 km	CO_2 Stored (M tonne/yr)	6.473		Transaction	$6,470,000	$0
Injection Depth (m)	2,000	CO_2 Avoided (M tonne/yr)	5.464		Transport	$80,200,000	$3,999,000
Ocean Pipeline Distance	100 km	LC Avoided GHG (M tonne/yr)	6.460		Sequestration	$74,755,000	$5,665,776
		LC Avoided GHG (M tonne/yr)	5.409		Monitoring	$0	$1,942,000
Economic Description							
After-Tax Discount Rate	6.09%				Total	**$161,430,000**	**$11,610,000**

Cost of CO_2 Capture & Storage

1. **Levelized Annual CO_2 Storage Costs** *(years 1-20)*	CO_2 Captured Basis		LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	35.75		35.75
CO_2 Stored or Avoided, M tonne/yr	6.47		6.46
Storage Cost, $/tonne CO_2	5.52		5.53

2. **Levelized Annual CO_2 Capture and Storage Costs** *(years 1-20)*	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	94.17	94.17	94.17
CO_2 Storage Cost, M $/yr	35.75	35.75	35.75
Capture + Storage Cost, M$/yr	129.92	129.92	129.92
CO_2 Stored or Avoided, M tonne/yr	6.47	5.46	5.41
Capture + Storage Cost, $/tonne CO_2	20.07	23.78	24.02

3. **CO_2 Capture and Storage Costs, NPV Basis** *(years 1-100)*	CO_2 Captured Basis	CO_2 Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	1,072.27	1,072.27	1,072.27
NPV of CO_2 Storage Costs, M$	416.75	416.75	416.75
NPV of Capture + Storage Costs, M$	1,489.02	1,489.02	1,489.02
NPV of CO_2 Stored or Avoided, M tonne	73.70	62.21	61.52
Capture + Storage Cost (NPV Basis), $/tonne CO_2	20.20	23.94	24.21

4. **Cost of Electricity, $/MWh**	
Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Storage Costs (years 1-20)	4.21
Storage Costs, Monitoring, etc. (years 21-100)	0.10
Total Cost of Electricity	59.40

8.7 Sensitivity Analysis

The sensitivity of the CO_2 storage cost for the ocean pipeline option is determined for offshore and pipeline distance. It can be seen in Figure 8-4 that an increase in both offshore and pipeline distance increases the storage cost. The storage cost is more sensitive to pipeline distance than offshore distance due to the fact that the ocean pipeline cost includes a fixed injector unit cost.
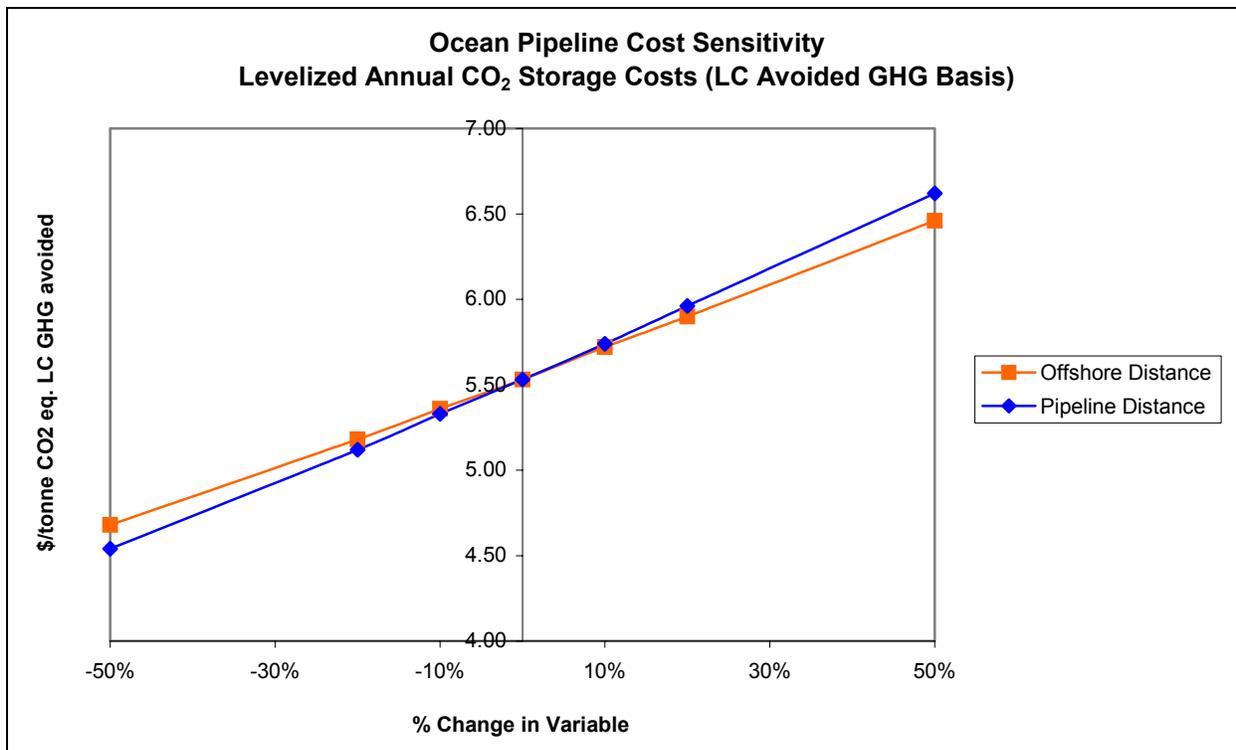
Figure 8-4
Sensitivity analysis for ocean pipeline

High and low cost cases have been chosen for the ocean pipeline option, and are presented together with the base case in Table 8-6.

Table 8-6
Ocean pipeline base, high cost and low cost cases

Parameter	Units	Ocean Pipeline Base Case	Ocean Pipeline High Cost Case		Ocean Pipeline Low Cost Case	
Pipeline Distance	km	100	300	+200%	0	-100%
Offshore Distance	km	100	300	+200%	50	-50%

The results for the high and low cost cases as well as the base case are given in Table 8-7. The CO_2 storage cost for the ocean pipeline option differ by about a factor of 5 for the high and low cost cases.

Ocean Via Pipeline

Table 8-7
Results for ocean pipeline base, high cost and low cost cases

Parameter	Units	Ocean Pipeline Base Case	Ocean Pipeline High Cost Case	Ocean Pipeline Low Cost Case
Pressure Drop per Unit Length	Pa/m	126	42	251
Pipe Diameter	inches	14.2	17.5	12.4
Nominal Pipe Size	inches	16	20	14
Levelized Annual CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG avoided	5.53	14.23	2.90

1 inch = 0.0254 meters

8.8 Comparison to Literature

8.8.1 Studies Used in Model Evaluation

The studies given in Table 8-8 all contain design and cost information for the transport of CO_2 by subsea pipeline. In all cases, except the 'GEODISC' study, the pipeline is to be used for the purpose of injecting CO_2 into the ocean. 'GEODISC' looks at subsea pipeline CO_2 transport in the context of storing the gas in an offshore aquifer.

Table 8-8
Subsea pipelines' characteristics

Study	CO_2 flow rate (Mt/y)	Initial CO_2 pressure (bar)	Diameter (m)	Length (km)	Injection depth (m)	Recompression station included
IEA Ocean[6]	19.00	74 (liquid CO_2)	0.800	100	500	Ignored
British Coal[7]	3.63	136	0.350	517	2,000	Yes
GEODISC[8]	5.67	205	0.660	200	100	No
McDermott[9]	200 (total) 33.3 (each)	130	0.760 (6 pipes)	500	3,000	Yes
UMass[10]	8.20	140	0.600	200	1,000	No

It should be noted that in the 'McDermott' study there is a large quantity of CO_2, taken to be the emissions from forty 500 MW_e coal-burning power stations, being injected into the ocean. This large quantity of CO_2, 200 Mt/y, is determined in the study to require the use of one 1.63-m-

diameter pipe or six 0.760-m-diameter pipes. For purposes of making a diameter comparison with the model, taking into account its inability to allow for bundling, one 0.760 m diameter pipe carrying 33.3 Mt/yr of CO_2 is assumed. It should be noted that a cost comparison is not made with the 'McDermott' study due to the fact that this study was used as a basis for costing.

The 'GEODISC' and 'IEA ocean' studies require the installation of a subsea pipeline up to a maximum depth of 100 and 500 m, respectively. The installation of these pipelines, at these relatively shallow depths, requires only the use of a 'S-lay' barge and does, as such, lie within the capabilities of existing technology. However, in the case of the 'UMass', 'British Coal,' and 'McDermott' studies, which require pipeline installation at depths of 1000, 2000, and 3000 m, respectively, a combination of 'S-lay' and 'J-lay' techniques is needed. In addition, in the case of 'British Coal', as for 'McDermott,' modifications to the existing 'J-lay' barge would be necessary. As this upgrade would only be a one-time cost, it is not included in the cost analysis.

The 'British Coal' study, like 'McDermott', requires a shore-based pumping station to transport the CO_2 a long distance. The cost of this pumping station is not included in the total cost of the scheme, calculated for the purpose of comparing the study value with the model output. The requirement of a pumping station in the 'IEA Ocean' study is ignored as this study deals with liquid, not supercritical, CO_2.

8.8.2 Comparison of Values from Model and Studies

The graph below in Figure 8-4 shows pipe diameter as a function of CO_2 mass flow rate. Also shown in the figure is the value of pipe diameter given in each of the five studies.
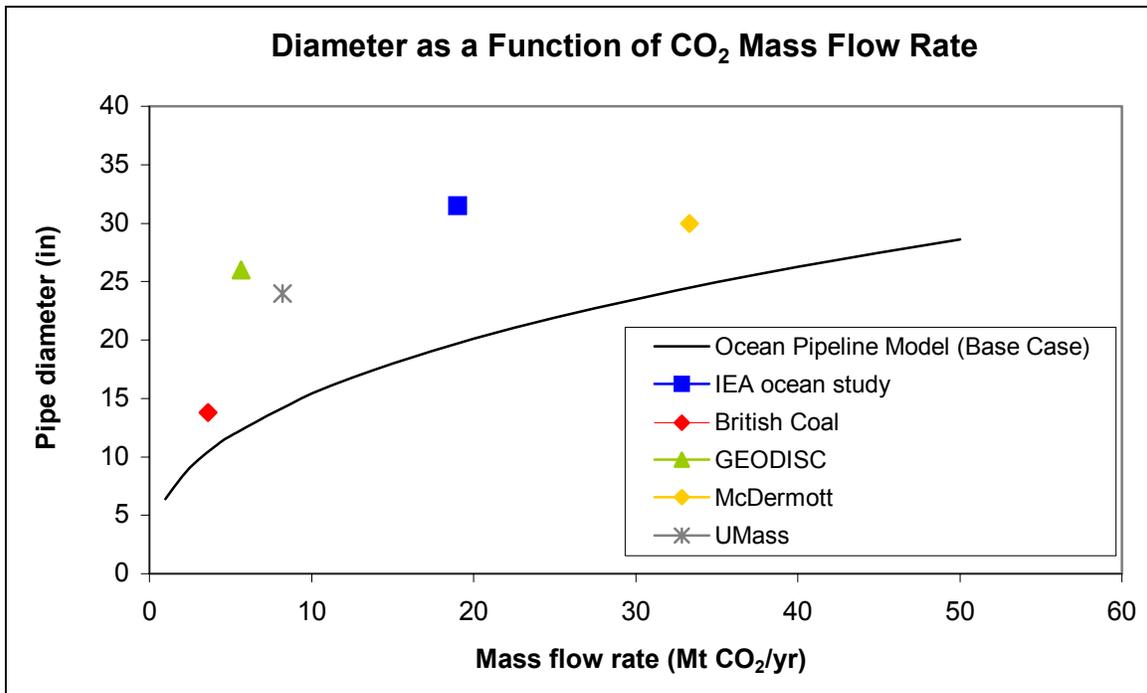
Figure 8-4
Comparison of pipe diameter values

Ocean Via Pipeline

Figure 8-5 shows the capital cost of the subsea pipeline as calculated by the model, where this excludes the cost of the boost compressor and transaction costs, as a function of CO_2 mass flow rate. As for pipe diameter, the capital cost values given in the studies are reasonably close to those calculated by the model considering the uncertainties in the data.
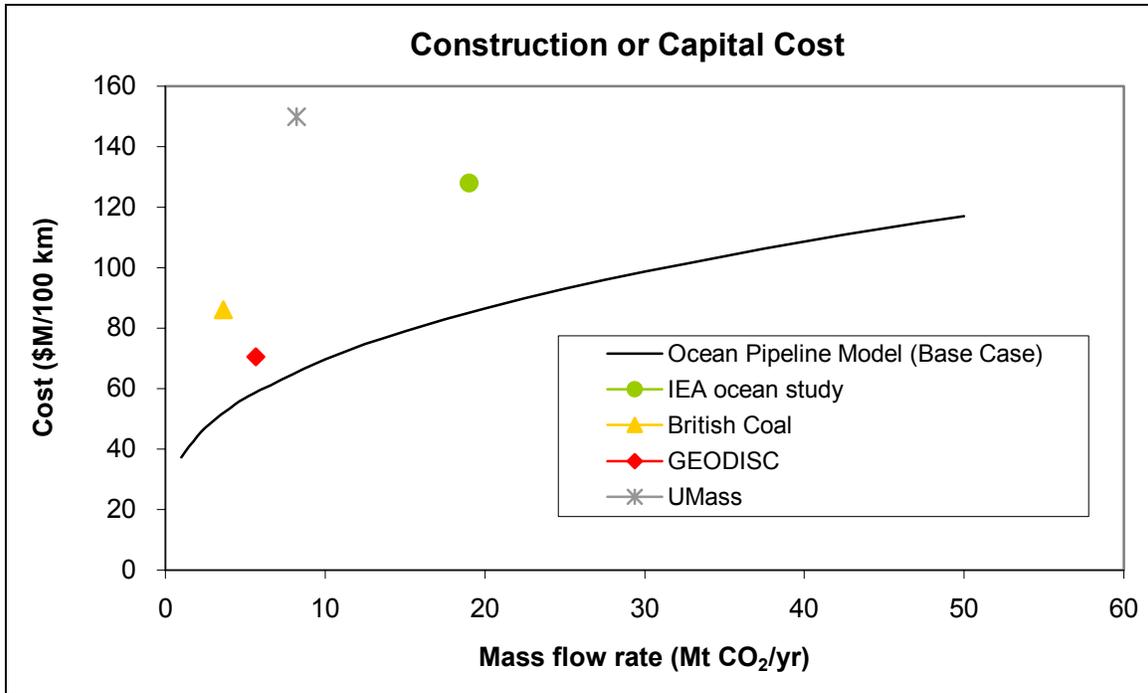
Figure 8-5
Comparison of subsea pipeline capital cost values

8.9 References

1   Herzog, H., "Ocean Sequestration of CO2: An Overview," presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken, Switzerland, August 30-September 2, 1998.

2   "Carbon Sequestration Research and Development," Chapter 3, Ocean Sequestration, http://www.fe.doe.gov/coal_power/sequestration/reports/rd/chap5.pdf

3   Sarv, H., "Large-scale CO2 transportation and deep ocean sequestration – Phase II final report," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, 2001.

4   Sarv, H., e-mail communication, Jan. 14, 2002.

5   Ormerod, B., "The disposal of carbon dioxide from fossil fuel fired power stations," IEA Greenhouse R&D Programme, Cheltenham. Tech. Rep. IEAGHG/SR3, Jun. 1994.

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7   Summerfield, I.R., S.H. Goldthorpe, N. Williams and A. Sheikh, "Costs of CO2 disposal options," *Energy Convers. Mgmt*, vol. 34, no. 9-11, pp. 1105-1112, 1993.

8   Allinson, G. and V. Nguyen, "The economics of CO2 sequestration in Australia," presented at Fifth International Conference on Greenhouse Gas Control Technologies Cairns, Australia, 2000.

9   Sarv, H., "Large-scale CO2 transportation and deep ocean sequestration," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, Mar. 1999.

10 Golomb, D., "Transport systems for ocean disposal of CO2 and their environmental effects," *Energy Convers. Mgmt*, vol. 38, suppl., pp. 279-286, 1997.

9
OCEAN VIA TANKER

9.1 Introduction

The ocean storage via tanker option involves transporting the CO_2 by refrigerated tanker from a port facility to an offshore floating platform, where the CO_2 is injected into the deep ocean through a vertical pipe.

9.2 State of the Art

To date, there have been no commercial or pilot-scale applications of this ocean storage option. The use of tankers to transport CO_2 to an offshore floating platform is however within the current state of technology. All that is required is that existing floating platforms and so-called 'semi-refrigerated' tankers that transport pressurized liquid chemicals, such as ammonia and liquid natural gas, be adapted for the purpose.[1]

Ocean storage via tanker would only be desirable where CO_2 was to be injected into the deep ocean at a great distance, say 800 km, from the shoreline, in which case it would be more economical than the subsea pipeline option. It does also have the advantage that it would allow for easy relocation of the injection site.

9.3 Process Description

It is assumed, as in the case of ocean storage via pipeline, that three IGCC power plants supply CO_2 to the shoreline collection point. Based on this, the ocean tanker system needs to be designed to handle three times the quantity of CO_2, i.e. 11.29 million scm (22,167 tonnes), as opposed to 3.76 million scm (7,389 tonnes) of CO_2 per day. As a final note, it is assumed that this facility, like the power plant, has a lifetime and design/construction time of 20 and 4 years, respectively.

9.4 Methodology Used

The storage option has been modeled based on design and cost information obtained from McDermott's Phase I and Phase II final reports on 'Large-scale CO_2 Transportation and Deep Ocean Sequestration'[1,2] as well as e-mail communications with the reports' author.[3,4] The method used for a conceptual design of this process can be broken down into a number of steps. First, the number of tankers required to transport the CO_2 to the offshore platform is determined. Second, the diameter of the vertical pipe to carry the CO_2 from the platform to the injection

depth is calculated. Third, the amount of CO_2 emitted by the tankers traveling to and from the offshore storage site, and emitted due to boil off, is found. It is then possible, as a final step, to calculate the capital cost of the tankers, port facility, offshore floating platform, and vertical pipe, and the non-fuel and fuel O&M costs as well as the cost per tonne of CO_2. These steps are described in greater detail below. An overview of the ocean tanker cost model is given in Figure 9-1.

9.4.1 Tanker Number Calculation

The number of tankers required is determined based on the use of tankers able to carry 22,000 m^3 of CO_2 at 7 bar and minus 50ºC. A tanker of this description is, according to McDermott, within the current state of shipbuilding technology. The aforementioned temperature and pressure properties of CO_2 give a CO_2 density of 1155 kg per m^3 and a tanker capacity, in terms of weight, of 25,410 tonnes of CO_2. Given this latter tanker CO_2 capacity, it is found from the design CO_2 flow rate of 22,167 tonnes per day that the loading time for each tanker will be approximately 27.5 hours. The unloading time, which unlike the loading time is not dependent on the CO_2 flow rate from the plant, is taken to be about six hours. Assuming a tanker speed of 33 km per hour, it is then possible to calculate the time taken for a round trip and the amount of time for which a tanker is not at the CO_2 collection point. Finally, this calculated value of time not at the collection point enables the number of tankers required to be en route at any given time to be determined. For the base case, it is found that two tankers would be needed. An additional tanker is, however, added, bringing the total number required to three, to allow for tanker downtime.

9.4.2 Vertical Pipe Diameter Calculation

The same method as is used for pipe sizing in the subsea pipeline ocean CO_2 storage model, described in Section 8.4.1, is used to calculate the diameter of the vertical pipe. The required pipe outlet pressure, taken to be equal to the hydrostatic pressure of water at a depth of 2,000 m, is calculated to be approximately 200 bar. Next, calculating the average value of CO_2 specific gravity over both the 0 to 1,000-m-depth and 1,000- to 2,000-m-depth intervals, and adding the respective CO_2 pressure head gains, gives the gravity head. Based on the set inlet pressure of 152 bar and these calculated values of outlet pressure and gravity head, a maximum allowable pressure drop per unit length of 7,281 Pa per m is then found. Finally, the diameter is determined from the equations for pressure drop and head loss due to frictional resistance in the pipe, assuming turbulent flow. For the base case, a nominal 8-inch-diameter vertical pipe is required.

Inputs:
CO_2 mass flow rate
Tanker volume
Tanker pressure
Tanker temperature
Tanker speed
Offshore distance

Inputs:
CO_2 mass flow rate
CO_2 inlet pressure
CO_2 temperature
Injection depth

Inputs:
Tanker fuel usage
Diesel energy content
Diesel CO_2 emissions factor
Offshore distance

Inputs:
CO_2 mass flow rate
Boil off

TANKER NUMBER CALCULATION
Internal Calcs:
CO_2 density
Tanker CO_2 capacity
Loading time
Unloading time
Time taken for round trip
Time not at collection point
Number of tankers

PIPELINE DIAMETER CALCULATION
Internal Calcs:
CO_2 density
CO_2 viscosity
CO_2 outlet pressure
Gravity head
Pressure drop per unit length
Vertical pipeline diameter

TANKER CO_2 EMISSIONS CALCULATION
Internal Calcs:
Number of round trips
Total annual distance traveled
Total annual fuel usage
Total annual CO_2 emitted

BOIL OFF CO_2 EMISSIONS CALCULATION
Internal Calcs:
Total annual CO_2 emitted

Time taken for round trip

Pipe diameter

Annual fuel usage
Annual CO_2 emitted

Number of tankers required

Annual CO_2 emitted
bbooff

COST MODEL
Internal Calcs:
Capital costs:
Tankers, offshore floating platform, onshore port facility, vertical pipeline, general facilities etc.
O&M costs:
Non-fuel, fuel

Inputs:
Diesel fuel price
Capital charge rate

Outputs:
Total capital cost
Total O&M cost
Total annual cost
Total cost per tonne CO_2

Figure 9-1
Ocean tanker cost model overview diagram

Ocean Via Tanker

9.4.3 CO$_2$ Emissions Calculations

The quantity of CO_2 to be emitted by the tankers needs to be determined. This requires that the quantity of fuel used by a 22,000 m^3-tanker, in terms of gallons per km, first be calculated. In order to do this, it was necessary to refer to the small tanker case study given in the McDermott reports. In this case study, the total capital cost of the required 38 22,000-m^3 tankers is $2,100 million. According to Hamid Sarv of McDermott, the annual tanker O&M cost was estimated as being equal to 5.6 percent of the tanker capital cost, of which the tanker fuel cost comprised 16.5 percent. Based on these percentages, the tanker fuel cost is equal to $19.4 million per year. Given that the price of diesel fuel is about $0.566 per gallon[4], the total annual quantity of fuel used by the tankers is found to be approximately 34.3 million gallons. The corresponding total annual distance traveled by the tankers is calculated to be 8.76 million km. Dividing the total annual distance traveled by the total annual fuel used, gives a tanker fuel usage of 3.91 gallons per km.

Given this calculated value of tanker fuel usage, it is possible to determine the CO_2 emitted by the tankers. Diesel fuel has an energy content of around 137 million joule per gallon and a CO_2 emissions factor of close to 70 milligrams per joule. Given that the fuel used by a tanker is 3.91 gallons per km, the amount of CO_2 emitted by a tanker per km traveled can be found to be 37,614 grams. The total annual distance traveled is calculated by multiplying the total number of round trips per year, equal to the number of hours in a year divided by the loading time of 27.5 hours, by the respective round-trip distance. The total distance traveled by the tankers is found to be 63,683 km. Multiplying the amount of CO_2 emitted per km by the total annual distance traveled gives a total annual amount of CO_2 emitted of 2,395 tonnes.

The amount of CO_2 emitted due to boil off is estimated as one percent per day of the amount of CO_2 transported by tanker based on industry experience with CO_2 truck tankers. It is important to note that the calculation assumes that the CO_2 is in the tanker, and therefore undergoing boil off, for only one half the number of hours taken for a round trip. This CO_2 quantity is then multiplied by 365 days to give the amount of CO_2 emitted per year. The annual quantity of CO_2 emitted is calculated to be 53,362 tonnes.

9.4.4 Cost Calculations

The total capital cost of the tanker ocean CO_2 storage option comprises the capital cost of the three required tankers, the offshore floating platform, the port facility, and a 2,000-m long, 8-inch diameter (0.20 meter) vertical pipe. The capital cost of the tankers is found using McDermott's cost estimate of $55.3 million for a single 22,000-m^3 tanker. For the offshore floating platform, the capital cost of $200 million also given in the McDermott report is used. In the case of the port facility, for which no cost estimate was provided, a capital cost of $50 million is assumed. Next, based on cost data in the report, the capital cost of the vertical pipe is calculated. The vertical pipe's capital cost is taken to include $351,445/in/km ($566,847/in/mi) for pipe marshalling and the attaching of buoys and corrosion anodes, a $0.3 million cost for towing the pipe to the offshore structure and a $3 million cost for pipe upending, securing, and

anchoring. Finally, a 30 percent surcharge is added to all capital expenses to cover costs associated with general facilities, engineering, permitting, and contingencies.

The total O&M cost is calculated as the sum of the non-fuel and fuel O&M costs. From e-mail communications with Hamid Sarv[3,4], it was learned that the total annual O&M cost in the case studies was estimated as the sum of 5.6 percent and 0.02 percent of the total tanker and non-tanker capital costs, respectively, where the fuel cost comprised 16.5 percent of the tanker O&M cost. The non-fuel O&M cost is calculated in the model as 4.7 percent of the total tanker capital cost, thus excluding the fuel cost, plus 0.02 percent of the total non-tanker capital costs. The fuel O&M cost is determined as the product of the total annual fuel usage, found from multiplying the tanker fuel usage by the total annual distance traveled, and a diesel fuel price of $0.566 per gallon.

The capital and O&M cost estimation factors are summarized in Table 9-1.

Table 9-1
Capital and O&M cost estimation factors

Parameter	Unit	Value
CAPITAL COSTS		
Tanker	$/tanker	55,263,000
Offshore Platform	$	200,000,000
Onshore Port Facility	$	50,000,000
Vertical Pipeline:		
Construction	$/in/km	351,445
Towing to Offshore Structure	$	300,000
Upending, Securing & Anchoring	$	3,000,000
General Facilities, Engineering, Permitting etc.	$	0.3*(Tanker_capital_cost + Offshore_platform_capital_cost + Onshore_port_facility_capital_cost + Vertical_pipeline_capital_cost)
O&M COSTS		
Non-fuel	$/yr	(Tanker_capital_cost*0.047) + ((Offshore_platform_capital_cost + Onshore_port_facility_capital_cost + Vertical_pipeline_capital_cost)*0.02)
Fuel	$/gal	0.566

1 inch = 0.0254 meters

9.5 Design Basis

9.5.1 System Design

The methodology described in Section 9.4.1 through Section 9.4.3 was used to calculate the required number of tankers, the diameter of the vertical pipeline, and the CO_2 emissions from the tankers and due to boil off. Table 9-2 shows the results.

Table 9-2
Design basis for ocean storage via tanker

Parameter	Unit	Ocean Tanker Base Case
Offshore Distance	km	100
Injection Depth	m	2,000
Tanker Volume	m^3	22,000
Tanker Pressure	bar	7
Tanker Temperature	deg C	-50
Tanker CO_2 Capacity	kg/m^3	25,410
Loading Time	h	27.5
Unloading Time	h	6
Tanker Speed	km/h	33
Time Taken for Round Trip	h	39.6
Number of Tankers		3
Vertical Pipe Inlet Pressure	MPa	15.2
Vertical Pipe Outlet Pressure	MPa	20.0
Gravity Head	MPa	19.4
Pressure Drop per Unit Length	Pa/m	7,281
Vertical Pipe Diameter	inches	6.5
Nominal Vertical Pipe Size	inches	8
Tanker Fuel Usage	gal/km	3.91
Diesel Energy Content	million joule/gal	137
Diesel CO_2 Emissions Factor	mg/joule	70
Total Annual Distance Traveled	km/y	63,683
Total Annual Fuel Usage	gal/y	249,001
CO_2 Emitted by Tankers	t/y	2,395
Boil Off	%/d	1
CO_2 Emitted by Boil Off	t/y	53,362

1 inch = 0.0254 meters, 1 gal = 3.79 liters

9.5.2 Capital and O&M Cost Inputs

The capital and O&M costs of ocean storage via tanker for the base case were calculated using the methodology described in Section 9.4.4. The results are shown in Table 9-3.

Table 9-3
Capital and O&M cost inputs for the ocean tanker base case

Parameter	Unit	Ocean Tanker Base Case
Number of Tankers		3
Vertical Pipeline Diameter	inches	6.5
Total Annual Fuel Usage	gal/y	249,001
CAPITAL COSTS		
Tanker	$	166,000,000
Offshore Floating Platform	$	200,000,000
Onshore Port Facility	$	50,000,000
Vertical Pipeline:		
Construction	$	4,580,000
Towing to Offshore Structure	$	300,000
Upending, Securing & Anchoring	$	3,000,000
General Facilities, Engineering, Permitting etc.	$	127,000,000
Subtotal	$	550,880,000
O&M COSTS		
Non-fuel	$	12,900,000
Fuel	$	140,935
Subtotal	$	13,040,935

1 inch = 0.0254 meters

9.6 Model Results

This section presents costs for CO_2 capture and storage for the base case described in Section 9.5. The storage costs comprise transaction, transportation, injection and monitoring costs. These costs are combined with capture costs from an IGCC power plant. The results are given on several bases as described in Chapter 2. Appendix B provides a detailed description of these spreadsheets.

Ocean Via Tanker

The Process Input sheet for the ocean tanker base case is presented in Table 9-4.

Table 9-4
Process input sheet for the ocean tanker base case

Ocean Tanker Storage Input Variables

Design Basis		Economic	
IGCC Plant		*IGCC Plant* (Case 3a)	
Capacity Factor	**80%**	CO_2 Capture Cost ($/tonne captured)	$14.55
Pipeline Distance	**100 km**	COE Including CO_2 Capture Cost ($/MWh)	$55.08
Pipeline Distance	62 miles		
Nominal pipe size (in)	12	*IGCC Plant & CO_2 Storage*	
		After-Tax Discount Rate	**6.09%**
CO_2 Storage		Levelized Carrying Charge Factor	15.0%
Injection Depth (m)	2000		
Offshore Distance	**100 km**		
Offshore Distance	62 miles		
Tanker CO_2 boil off rate (%/day)	**1.0%**		
Nominal vertical pipe size (in)	8		
Number of tankers needed	3		

The Summary sheet for the ocean tanker base case is presented in Table 9-5.

Table 9-5
Summary sheet for the ocean tanker base case

========= **Ocean Tanker Storage Summary** =========

Process Description					**Capital & O&M Cost**		
						Capital	*O&M*
Pileline Distance	100 km	CO_2 Stored (M tonne/yr)	6.473				
Injection Depth (m)	2,000	CO_2 Avoided (M tonne/yr)	5.411		Transaction	$6,470,000	$0
Offshore Distance	100 km	LC Avoided GHG (M tonne/yr)	6.408		Transport	$80,200,000	$3,999,000
		LC Avoided GHG (M tonne/yr)	5.358		Sequestration	$550,880,000	$13,040,935
					Monitoring	$0	$647,000
Economic Description							
After-Tax Discount Rate		6.09%			Total	**$637,550,000**	**$17,690,000**

Cost of CO₂ Capture & Storage

1. Levelized Annual CO_2 Storage Costs *(years 1-20)*

	CO₂ Captured Basis		LC Avoided GHG Basis *(storage only)*
CO_2 Storage Cost, M $/yr	113.03		113.03
CO_2 Stored or Avoided, M tonne/yr	6.47		6.41
Storage Cost, $/tonne CO_2	17.46		17.64

2. Levelized Annual CO_2 Capture and Storage Costs *(years 1-20)*

	CO₂ Captured Basis	CO₂ Avoided Basis	LC Avoided GHG Basis
CO_2 Capture Cost, M $/yr	94.17	94.17	94.17
CO_2 Storage Cost, M $/yr	113.03	113.03	113.03
Capture + Storage Cost, M$/yr	207.20	207.20	207.20
CO_2 Stored or Avoided, M tonne/yr	6.47	5.41	5.36
Capture + Storage Cost, $/tonne CO_2	32.01	38.29	38.67

3. CO_2 Capture and Storage Costs, NPV Basis *(years 1-100)*

	CO₂ Captured Basis	CO₂ Avoided Basis	LC Avoided GHG Basis
NPV of CO_2 Capture Costs, M$	1,072.27	1,072.27	1,072.27
NPV of CO_2 Storage Costs, M$	1,290.21	1,290.21	1,290.21
NPV of Capture + Storage Costs, M$	2,362.48	2,362.48	2,362.48
NPV of CO_2 Stored or Avoided, M tonne	73.70	61.61	60.93
Capture + Storage Cost (NPV Basis), $/tonne CO_2	32.05	38.34	38.77

4. Cost of Electricity, $/MWh

Reference Plant (no capture)	43.98
Capture Costs (years 1-20)	11.10
Storage Costs (years 1-20)	13.32
Storage Costs, Monitoring, etc. (years 21-100)	0.03
Total Cost of Electricity	68.44

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9.7 Sensitivity Analysis

The sensitivity of the CO_2 storage cost for the ocean tanker option is determined for four key parameters: pipeline and offshore distance, boil off and diesel price. It can be seen in Figure 9-2 that increases in pipeline and offshore distance, boil off and diesel price all increase the storage cost.   More noteworthy, the figure shows that changes in pipeline distance have the greatest effect on storage cost.
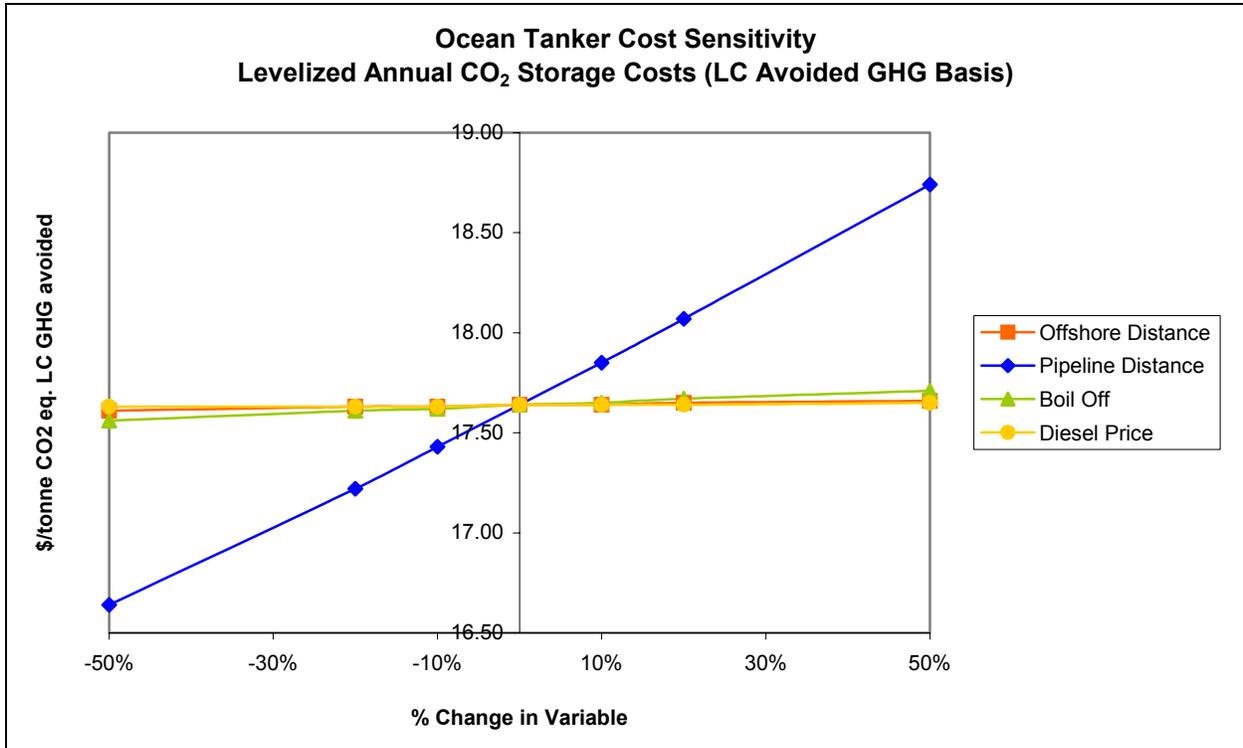
Figure 9-2
Sensitivity analysis for ocean tanker

High and low cost cases have been chosen for the depleted gas reservoir option, and are presented together with the base case in Table 9-6. For the high and low cost values for each of the four key parameters, the percentage change in the value from the base case is shown. This is done to illustrate the fact that the range in the values of some parameters is expected to be greater than for others.

Table 9-6
Ocean tanker base, high cost and low cost cases

Parameter	Units	Ocean Tanker Base Case	Ocean Tanker High Cost Case		Ocean Tanker Low Cost Case	
Pipeline Distance	km	100	300	+200%	0	-100%
Offshore Distance	km	100	300	+200%	50	-50%
Boil Off	%/day	1	2	+100%	0.5	-50%
Diesel Price	$/gal	0.566	0.8	+41%	0.45	-20%

The results for the high and low cost cases as well as the base case are given in Table 9-7. The CO_2 storage cost for the depleted gas reservoir option varies very little for the high and low cost cases.

Table 9-7
Results for ocean tanker base, high cost and low cost cases

Parameter	Units	Ocean Tanker Base Case	Ocean Tanker High Cost Case	Ocean Tanker Low Cost Case
Number of Tankers		3	3	3
Total Annual Fuel Usage	gal/yr	249,001	747,004	124,501
CO_2 Emitted by Tankers	t/yr	2,395	7,186	1,198
CO_2 Emitted by Boil Off	t/yr	53,362	139,415	24,638
Levelized Annual CO_2 Storage Cost	$/tonne CO_2 Eq. LC GHG avoided	17.64	22.79	15.76

9.8 Comparison to Literature

There is no cost data in the literature with which to make a comparison.

Ocean Via Tanker

9.9 References

1   Sarv, H., "Large-scale CO2 transportation and deep ocean sequestration," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, Mar. 1999.

2   Sarv, H., "Large-scale CO2 transportation and deep ocean sequestration – Phase II final report," McDermott Technology Inc., Ohio. Tech. Rep. DE-AC26-98FT40412, 2001.

3   Sarv, H., e-mail communication, Feb. 4, 2002.

4   Sarv, H., e-mail communication, Feb. 20, 2002.

10
CO$_2$ SINK ENHANCEMENT IN FORESTS—BASIS AND APPROACH

10.1 Introduction

From a utility perspective, the cost of GHG emission offsets ($/tonne C equivalent GHG avoided) from forestry sink enhancement options depends on the following: (1) levels of CO$_2$ sink enhancement, (2) changes in GHG emissions other than from CO$_2$ sink enhancement (e.g., from methane and nitrous oxide emissions), (3) reimbursement of forest management companies for net costs of changes in forest land area and/or management, (4) transaction costs for aggregating and brokering GHG credits, and (5) monitoring costs for assuring that contractual obligations are fulfilled. These aspects are addressed below.

The IEA Greenhouse Gas R&D Programme (IEA GHG), in consultation with the Edinburgh Centre for Carbon Management (ECCM), provided the following data on the economics of forestry CO$_2$ sink enhancement options. Most of this information relates to developing countries, because that is where the greatest amount of forestry CO$_2$ sink enhancement is likely to occur, but some information is also provided on carbon sequestration in U.S. forests.

10.2 Study Basis

10.2.1 Overall Basis

Some forestry carbon sink enhancement projects have already been implemented on a voluntary basis. A brief summary of the extent and costs of these projects is provided as background information in Appendix C, but the costs of these pioneer projects cannot be compared directly to the costs of other sink enhancement techniques because they have been derived using a variety of economic conventions and the price of carbon credits has been greatly affected by supply and demand. In this study, costs of sink enhancement are calculated from the quantities and timing of carbon stored and costs of forest establishment, maintenance, land, and timber revenue.

The performances and costs of forestry sequestration cover a very wide range, depending on local factors such as existing land uses, climate, soil conditions, the type of sequestration scheme, types of trees, land values and labor costs. It is not possible to cover all of these factors in a study such as this. Instead, information is provided for a diverse range of seven forestry sequestration cases, described in Section 10.3 and Chapters 11-17. These cases cover afforestation, reforestation, and avoidance of deforestation, developed and developing countries, and temperate and tropical climates.

10.2.2 Carbon Sink Enhancement

When a forest grows, it removes CO_2 from the atmosphere and sequesters carbon in trees and other above ground biomass, litter, humus, roots and soil. Eventually the forest reaches a dynamic equilibrium when the rate of new sequestration of carbon is equal to the rate of natural conversion of carbon back to CO_2. The amount of carbon sequestered in forests can be increased by planting new forests (afforestation), restoring degraded forests (reforestation) or avoiding the destruction of existing forests (deforestation).

Carbon is sequestered in forests in above-ground biomass (stems and foliage) and in roots, litter on the forest floor, humus and soil. This study considers carbon stored in above-ground biomass, the most easy to verify, and carbon stored below ground.

Greenhouse gas emissions can also be reduced beyond the forest itself. Wood can be harvested sustainably from forests and converted into useful products such as timber for buildings, furniture, paper etc. Some of the carbon in these products will be quickly converted back to CO_2 but some will remain sequestered as carbon for many decades. Carbon stored in wood products is included in this study.

Further information on carbon sequestration is given in Section 10.3.

10.2.3 Reduction in Emissions Resulting from Use of Wood and Biomass

Wood products can displace materials such as steel or concrete which generate significant amounts of CO_2 during their production. Reductions in emissions of greenhouse gases from production of materials which are displaced by wood are beyond the scope of this study.

Wood and other forest biomass can be used as fuel, displacing fossil fuels. Production and use of biomass fuels is beyond the scope of this study.

10.2.4 Non-CO_2 Greenhouse Gases

Forests and other land-uses emit significant quantities of non-CO_2 greenhouse gases, particularly N_2O. Emissions of N_2O and CH_4 are taken into account in this study but emissions of other non-greenhouse gases and particulates which can indirectly affect the climate are not. Further information on non-CO_2 greenhouse gases is given in Section 10.3.

10.2.5 Ancillary Benefits

Forestry projects have many benefits in addition to those related to greenhouse gases. Natural forests, usually have high biodiversity, so preserving existing forests can be especially beneficial. Forest plantations can negatively affect biodiversity if they replace biologically rich native grasslands or wetland habitat but they can be designed to enhance biodiversity by stimulating restoration of natural forests.

By reducing run-off, forests can conserve water resources and reduce the risk of flooding. They can also control erosion which can reduce siltation of rivers and protect fisheries and investment in hydro-electric power facilities.

Forests tend to have a higher landscape value than alternative land uses such as scrub and agricultural land and they have more potential for recreational activities. These benefits are likely to be greatest in areas which are accessible to large numbers of people and which currently have little variation in land form.

The overall philosophy of this study is that ancillary costs and benefits, such as those described previously, are not taken into account in the economic assessment. The reasons for this are:

- Attempting to quantify these costs and benefits involves a large amount of work that is beyond the scope of this study.

- The costs and benefits are very uncertain. They depend greatly on small scale local factors and the values of many of the benefits, for example preservation of biodiversity, are very subjective.

- The economic mechanisms do not usually exist to enable ancillary benefits or costs to accrue to the owners and operators of forest projects.

10.2.6 Concerns and Uncertainties

There are several concerns and uncertainties about forestry sequestration as a greenhouse gas abatement technique, including additionality, baselines, leakage, security and effects on the climate other than those due to greenhouse gases. To allow for these concerns, a tonne of carbon sequestered in forests is sometimes assumed to be not equivalent to a tonne of carbon emissions avoided by other means. It has been proposed that credit should be claimed for only a fraction of the carbon thought to be sequestered in forests, to allow for the concerns mentioned above. Such reductions in carbon credits are highly subjective and may be influenced by political factors, so they are not used in this study. However, when comparing costs and performances it should be recognized that international climate treaties, regulators and the public may regard a tonne of carbon sequestered in forests as not of equal value to a tonne of carbon emissions permanently avoided.

10.2.6.1 Additionality

Additionality essentially means "would the project have occurred anyway, regardless of carbon sequestration subsidies." Large areas of forests are already being planted for commercial production of wood and also large areas of existing non-commercial forests are not being destroyed, despite the absence of carbon sequestration subsidies. Project developers need to demonstrate that their project would not have occurred without carbon sequestration credits. The probability that the project would have occurred anyway is greatest for projects that are economically attractive without carbon sequestration credits. However, just because a project is economically viable without carbon credits does not mean that it would have gone ahead anyway. There are many potential barriers; capital may not be available, risks may be too high,

infrastructure may be inadequate, legal or technological barriers may exist etc. Overcoming these barriers may enable a project to go ahead.

10.2.6.2 Leakage

In the context of forestry sequestration, leakage means the indirect impact that a targeted activity in a certain place at a certain time has on carbon storage at another place or time. Leakage in this sense should not be confused with physical leakage of CO_2 from an underground or ocean storage reservoir due to geological faults, ocean currents etc.

Leakage can be induced through several different mechanisms, particularly activity shifting and demand displacement. Activity shifting tends to arise around the boundaries of the project and is related to socio-economic conditions of the surrounding population. For example, local people may be using land for agriculture and grazing purposes. If this land is then reforested or afforested, the local people may be forced to move to other areas where they will clear forest resulting in emissions that would not have arisen if the project were not implemented.

Market based leakage occurs when a forest protection or plantation project reduces the supply of a marketed product, either wood or agricultural products, resulting in increased felling of trees elsewhere to satisfy the demand for the product. This occurs in a diffuse way through global markets. Output from plantations that are subsidized for their carbon sequestration benefits can increase the supply, and hence reduce the price, of wood. This would tend to make forests that cannot claim carbon sequestration credits less economically attractive, so the amount of non-subsidized plantations may decrease, resulting in less carbon sequestration. A study of the impacts on timber markets of 50 million ha of sequestration forests[1] predicted that the impacts on the net quantity of carbon sequestered would be fairly small, about 10 percent. If forests were planted on agricultural land, this would tend to reduce the supply of food. The price of food would therefore increase, making conversion of forest elsewhere to agricultural land more attractive.

The only way to address leakage resulting from unfulfilled demand for wood or agricultural products is to invest in the supply chain elsewhere or reduce demand for products. For example, some of the revenue from a sequestration project could be invested in intensification of agriculture, to enable the same amount of food to be produced from a smaller area or land. This intensification of agriculture may affect greenhouse gas emissions, for example CO_2 emitted during production of fertilizers and increased emissions of N_2O from agricultural land. These effects are beyond the scope of this study.

10.2.6.3 Security

In common with most sequestration options, there is a potential for carbon stored in forests to be converted to CO_2 and emitted to the atmosphere. Losses of carbon from forests could be classified as permanent or non-permanent. Non-permanent losses include forest fires and pest infestations. In most cases forests would re-grow naturally or they could be re-planted after such occurrences. There would be a temporary emission of CO_2 but in the long term the carbon

sequestration at the site could be restored, although there would be an economic cost of re-establishing the forest.

Permanent loss of sequestration could occur due to social and political factors or climate change. Climate change could mean that some areas could become no longer suitable for forests because of changes in temperature and rainfall. For example, some global climate modeling has predicted that vast areas of tropical forests in northern Brazil will die back around the middle of this century because of anthropogenic climate change[2]. Temperate grasslands are also expected to expand into regions of Europe and North America that are currently dominated by temperate or coniferous forests. Areas suitable for forests are predicted to expand northwards in North America and Asia and there are even suggestions that climate change may enable forests to grow in the Sahara region[3]. It may therefore be possible to replace sequestration forests lost due to climate change by planting or encouraging the natural growth of forests in other regions but this would involve disruption and economic costs. It is very difficult to predict these risks of forest loss because of the large uncertainties in predictions of regional impacts of climate change.

Forests can be lost due to social factors, for example population growth leading to increased requirements for agricultural and urban land. It is important that forest projects are structured to provide benefits to local inhabitants to reduce the risks of forest loss. The legal status of forests in some countries, where land ownership or tenure is less secure, may result in an increased risk of forest loss.

10.2.6.4 Non-Greenhouse Gas Effects

Vegetation cover can have a significant impact on the albedo (reflectivity) of the Earth. Dark green forests tend to absorb more solar energy than crop lands. The greatest effect is during the winter months when large unforested areas are covered in highly reflective snow. In a coniferous forest the snow tends to fall to the ground and the dark surface of the treetops is exposed and absorbs more solar energy. Recent work using global climate models[4] has indicated that in some parts of the world, including large parts of Canada and the Russian Far East, the extra solar energy absorbed would more than offset the greenhouse gas benefits of carbon sequestered by forests. Even in the US South, the albedo effect is predicted to offset around 10-20 percent of the carbon sequestration benefits of forests. These estimates are subject to many uncertainties, notably the predictions of snow amount and surface reflectivity and they are based on the current climate. However, they do show that solar reflectivity could have a significant impact on the climate change impacts of forests. Non-greenhouse has effects are beyond the scope of this study.

10.3 Sequestration Cases

10.3.1 Descriptions

The seven forestry sequestration cases assessed in this study are summarized in Table 10-1 and are described in detail in Chapters 11-17.

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Table 10-1
Summary of forestry sequestration cases

Case	Type of management	Type of trees	Country/region
1	Plantation	Loblolly pine	USA (South)
2	Plantation	Douglas fir	USA (Pacific North-west)
3	Plantation	Spanish Cedar	Mexico
4	Restoration	Pine-oak	Mexico
5	Restoration	Miombo	Southern Africa
6	Agro-forestry	Mango-tamarind	India (South)
7	Avoidance of deforestation	Various	Mexico

In the case studies, descriptions of the ecology, economics and management of these forestry systems are provided and case 7 (avoided deforestation) contains a description of the methodology to be applied to derive factors to parameterize the deforestation model.

The information provided in the case studies provides an indication of the costs and performances of forestry sequestration projects but it should be recognized that the results depend on many local factors. Actual carbon uptake and economic performance of forestry systems will depend upon local factors, such as micro-climate, soil conditions and rainfall patterns that require on the ground assessment and monitoring of conditions. Individual site / project inspections will also be necessary to determine factors such as potential leakage of project benefits, what the baseline level of carbon storage is likely to be and whether the project implementers actually have the technical skill, equipment, legal rights, financial and management capabilities to implement a project, as proposed.

In developing countries the social context for forestry projects is extremely important. Forestry systems are but one of a number of components that form the basis for rural livelihoods.

10.3.2 Quantities of Carbon Sequestered

The quantity of carbon sequestered depends on the site productivity. For some of the cases, information on the quantities of carbon sequestered is provided for high, medium and low productivity sites. For other cases, because of limited available information, information is only provided for typical sites.

10.3.2.1 Above-Ground Carbon

The quantities of carbon sequestered in above ground biomass in each of the cases, and how they vary with time, are summarized in Figure 10-1. This information is for medium productivity sites.
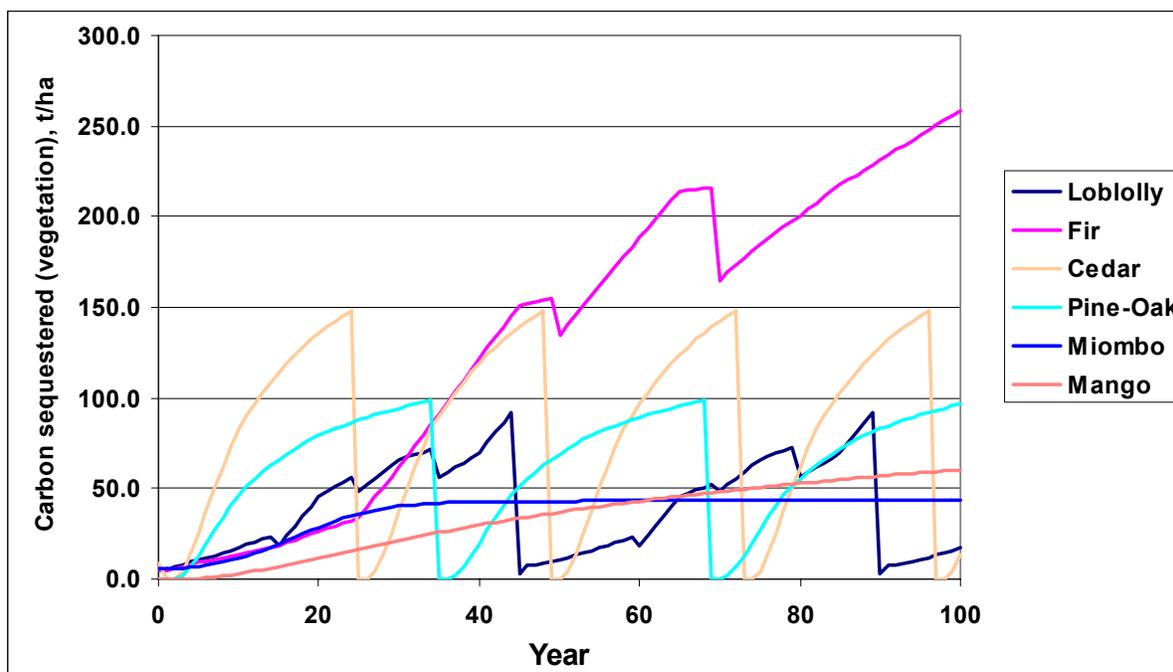
Figure 10-1
Quantities of carbon sequestered (medium productivity sites)

It can be seen that the quantities differ substantially between the cases, in terms of both carbon sequestration rate and the maximum quantity of carbon sequestered per hectare. The cases which give the fastest sequestration rates in early years do not necessarily sequester the largest quantities of carbon in the long term.

The quantities of carbon stored increase until the time when wood is harvested. If wood were not harvested the quantities of carbon stored may increase further but would then begin to decline, due to increased mortality. Harvesting wood and replanting has the benefit of producing revenue which offsets some of the costs of planting and maintaining the forests. Providing revenue and products for local use can be particularly important for developing countries, to maintain the support of local communities and reduce the risks of human induced forest loss.

The quantity of carbon sequestered depends on the site productivity. An example of this, for the Spanish Cedar plantations case, is shown in Figure 10-2. The quantities of carbon sequestered differ significantly between different site productivities but, in general the differences are less than between the different forest cases.
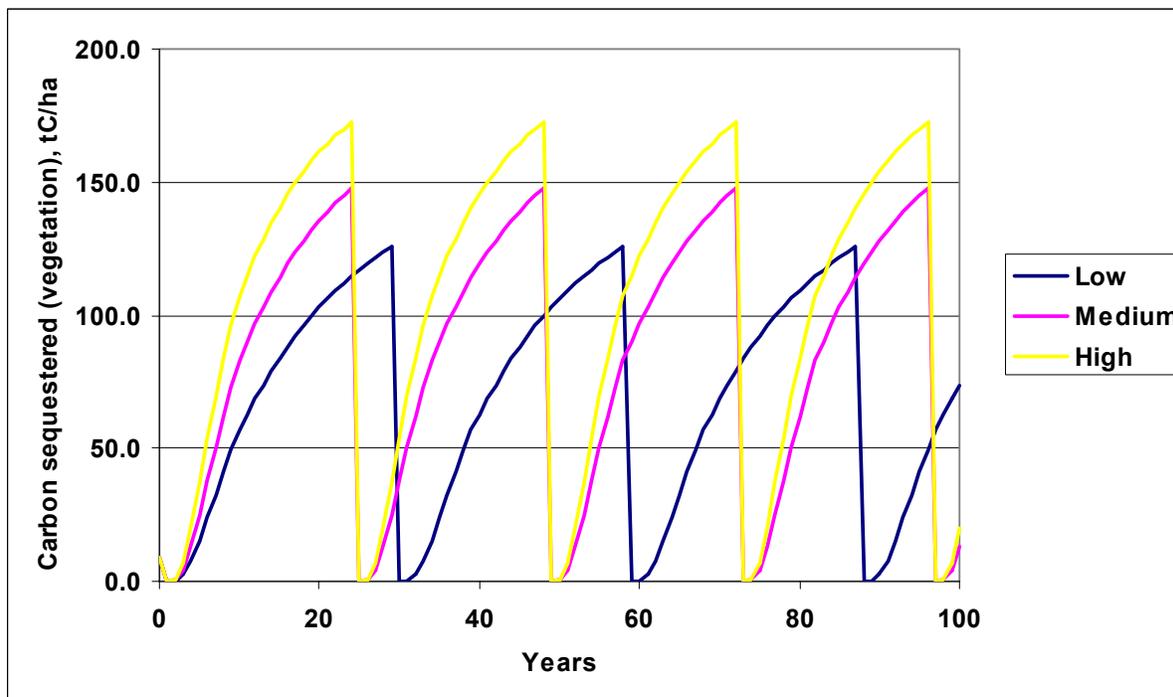
Figure 10-2
Carbon sequestered in Spanish Cedar plantations at different site productivities

10.3.2.2 Below-Ground Carbon

It is relatively easy to monitor and verify carbon stored in above-ground trees. Carbon sequestration credits are often based only on above ground carbon. Carbon in soils can be measured but it is more uncertain and many more measurements are required. This study includes both above-ground and carbon stored in soils. The base case economic assessments include both above ground carbon and carbon in soil, roots.

10.3.2.3 Wood Products

Carbon stored in products made from harvested wood is also considered in this study. Some wood products, e.g., paper, have short lifetimes, but others, e.g., wood used in buildings, can have lives of up to 100 years or more. Carbon stored in wood products is sometimes included in assessments of carbon sequestration but there are many uncertainties and there is no simple way to verify the quantity of carbon stored.

The quantities of carbon sequestered in above ground vegetation, soil (including roots, litter and , humus) and timber products in the medium productivity Spanish Cedar case are shown in Figure 10-3. The quantities of carbon shown in Figure 10-3 are in addition to those already existing at the start of the project. The figure illustrates the characteristic pattern of carbon stored in wood products.
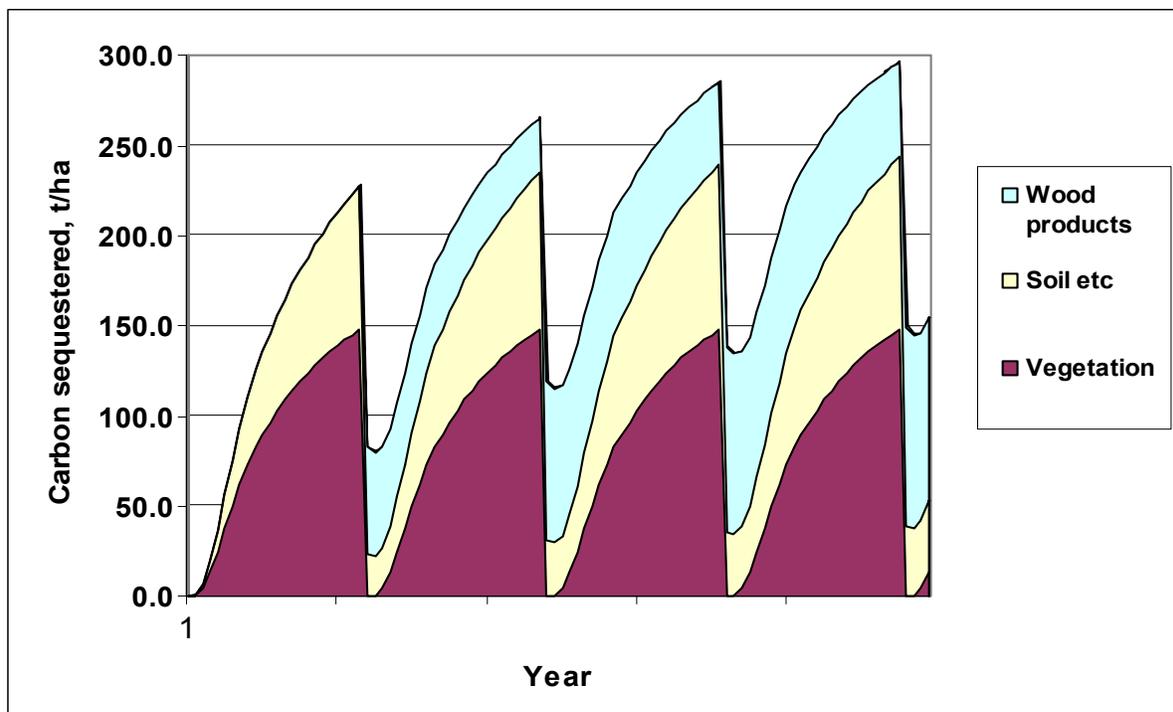
Figure 10-3
Carbon sequestered in vegetation, soil etc. and timber products (Spanish Cedar)

Wood products can displace other products, including steel and concrete. Significant amounts of greenhouse gases are emitted during their production, so substitution by wood products can result in substantial greenhouse gas benefits. The quantity of carbon sequestered in wood products can reach saturation, as the rate of decomposition equals the rate of creation of new products but the benefits of reduced emissions from production of alternative materials continues. A material substitution effect of 0.28 tC/m^3 of final wood product has been suggested[5]. Although this estimate is highly uncertain, it is possible that the substitution impact for wood products is greater than the sequestration impact. Material substitution effects are beyond the scope of this study.

Harvested wood can also be used as fuel, reducing greenhouse gas emissions from use of fossil fuels. The scope of this study was limited to carbon sequestration. Biomass fuel production is a broad subject in its own right and is beyond the scope of this study.

10.3.3 Non-CO$_2$ Greenhouse Gases

Greenhouse gases other than CO$_2$ are emitted and absorbed by forests. Forests are one of the main sources of nitrous oxide and they can be a source or sink for methane. Greenhouse gases may also be released during land clearance prior to planting of forests and during deforestation.

Little information is available on non-CO$_2$ GHG emissions from forests. Non-CO$_2$ greenhouse gases are not normally included in assessments of forestry sequestration schemes. Including

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non-CO_2 GHGs would greatly increase data requirements and monitoring costs. In this study, non-CO_2 greenhouse gases are included as a sensitivity to indicate whether they are likely to be significant compared to carbon sequestration.

10.3.3.1 Nitrous Oxide from Forests and Baseline Land Uses

Global N_2O sources related to land-use are summarized in Table 10-2[6]. The carbon equivalents of these emissions, based on a 100 year global warming potential, are also shown in Table 10-2. The estimated emissions of N_2O from natural forests are 1.1 Gt carbon-equivalent per year, equivalent to about 18 percent of current emissions of CO_2 from fossil fuel use. Emissions of N_2O are enhanced under warm and wet conditions, e.g., those present in the soils of moist tropical forests, and when nitrogen is applied as fertilizer. The uncertainty in N_2O emissions from forests is large, particularly for temperate forests, where the range of uncertainty is a factor of 16.

Table 10-2
Global N_2O sources

	Mt N y^{-1}		Gt C eq. y^{-1}	
	Central Estimate	Range	Central Estimate	Range
Forest soils - wet tropical forests	3	2.2-3.7	0.8	0.6-1
- temperate forests	1	0.1-2	0.3	0.03-0.5
Natural savanna soils	1	0.5-2	0.3	0.1-0.5
Natural temperate grassland soils	1	0.5-2	0.3	0.1-0.5
Cultivated soils	3.5	1.8-5.3	0.9	0.5-1.4
Biomass burning	0.5	0.2-1	0.1	0.05-0.3
Livestock	0.4	0.2-0.5	0.1	0.05-0.13
Total	10.4		2.8	

10.3.3.2 Methane from Forests and Baseline Land Uses

Although the overall global emission of methane is relatively well known, the magnitude of individual sources and the likely changes in methane sources and sinks associated with changes in land use and other modifications or terrestrial ecosystems are uncertain[6]. Tropical wetlands and termites emit methane but microbial activity in soils is a significant sink for atmospheric methane. Overall net emissions of methane from forests compared to alternative land uses are estimated to be an order of magnitude less significant than emissions of N_2O.

10.3.3.3 Net Emissions of Nitrous Oxide and Methane From Forestry

Estimating the impacts on N_2O and methane emissions of forestry sequestration depends on the emissions from the baseline land use. Forests are large emitters of N_2O and in some circumstances are also emitters of methane, but alternative uses of the land would also emit significant amounts of these gases. In this study it is assumed that planted forests will replace pasture or abandoned farmland. If forests were planted on croplands there could be a significant reduction in emissions because croplands often have higher emissions than forests. However, if an area of cropland was forested, another area of land elsewhere may be converted to cropland to maintain food production, so the benefits would be illusory.

The net emissions of forests and baselines used in this study are shown in Table 10-3[7, 8].

Table 10-3
Forest and baseline N_2O And CH_4 emissions

	U.S. afforestation / deforestation	Non-U.S. afforestation / deforestation	Avoidance of deforestation
CH_4 emissions, kg ha^{-1} y^{-1}			
Baseline	-1.1	-1.1	-3.5
Forests	-1.2	-3.5	-1.1
Net	-0.1	-2.4	2.4
N_2O emissions, kg ha^{-1} y^{-1}			
Baseline	0.4	0.4	2.2
Forests	1.2	2.2	0.4
Net	0.8	1.8	-1.8
Overall emissions, tCeq ha^{-1} y^{-1}	0.06	0.13	-0.13

Note: emissions for avoidance of deforestation are per hectare of land deforested

10.3.3.4 Emissions From Biomass Burning

Deforestation often involves open burning of biomass and some biomass is also often burned when ground is cleared prior to planting of forests. When vegetation is burned about 10 percent of the carbon contained in the biomass is converted to charcoal, which will remain stored in the soil for a very long time[9]. Most of the rest is oxidized and released to the atmosphere as CO_2. Some methane and N_2O are also produced during open burning of biomass and their total greenhouse gas effect is estimated to be about 0.1 tC equivalent/ tC burned, based on 100 year global warming potentials and emissions data[9]. The carbon equivalent of methane and nitrous oxide missions from open burning of biomass appears to be approximately equal to the quantity of carbon that is converted to charcoal and therefore not emitted as CO_2. For this study it is therefore assumed that, in effect, all of the carbon released during deforestation and ground clearance prior to planting of forests is released as CO_2.

10.3.3.5 Other Atmospheric Emissions

Vegetation emits large quantities of volatile organic compounds (VOC) to the atmosphere, substantially more than are emitted from use of fossil fuels (5). VOC is also emitted during biomass burning, along with CO and NO_x (NO and NO_2). These gases have only a small direct impact on radiative forcing but they have a large indirect effect, as they affect formation of ozone, which is an important greenhouse gas, and OH, which affects the atmospheric burden of methane. Particulates are emitted during biomass burning and they too can have a significant impact on the climate. The climate impacts of these emissions are highly uncertain and Global Warming Potentials of these gases have not been agreed. They have therefore not been included in this study.

10.3.4 Costs

Cost information for each of the forestry cases has been provided by ECCM, based on published information and direct experience within developing countries. Details are given in Chapters 11-17. The costs provided by ECCM are within the ranges of costs quoted in published references. Costs from a variety of published references are given in Appendix C for comparison.

10.3.4.1 Establishment and Maintenance

Establishment costs provided by ECCM range from 100 to 700 $/ha. The costs provided by ECCM are within the ranges of costs quoted in published references. Costs from a variety of published references are given in Appendix D for comparison. Costs tend to be higher in developed countries because of higher labor costs.

10.3.4.2 Land Costs

Land costs are based on typical marginal costs of alternative land uses. The costs range from zero, where the land would not otherwise be used, to 1750 $/ha.

Large-scale application of carbon sequestration would affect the balance of supply and demand, and hence the price of fertile land. The cost of forestry carbon sequestration would therefore increase as the extent of sequestration forests increases. In some places, particularly developing countries, land owners may be reluctant to convert their land to sequestration forests because of uncertainties about making long term commitments, social and cultural attachments to current agricultural practices, a wish to ensure production of subsistence agricultural products and concerns about land ownership rights. The price paid for land for forestry sequestration may need to be greater than the current marginal value, to encourage land owners to change to sequestration forestry. No attempt is being made in this study to produce cost-supply curves for any of the sequestration options. These issues are therefore beyond the scope of this study.

10.3.4.3 Timber Revenues

Forests produce useful products, particularly timber and fuel wood and also in some cases food, medicinal and other types of plants. Revenue from the sale of timber is included as in the economic assessment. Other products are mainly used locally and their value is assumed to help ensure the long term maintenance of the forests.

In the model, timber prices in the future are assumed to be the same as at present. A similar assumption is made in the EOR and ECBM cases, where oil and gas prices are assumed to remain constant. However, it is recognized that future timber prices are uncertain and large scale adoption of sequestration forestry could itself significantly affect timber prices. This report therefore presents sequestration costs with and without timber revenues.

10.3.4.4 Monitoring

The change in carbon stocks of stands of forest trees over a 5-year period can be assessed with good precision through standard inventory methods. Carbon stocks in soils have been determined by standard sampling techniques but large numbers of samples are required to achieve adequate precision[6]. Third party organizations offer independent carbon verification services, to give increased confidence to purchasers of carbon credits. A combination of remote satellite monitoring and on-the-ground measurements is normally used.

The costs of measuring and monitoring carbon sequestration in forests are a function mainly of the desired level of precision, which may vary by the type of project activities, the size of the project and the natural variation within the various carbon pools. The level of precision has a very large effect on the costs, for example variable costs for a precision of ±5 percent may be a factor of a hundred greater than for a precision of ±30 percent[6]. If projects could only claim carbon credits for the lower bound of the confidence interval and the value of carbon credits was high, it would be worthwhile monitoring to a high level of precision.

A few data are available to provide preliminary estimates of the costs of measuring and monitoring of carbon in forestry projects. Based on available information[6], an annual monitoring cost of $5/ha has been assumed for this study.

10.3.4.5 Financial Parameters

The same financial parameters were used for forestry options as for CO_2 capture and storage options included in this project. The rationale is that we assume that funding for both types of projects would come from an energy company seeking to receive credits for reducing GHG emissions. An energy company likely would use the same financial parameters for evaluating GHG abatement investments regardless of whether the investments involve CO_2 capture and storage or CO_2 sink enhancement. Costs were estimated on a constant-dollar basis using an interest rate of 5.83 percent, income tax rate of 38 percent, and after-tax discount rate of 6.09 percent (see the Section 2.4 for more details and rationale). Land, initial transaction, and establishment costs were levelized over the first 20 years using a 5.83 percent interest rate.

Taxable income was based on revenues from a given harvest minus expenses that accumulated to that point. If accumulated expenses were greater than accumulated revenues at a given harvest, then expenses that were not yet offset by revenues were carried over to the next harvest for calculating taxes.

Costs of GHG mitigation ($/tonne life-cycle avoided C equivalents) were calculated on an NPV basis as described in detail in Section 2.4. An after-tax discount rate of 6.09 percent was used to calculate NPV's. Costs calculated on this basis can be compared with costs from other CO_2 storage or sink enhancement options that differ in timing of costs and in timing and permanence of GHG mitigation.

10.4 References

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9   UNEP/OECD/IEA/IPCC 1997, Revised IPCC Guidelines for National GHG Inventories Vol. 3: GHG Inventory Reference Manual, IPCC, Bracknell, UK.

11
CASE 1: SOUTHERN U.S. LOBLOLLY PINE PLANTATIONS

11.1 Introduction

Loblolly pine (*Pinus taeda*) is a versatile, fast-growing softwood species that thrives in much of central and eastern US. It is the most important timber species in the United States, with an estimated growing stock of 1.4 billion m^3 across approximately 13.4 million ha, with around 2.4 million ha of loblolly pine plantations. In some States there has been a threefold increase in the area for Loblolly pine plantations since the 1970s.

11.2 Ecology

Loblolly pine grows in a variety of conditions; its natural range extends across several States, from 28ºN in Florida, Texas and Oklahoma to 39ºN in Delaware, New Jersey and Maryland. East-west its range stretches from 75-97°W. It is found naturally between the flat Atlantic coastal plains up to altitudes of 1520 m in the Appalachian Highlands. Mean annual rainfall is between 1020-1520 mm per year and the mean annual temperature is 13-24ºC. It will grow on a variety of soils but grows best on moderately acid soils with imperfect to poor drainage. It does not normally thrive on base-rich soils with high pH.

11.3 Management Operations

Typical management operations are described in the following subsections.

11.3.1 Establishment

Establishment of Loblolly pine plantations usually involves high intensity site preparation using mechanical methods to remove above-ground biomass, scarification and bedding of soils and application of fertilizer. Herbicides may be used to control vegetation on low productivity sites but are less effective on high productivity sites. Planting normally takes place between December and March, depending on adequate soil moisture availability. Planting density is between 625 and 1,100 stems per ha (4x4 to 3x3m). For sites under 50 ha the unit costs of mechanical operations and fencing may be uneconomic.

Case 1: Southern U.S. Loblolly Pine Plantations

11.3.2 Maintenance

Maintenance of Loblolly pine plantations consists of:

- control of competing vegetation, in particular during the early years

- control of hardwoods

- application of P and N fertilizers that can significantly improve growth (no fertilizer assumed in this study)

11.3.3 Harvesting

Thinning can take place in years 15, 25, and 35 to remove saleable trees which would not survive to the end of the rotation and to release higher quality trees. Final clearcut takes place at 45 years.

11.3.4 Re-establishment

Planting of nursery grown seedlings is the most common method of re-establishment. Artificial regeneration by direct seeding may also be considered as a cheaper option but is less likely to produce good regeneration.

11.3.5 Classification of Productivity

Productivity on the southern coastal plains is generally relatively high and declines in the shale and sandstone regions of the highlands. Site indices are used to indicate site quality and potential growth, classified by height at a reference age (usually 25 for plantations, 50 for natural stands). Table 11-1 shows the two productivity levels for Loblolly pine.

Table 11-1
Productivity classes for Loblolly Pine in the southern United States

Productivity	Site Index	Conditions	Production
High	21-32	Loam hills and plains	$220m^3$ 45 years
Medium	20-23	Sand hills and plains (deep sands)	$190m^3$ 45 years
Low	18-24	Mixed sandstone shale	n.a.

11.4 Carbon Sequestration Potential

11.4.1 Baseline

The following are the initial assumptions for existing stored carbon at the site based on ECCM information.

*   Vegetation: 5 tC/ha.

*   Soils: approximately 24 tC/ha under cropland

11.4.2 Carbon Uptake and Storage by Pinus Taeda

Pinus taeda is a fast growing species with maximum annual growth from 15 to 30 years. Rotations vary but a 45-year cycle is common, with earlier thinnings to produce some income. Values selected for this case are shown in Table 11-2.

Table 11-2
Expected carbon storage from Loblolly Pine plantations over 100 years

Productivity	*Low*	*Medium*	High
Rotation length (years)	n.a.	45	45
Maximum above ground carbon (tC ha^{-1})	n.a.	92	95
Average above-ground carbon (tC ha^{-1})	n.a.	40	53
Average soil etc. carbon (tC ha^{-1})	n.a.	67	72.

11.5 Costs

11.5.1 Establishment and Maintenance

Site preparation costs for intensive management can range from $370-$480/ha with chemical treatments ranging from $136-$395/ha. The overall average cost has been assumed to be $690/ha for this study. Establishment grants are available in many US states but they have not been included in this study. The amount of grant aid available varies between states.

The main post-establishment costs are associated with weed control (particularly in high-rainfall areas). The main weeds are competing broadleaved, hardwood trees; these will be treated with herbicides annually for the first 3 to 5 years, depending on the site concerned. The cost of each treatment will be $40 to $60 per hectare. A cost of $40 per year for the first 4 years has been assumed for this study.

11.5.2 Land Costs

Most new plantations are likely to be established on marginal agricultural or range land, where the profitability of existing production (usually cattle grazing) is relatively low. Since the market for land in the southern US is fairly liquid, the price of land would appear to be a reasonable indicator of the net present value of income foregone. Land prices for medium quality range land and moderate to poor quality grazing land in the states of Missouri, Tennessee, Eastern Texas and Louisiana are in the range of $1000 to $2,500 per hectare. At the lower end of this range one would probably obtain below average yields of timber and carbon storage, with the exception of waterlogged river valleys, which are poor for cattle but could be highly productive as plantations.

11.5.3 Potential Income

Plantations are likely to turn out around $200m^3$ timber at the end of the rotation. At $22/m^3$, this gives an income of around $4,400, depending on site productivity.

11.6 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Loblolly pine is presented in Table 11-3. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 11-4. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 11-4 for the medium productivity case. For the high productivity case, the timber yield at the end of the rotation is 220 m^3/ha and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the high productivity case on several accounting bases in Table 11-5. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 11-5 for the high productivity case. Data were unavailable for a low productivity case for Loblolly pine.

Costs in Tables 11-4 and 11-5 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis. The same establishment, land, maintenance, and harvesting costs were assumed for medium and high productivity cases in Tables 11-4 and 11-5. This assumption likely resulted in a slight underestimation of costs for the high productivity case but the general comparison is still considered valid.

Table 11-3
Forestry input variables for Loblolly Pine

Forestry: Input Variables

⦿ Plantation, USA, Loblolly Pine
◯ Plantation, USA, Douglas Fir
◯ Plantation (Taungya), Mexico, Spanish cedar
◯ Restoration, Mexico, Pine-oak
◯ Restoration, Southern Africa, Miombo
◯ Agro- forestry, Southern India, Mango- tamarind
◯ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Plantation*
Country:	*USA*
Trees:	*Loblolly Pine*

Establishment cost ($/ha)	**690**
Land cost ($/ha)	**1,750**
Annual maintenance ($/ha)	**50**
Maintenance (years)	**4**

Timber revenue ($/m^3)	**22**

Timber yield (m^3/ha) :		Time Between Harvests (yrs)
End of rotation	190	45
Thinning 1		
Thinning 2		

Case 1: Southern U.S. Loblolly Pine Plantations

Table 11-4
Forestry summary of results for Loblolly Pine medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

	Management:	*Plantation*
	Country/Region:	*USA*
	Trees:	*Loblolly Pine*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	129.85
Above & below ground carbon	64.62
Above & below ground & timber product carbon	59.24
Above & below ground carbon & non-CO$_2$ GHGs	66.28
Above ground carbon with timber revenues	115.94
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	54.13

* C Equivalent LC GHG Avoided Basis
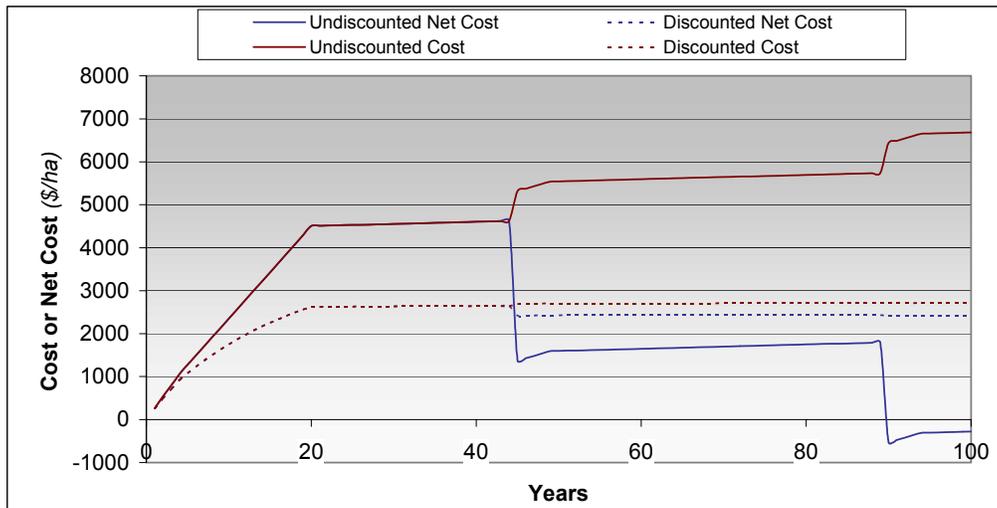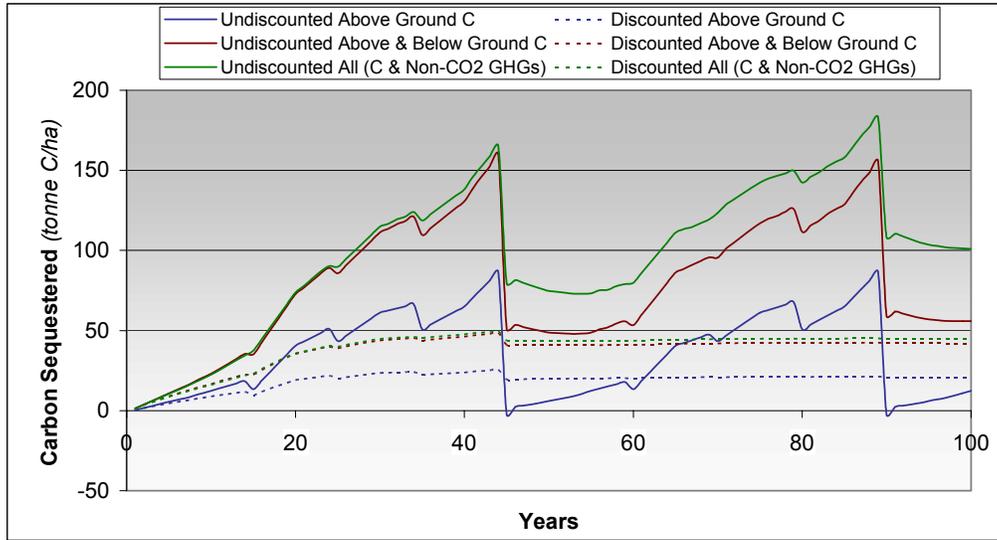
Table 11-5
Forestry summary of results for Loblolly Pine high productivity case

Forestry: Summary of Results *(Single System)*
High Productivity

CO₂ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Plantation*
Country/Region:	*USA*
Trees:	*Loblolly Pine*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	84.25
Above & below ground carbon	48.37
Above & below ground & timber product carbon	44.86
Above & below ground carbon & non-CO₂ GHGs	49.29
Above ground carbon with timber revenues	74.27
Above & below ground carbon, non-CO₂ GHGs, with timber products & revenues (*All*)*	40.24

* C Equivalent LC GHG Avoided Basis

Case 1: Southern U.S. Loblolly Pine Plantations
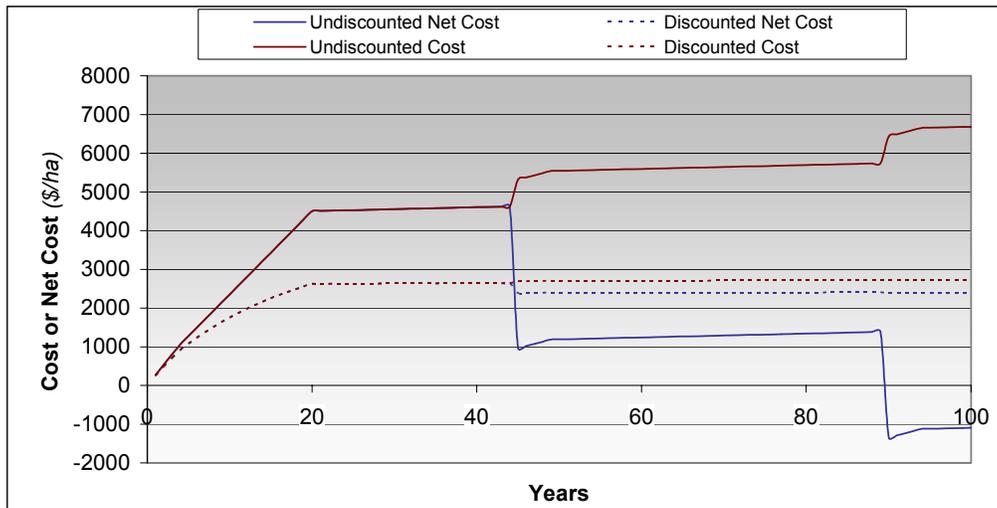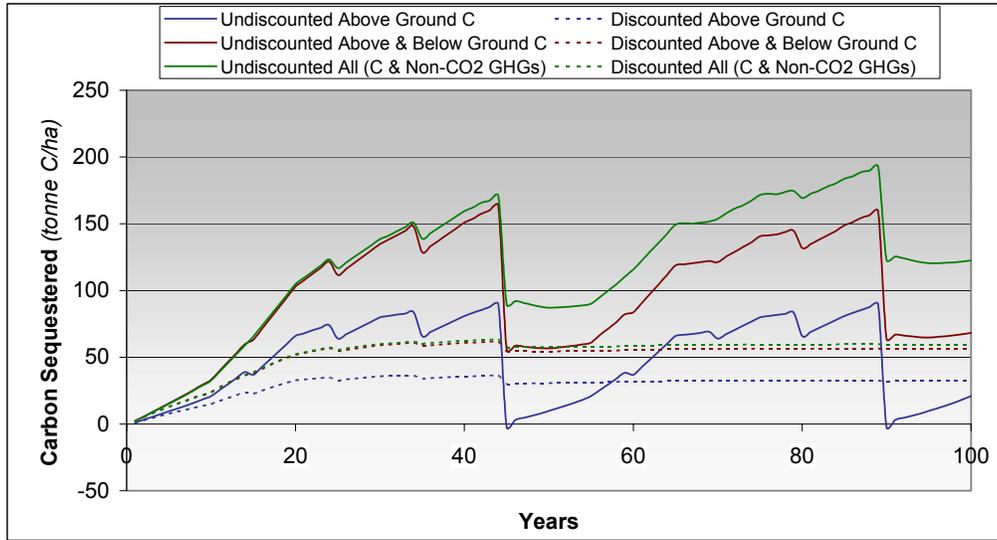
11.7 References

These references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

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12
CASE 2: PACIFIC NORTHWEST DOUGLAS FIR PLANTATIONS

12.1 Introduction

Douglass fir (*Pseudotsuga menziesii*) occurs naturally across a large area of western North America. Coastal Douglas fir is a valuable timber tree, with very high yields over long rotations and has been planted extensively. Old-growth stands are of considerable amenity and biodiversity value. Douglas fir plantations have the potential to sequester large amounts of carbon, and new planting may help protect old-growth forests under threat of exploitation.

12.2 Ecology

Pseudotsuga menziesii is a highly valuable timber tree, which has been extensively planted outside its natural range in western North America. There are two varieties, Rocky Mountain Douglas fir (*P. menziesii var. glauca*) and Coastal Douglas fir (*P. menziesii var. menziesii*). The latter extends from central British Columbia, southwards to a latitude of 34° 44'N. It is the most dominant tree species in the Pacific West and occurs from near sea level up to 1,500m, often in pure stands. It grows best on well-aerated, deep soils with a pH between 5-6. It does not do well on poorly drained, oligotrophic soils. The Pacific Northwest has a maritime climate characterized by mild wet winters and cool dry summers, with annual average temperatures of 9-13°C and annual rainfall between 380-3,000 mm. Douglas fir will not tolerate frost below -10°C for periods longer than a week. It is initially relatively slow growing and attains the largest height increments between 20-30 years. It can however maintain relatively rapid rates of growth for over a century. Long rotation times of up to 100 years can produce high yields and high quality timber. Douglas fir timber has a variety of uses including timbers, pilings, railroad ties, posts and poles, flooring, veneers, pulp and furniture.

12.3 Management Operations

Typical management operation practices are described in the following subsections.

12.3.1 Establishment

Douglas fir plantations are most readily established using nursery-grown seedlings. Light shade improves survival of first-year seedlings but thereafter control of competing vegetation is

essential. Planting is at densities between 750 and 1,500 stems per hectare (3.6 x 3.6 to 2.6 x 2.6m spacing).

12.3.2 Maintenance

Maintenance of Douglas fir plantations includes:

*   weed control
*   fertilizer application

12.3.3 Harvesting

Rotations are 100 years +, i.e., beyond the timescale of this study. Pre-harvest thinnings at 50 and 70 years will allow improved growth of remaining trees and provide interim income.

12.3.4 Re-establishment

Regeneration is usually by planting of nursery-stock, due to the requirements by forest laws for prompt regeneration of harvested areas.

12.4 Classification of Productivity

Productivity is classified by site index, according to height at a base year (usually 50 or 100 for Douglas fir)

Table 12-1
Productivity classes for Douglas Fir in pacific northwest USA

Productivity	Site Index	Conditions	Production
High	25+	Annual precipitation: >1500 mm Soils: well-aerated, deep soils	>1000m^3 100 years
Medium	18-24	Intermediate	>700m^3 100 years
Low	n/a	Annual precipitation: <1000 mm Soils: poorly drained, nutrient poor soils	Not available

12.5 Carbon Sequestration Potential

12.5.1 Baseline

It is assumed that plantations will be established on grassland or open ground. However, for actual projects, caution should be taken to assess whether sites are part of an established plantation cycle. The following are the initial assumptions for existing stored carbon at the site based on ECCM information.

- Vegetation: 5 tC/ha.

- Soils: approximately 37 tC/ha under cropland

12.5.2 Carbon Uptake and Storage by Pseduotsuga Menziesii

Values selected for this case are shown in Table 12-2.

Table 12-2
Expected carbon storage from Douglas Fir plantations over 100 years

Productivity	Low	Medium	High
Rotation length (years)	n.a.	100	100
Maximum above ground carbon (tC ha^{-1})	n.a.	258	352
Average above-ground carbon (tC ha^{-1})	n.a.	132	181
Average soil etc. carbon (tC ha^{-1})	n.a.	137	147

12.6 Costs

12.6.1 Establishment and Maintenance

Establishment costs for Douglas fir plantations are around $400 per hectare. However, where there is a strong presence of Himalayan blackberry, Scotch broom or other weeds, the forest manager may well incur weeding costs of $200 to $300 per hectare over and above the planting costs. An establishment cost of $500 per hectare has been assumed for this study.

The maintenance costs for Douglas fir are considerably lower than for Southern pines. A cost of $20/ha per year over 4 years has been assumed for this study.

12.6.2 Land

A net present opportunity cost of around $800 per hectare was selected for this case based on judgment and available existing information.

Case 2: Pacific Northwest Douglas Fir Plantations

12.6.3 Potential Income

High quality Douglas fir timber is a valuable commodity. Thinnings at 50 and 70 years can produce a total of about 350 m^3/ha, giving an income of $33,000 - $80,000 at current prices, with a final felling generating $200,000 - $400,000.

12.7 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Douglas fir is presented in Table 12-3. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 12-4. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 12-4 for the medium productivity case. For the high productivity case, the timber yields are 175 and 225 m^3/ha for thinnings 1 and 2, respectively, and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the high productivity case on several accounting bases in Table 12-5. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 12-5 for the high productivity case. Data were unavailable for a low productivity case for Douglas fir.

Costs in Tables 12-4 and 12-5 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis. The same establishment, land, maintenance, and harvesting costs were assumed for medium and high productivity cases in Tables 12-4 and 12-5. This assumption likely resulted in a slight underestimation of costs for the high productivity case but the general comparison is still valid.

Table 12-3
Forestry input variables for Douglas Fir

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
◉ Plantation, USA, Douglas Fir
○ Plantation (Taungya), Mexico, Spanish cedar
○ Restoration, Mexico, Pine-oak
○ Restoration, Southern Africa, Miombo
○ Agro- forestry, Southern India, Mango- tamarind
○ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Plantation*
Country:	*USA*
Trees:	*Douglas Fir*

Establishment cost ($/ha)	**500**
Land cost ($/ha)	**800**
Annual maintenance ($/ha)	**20**
Maintenance (years)	**4**

Timber revenue ($/m^3)   **150**

Timber yield (m^3/ha) :		Time Between Harvests (yrs)
End of rotation		
Thinning 1	135	50
Thinning 2	215	70

Case 2: Pacific Northwest Douglas Fir Plantations

Table 12-4
Forestry summary of results for Douglas Fir medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO₂ Sink Enhancement, NPV Basis *(years 1-100)*

	Management:	*Plantation*
	Country/Region:	*USA*
	Trees:	*Douglas Fir*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	47.58
Above & below ground carbon	23.21
Above & below ground & timber product carbon	22.79
Above & below ground carbon & non-CO₂ GHGs	23.61
Above ground carbon with timber revenues	14.01
Above & below ground carbon, non-CO₂ GHGs, with timber products & revenues (*All*)*	6.83

* C Equivalent LC GHG Avoided Basis
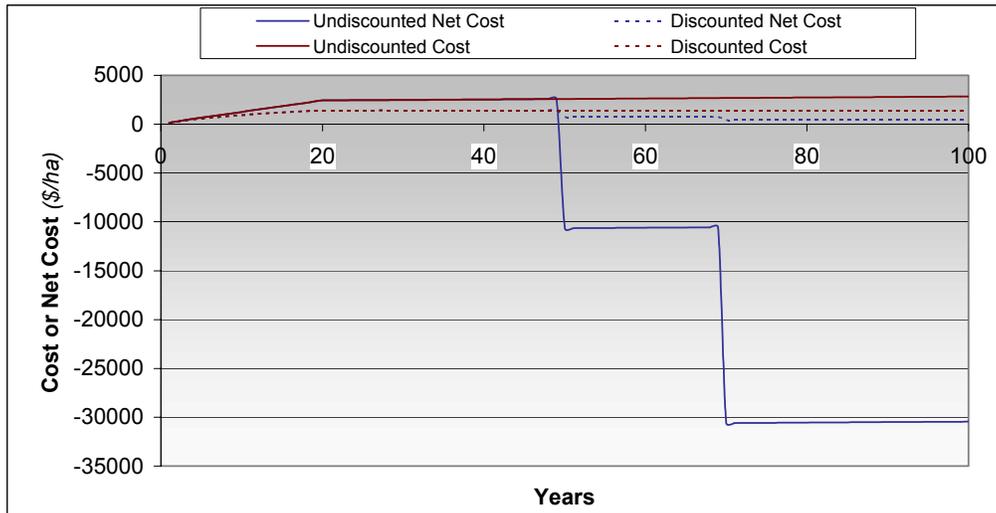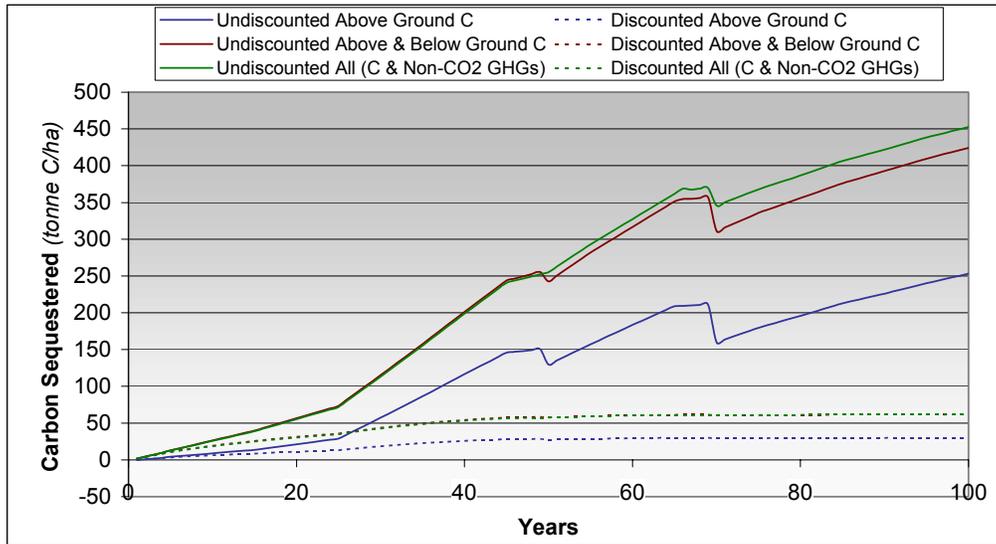
Table 12-5
Forestry summary of results for Douglas Fir high productivity case

Forestry: Summary of Results *(Single System)*
High Productivity

CO₂ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Plantation*
Country/Region:	*USA*
Trees:	*Douglas Fir*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	33.55
Above & below ground carbon	18.66
Above & below ground & timber product carbon	18.35
Above & below ground carbon & non-CO₂ GHGs	18.92
Above ground carbon with timber revenues	4.99
Above & below ground carbon, non-CO₂ GHGs, with timber products & revenues *(All)**	2.76

* C Equivalent LC GHG Avoided Basis

12-7
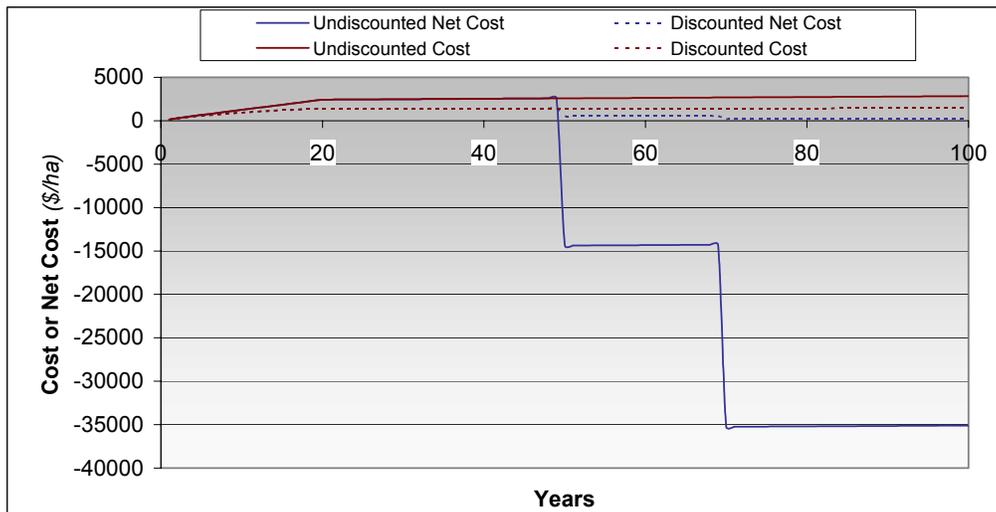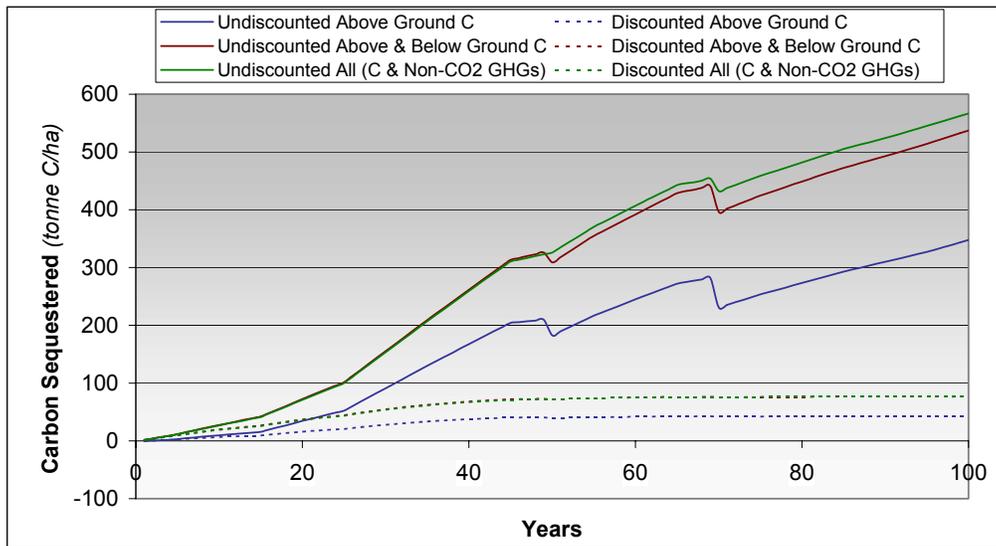
12.8 References

These references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

1   Birdsey, Richard, A. 1996. Carbon Storage for Major Forest Types and Regions in the Conterminous United States, in *Forests and Global Change: Vol. 2. Forest Management Opportunities for Mitigating Carbon Emissions*. American Forests, Washington, DC.

2   Burns, Russell M., and Barbara H. Honkala, (tech. •ords.) 1990. *Silvics of North America: Vol.1. Conifers*. Agriculture Handbook 654. U.S. Department of Agriculture, Forest Service, Washington, DC.

3   Howard, James L. 1999. *US Timber Production, Trade, Consumption and Price Statistics 1965-1997*. General Technical Report GPL-GTR-116. US Department of Agriculture, Forest Service, Washington, DC.

13
CASE 3: SPANISH CEDAR PLANTATIONS IN MEXICO USING THE TAUNGYA SYSTEM

13.1 Introduction

The "Taungya system" for establishing plantations of Spanish cedar or "cedro" (*Cedrela odorata*) reduces the opportunity costs of plantation establishment by allowing the farmer to grow annual crops between the trees during the initial years. The annual crops provide some additional income and the saplings benefit from the maintenance of the crops. Furthermore, as the planting density is lower than in a mono-culture plantation, the cost of buying seedlings is reduced. After 3-4 years the tree will shade-out the annual crops. This system is best suited to areas of higher rainfall where competition for water is not a problem, and where there is sufficient labour to carry out the cropping and tree maintenance activities by hand.

13.2 Ecology

Cedrela odorata is a fast-growing, high-value timber tree that is native to large areas of Central and South America from southern Mexico to Bolivia, 28ºS–26ºN. It is found naturally at altitudes between 0 and 1500 m, where mean annual rainfall is between 1200-3000 mm per year, and where the mean annual temperature is 20-32ºC. It will grow on light, medium or heavy soils but thrives on free draining, fertile soils. *Cedrela odorata* is a light demanding species that develops best in open spaces or large clearings in the highly diverse tropical broadleaved forests but in much of its native range the gene pool has been severely depleted due to the high demand for its valuable timber. *Cedrela odorata* is grown as a plantation tree throughout the tropics.

13.3 Management Operations

The primary objective of the Taungya system is timber production. Crop yields (maize for this study) during the first few years will help cover planting costs. Thinning is used to liberate selected individuals of good form. *Cedrela odorata* produces a very high quality, valuable timber for which there is a ready market. Although plantations have lower biodiversity value, the production of this species may lessen pressure on surviving populations in native forests. Soil conservation is improved on steep slopes. Typical management operations are described in the following subsections.

Case 3: Spanish Cedar Plantations in Mexico Using the Taungya System

13.3.1 Establishment

Techniques used for planting maize are used to prepare the site for establishing the tree crop / maize mixture. Although these techniques vary with location the following activities are undertaken:

• Clearing weeds and other vegetation

• Sowing maize (according to local practices)

• Making holes for seedlings – large holes 30cm diameter and depth produce better conditions for root development, the topsoil is more fertile and should be placed in the bottom of the hole for better rooting.

• In very compact soils holes may be dug after the start of the rains.

It is important to obtain good quality planting stock, which should be ready for planting at the beginning of the rainy season. Planting a mixture of species as well as *Cedrela odorata* may help reduce the occurrence of the shoot borer *Hypsipyla grandela*. Note if other species used have similar growth rates or account for not more than 20 percent of the crop, carbon estimates will not be significantly affected. Planting density should be between 1100 and 625 stems per ha (3x3 to 4x4m). The roots of seedlings should be pruned just prior to planting to help root development

13.3.2 Maintenance

• Weeding should be carried out at least twice per year until canopy closure.

• Pruning is vital to maintain tree form, whenever is there is evidence of attack by *Hypsipyla grandela*

The most important pest of *Cedrela odorata* and one of the most important factors in establishment is the shoot borer *Hypsipyla grandela*. The larvae of the moth develop in the apical bud of young trees causing the shoot to die. This does not kill the tree but leads to the growth of several subsidiary shoots. If not pruned this will lead to forking of the main stem and drastically reduce the value of the timber. However if all but the strongest, straightest shoots that result are removed the tree will continue to grow with good form and the length of saleable timber will be much increased. Pruning of subsidiary shoots must take place within one or two years of *Hypsipyla* attack as the removal of older branches will put the tree at risk of disease. One means of reducing the occurrence of the shoot borer is to use a mixture of species.

Although not conclusively proven, inter-planting of other fast growing species with the Cedrela may help prevent infestation through reducing the chances of the moth finding its host in the plantation. Chemical and biological means of control do exist but the cost might make these unfeasible. The great advantage in small- scale plantations is that the farmer can quickly spot damaged trees and prune the shoots where necessary during routine maintenance. After approximately 5 years the trees become less susceptible to the shoot borer. It is extremely important that farmers are given training in pruning trees if they are to realize the full value of this species.

13.3.3 Harvesting

Harvesting should take place in year 25, however in poorer sites the rotation length may be up to 30 years.

13.3.4 Re-establishment

Two methods of re-establishment may be used in subsequent rotations:

1. Shelterwood: 25 to 30 trees/ha (approx. 20x20m) may be retained as seed trees when the main crop is felled to provide seed for the new crop. Regeneration should be maintained by regular weeding.

2. Repetition of the taungya system: if the crop is clear felled then the taungya system of establishment with annual crops may be repeated.

13.4 Classification of Productivity

Productivity is classified on three levels (low, medium and high): according to the altitude, rainfall and soil conditions shown in Table 13-1. Production figures are in cubic metres of timber harvested at the end of the specified rotation.

Table 13-1
Productivity classes for Spanish Cedar in central America

Productivity	Conditions		Production
High	Altitude: Rainfall: Soil:	300-1200 m 1450 – 3000 mm/y Well-drained, brown-black	450 m^3 25y
Medium	Altitude: Rainfall: Soil:	<300 or >1200 m <1450 mm/y Heavy clays; sandy	400 m^3 25 y
Low	Altitude: Rainfall: Soil:	<300 or >1200 m <1450 mm/y Stony, compacted or oxidised clays	350 m^3 30 y

13.5 Carbon Sequestration Potential

13.5.1 Baseline

The baseline conditions for Taungya systems in Central America vary considerably: most are established on land that is marginal for agricultural crops, where the land is cultivated sporadically, perhaps 2 years out of 10 using slash and burn methods. For most of the interim

Case 3: Spanish Cedar Plantations in Mexico Using the Taungya System

period the land is covered with a low, tangled thicket, containing a mixture of herbs, shrubs and small trees, with the occasional large or very large tree.

Because of this diversity it is necessary to assess the conditions in each plot individually. Table 13-2 gives a rapid method for assessing the components of baseline carbon-density prior to establishment of Taungya on individual plots.

Table 13-2
Components of baseline carbon stock (tC)

Vegetation	*None* <10% cover	*Few* 10-20% cover	*Moderate* 20-60% cover	*Abundant* >60% cover
Herbs	0	0.4	1.2	2.0
Shrubs	0	0.8	2.4	4.0
Small trees 1-5m	0	1.4	4.2	12.0
Medium trees 5-10m	0	2.4	7.2	18.0
Large trees 10-20m	1 tC per tree			
Very large trees >20m	3 tC per tree			

For the purposes of this assessment the baseline vegetation carbon content was assumed to be 8.6 tC/ha.

13.5.2 Carbon Uptake and Storage by Cedrela Odorata

Following the first 3 years of establishment, the system will accumulate carbon rapidly at 8 to 15 tC ha^{-1} y^{-1} during most of the 25-30 year rotation. Carbon storage for different productivity classes will be approximately as shown in Table 13-3:

Table 13-3
Expected carbon storage from Spanish Cedar over 100 years

Productivity	Low	Medium	High
Rotation length (years)	30	25	25
Maximum above ground carbon (tC ha^{-1})	126	148	173
Average above-ground carbon (tC ha^{-1})	68	82	102
Average soil etc. carbon (tC ha^{-1})	121	132	147

13.6 Costs

13.6.1 Establishment and Maintenance

The cost of implementation by small farmers in Chiapas, southern Mexico (2000) was estimated at $385/ha. In the first three years most of the weeding costs are paid for by the cultivation of maize between the young trees. The only other significant cost is pruning of trees attacked by shoot borer. The cost depends upon the severity of the attack and could be anything from zero in unaffected plantations to $50 per hectare per year up to year 7 on severely affected plots. A cost of $25/ha for 7 years was assumed for this study.

13.6.2 Land Cost

These systems are generally established on marginal agricultural land, where slope or soil conditions are sub-optimal for maize production. The opportunity cost (lost production from land) is estimated at $0-1350/ha, depending upon site quality (agricultural production on poor quality sites has virtually zero opportunity cost). An average value of $675/ha was chosen for this study.

13.6.3 Potential Income

Potential income from timber production of 400 m^3/ha at a price of $100 /$m^3$ gives a total of $40k $/ha per rotation.

13.7 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Spanish cedar is presented in Table 13-4. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 13-5. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 13-5 for the medium productivity case. For the low productivity case, the timber yield at the end of the rotation is 350 m^3/ha, time between harvest is 30 years, and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the low productivity case on several accounting bases in Table 13-6. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 13-6 for the high productivity case. For the high productivity case, the timber yield at the end of the rotation is 450 m^3/ha, time between harvest is 25 years, and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the high productivity case on several accounting bases in Table 13-7. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 13-7 for the high productivity case.

Costs in Tables 13-5 to13-7 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis. The same establishment, land, maintenance, and harvesting

costs were assumed for medium, low, and high productivity cases in Tables 13-5 to 13-7. This assumption likely resulted in a slight overestimation of costs for the low productivity case and a slight underestimation of costs for the high productivity case but the general comparison is still valid.

In the graphs associated with Tables 13-5 to 13-7, the change in aboveground carbon becomes negative at the beginning of the accounting period. The initial negative change in aboveground carbon is due to clearing of some existing vegetation in preparation for establishment of the Spanish Cedar plantation. The cumulative change in aboveground carbon becomes positive as the new tree growth more than compensates for the clearing of vegetation before planting.

Table 13-4
Forestry input variables for Spanish Cedar

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
○ Plantation, USA, Douglas Fir
◉ Plantation (Taungya), Mexico, Spanish cedar
○ Restoration, Mexico, Pine-oak
○ Restoration, Southern Africa, Miombo
○ Agro- forestry, Southern India, Mango- tamarind
○ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Plantation (Taungya)*
Country:	*Mexico*
Trees:	*Spanish cedar*

Establishment cost ($/ha)	**385**
Land cost ($/ha)	**675**
Annual maintenance ($/ha)	**25**
Maintenance (years)	**7**

Timber revenue ($/m^3)	**100**

Timber yield (m^3/ha) :		Time Between Harvests (yrs)
End of rotation	400	25
Thinning 1		
Thinning 2		

Table 13-5
Forestry summary of results for Spanish Cedar medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO_2 Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Plantation (Taungya)*
Country/Region:	*Mexico*
Trees:	*Spanish cedar*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	23.68
Above & below ground carbon	14.35
Above & below ground & timber product carbon	12.81
Above & below ground carbon & non-CO_2 GHGs	14.67
Above ground carbon with timber revenues	(101.36)
Above & below ground carbon, non-CO_2 GHGs, with timber products & revenues (*All*)*	(55.88)

* C Equivalent LC GHG Avoided Basis
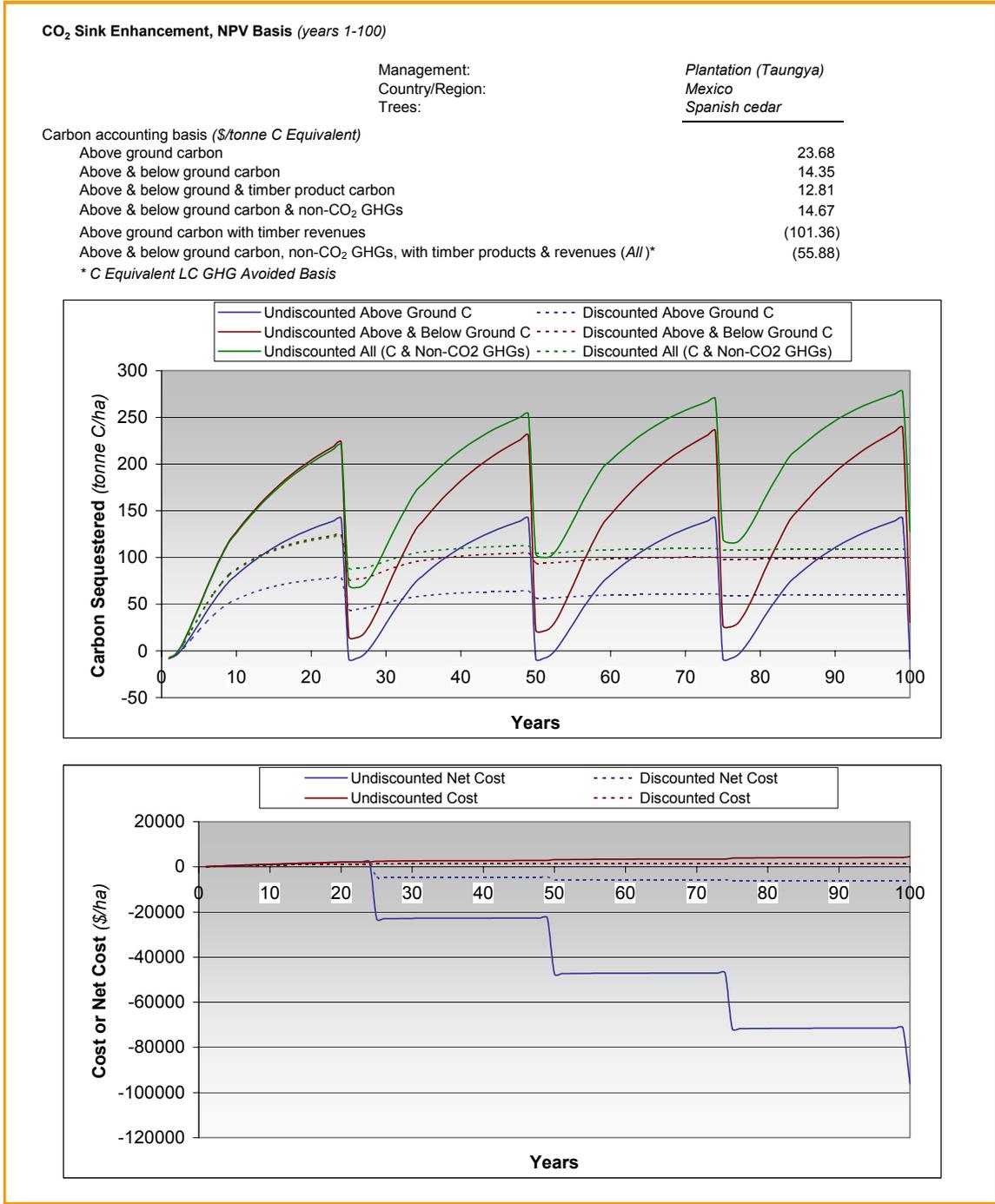
Case 3: Spanish Cedar Plantations in Mexico Using the Taungya System

Table 13-6
Forestry summary of results for Spanish Cedar low productivity case

Forestry: Summary of Results *(Single System)*
Low Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Plantation (Taungya)*
Country/Region:	*Mexico*
Trees:	*Spanish cedar*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	29.66
Above & below ground carbon	17.95
Above & below ground & timber product carbon	16.42
Above & below ground carbon & non-CO$_2$ GHGs	18.46
Above ground carbon with timber revenues	(68.69)
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	(39.01)

* C Equivalent LC GHG Avoided Basis

Table 13-7
Forestry summary of results for Spanish Cedar high productivity case

Forestry: Summary of Results *(Single System)*
High Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Plantation (Taungya)*
Country/Region:	*Mexico*
Trees:	*Spanish cedar*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	18.42
Above & below ground carbon	11.22
Above & below ground & timber product carbon	10.11
Above & below ground carbon & non-CO$_2$ GHGs	11.41
Above ground carbon with timber revenues	(90.70)
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	(50.55)

* C Equivalent LC GHG Avoided Basis

13-9

Case 3: Spanish Cedar Plantations in Mexico Using the Taungya System

13.8 Reference

These references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

1   Mayhew J.E. and Newton A.C. 1998 The Silviculture of Mahogany. CABI Publishing, Wallingford, UK

2   Webb D.B., Wood P.J., Smith J.P. and Henman G.S. (1984) A Guide to Species Selection for Tropical and Subtropical Plantations. Tropical Forestry Paper 15, Oxford, UK

3   CABI Forestry Compendium

4   ECCM technical note for classifying productivity in the absence of yield class information

5   Data adapted from Tipper R., de Jong B., Ochoa-Gaona S., Soto-Pinto M., Castillo-Santiago M., Montoya-Gomez G. and March-Mifsut I. (1999) Assessment of the cost of large scale forestry for CO2 sequestration: evidence from Chiapas, Mexico. IEA Greenhouse Gas R&D Programme.

6   de Jong unpublished data

7   Montoya G., Soto L., de Jong B., Nelson K., Farias P., Taylor J. and Tipper R. (1995) Desarrollo forestall sustenable: captura de carbono en las zones tzeltal y tojolabal del estado de Chiapas. Cuadernos de Trabajo 4, Instituto Nacional de Ecología, Mexico.

8   Cibrian 1995.

14
CASE 4: RESTORATION OF DEGRADED PINE-OAK WOODLAND IN CHIAPAS, MEXICO THROUGH ENRICHMENT PLANTING WITH *PINUS OOCARPA*

14.1 Introduction

This case is based on a system used in the central highlands of Chiapas, Mexico. It involves the management of secondary pine/oak vegetation for the production of timber, fuelwood and other products through enrichment planting with *Pinus oocarpa* and liberation thinning to encourage the growth of naturally regenerating oak (*Quercus* sp).

Pinus oocarpa produces good quality timber. There is a ready market for both round and sawn wood, and it is also used locally for house construction. Oak trees of good form can produce a high value timber and it is also the preferred species for fuelwood. Other species present are used for various purposes including poles, stakes, fruits and flowers. Regenerating pine/oak forest has a high biodiversity value due to the variety of tree species and other flora and fauna present. Soil conservation is improved on steep slopes.

14.2 Ecology[1,2,3,4]

Pine-oak forest occurs naturally in temperate to sub-tropical mountain regions of Central America. The composition of pine-oak forests is extremely varied and different mixtures of at least 5 species of oak, the most common, and economically important of which are *Q. segouiensis* (roble) and *Q. crispipilis* (chicinb), and 4 species of pine occur in different locations in the highlands of southern Mexico. Well-preserved areas of forest are noted for their diverse flora and fauna, including bromeliads, orchids and hummingbirds. However, these highland areas are among the most densely populated regions of Central America and the composition and structure of these forests are heavily influenced by human activities, such as slash and burn agriculture, timber harvesting browsing by sheep and goats and the collection of firewood. In many cases the forests have been severely degraded, such that only scrubby vegetation remains.

Pinus oocarpa is one of the native pine species of the region. It occurs over a wide range of altitude, 250-2500 m, and rainfall, 700-3000 mm/yr. It grows best between 700 and 2000 m and with 1200-2000 mm rain/yr on free draining soils[1] and will tolerate shallow or infertile soils and steep slopes. The mean annual temperature in its natural range is 13-21ºC with a mean range of 8-32ºC from the hottest to coldest month.

Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

14.3 Management Operations

Typical management operations are described in the following subsections.

14.3.1 Establishment

Planting lines at 2 m widths are cleared through the existing secondary vegetation to reduce competition for light. It is recommended to cut these lines on an east-west axis to maximize the available sunlight. The planting lines are cleared of all herbaceous and shrubby vegetation and all overhanging branches are cut back; planting lines may be diverted around larger trees to save labor.

Holes are dug for seedlings (30cm depth and 30cm diameter) – large holes produce better conditions for root development. Seedlings are planted at a density between 5-700 stems /ha (7x2 to 7x3m). The roots of seedlings are pruned just prior to planting to help root development. It is important to obtain good quality planting stock, which should be ready for planting at the beginning of the rainy season.

14.3.2 Maintenance

Weeding is carried out twice per year until canopy closure. Pruning is carried out when necessary to prevent forking and to reduce lateral branching. Planting lines are maintained clear of overhanging branches until the pine trees reach the height of surrounding secondary vegetation.

14.3.3 Harvesting

The harvest takes place in year 30-35 when the trees have a diameter of 40cm.

14.3.4 Re-establishment

Two methods of re-establishment may be used in subsequent rotations:

1. Shelterwood: 25 to 30 trees per ha (approx. 20x20 m) may be retained as seed trees when the main crop is felled to provide seed for the new crop. Regeneration should be maintained by regular weeding.

2. Re-establishment through the taungya system. An increase in soil fertility may make the plot suitable for replanting with pine seedlings combined with cultivation of maize for the first 3-4 years.

14.4 Classification of Productivity

In Table 14-1, productivity is classified according to climatic and soil conditions[1]; site productivity is classified by soil characteristics (under development) and the production of maize[5].

Table 14-1
Productivity classes for Pinus Oocarpa in Chiapas, Mexico

Productivity	Conditions	Production
High	Altitude: 700 - 2000 m Rainfall: 1500 - 2000 mm Soil: Well-drained sandy loams, >30cm depth	320 m^3 30 y
Medium	Altitude: 700 - 2000 m Rainfall: 1200 - 1500 mm Soil: Intermediate	280 m^3 35 y
Low	Altitude: <700 or >2000 m Rainfall: <1200 mm/y Soil: Impermeable clays or stony <20cm depth	220 m^3 35 y

14.5 Carbon Sequestration Potential

14.5.1 Baseline

Since the condition of the forest resource at the start of a project will vary from place to place it is important to assess the baseline carbon storage at each site. Table 14-2 provides a rapid method for estimating baseline carbon density at year 0.

Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

Table 14-2
Components of baseline carbon stock (tC)

Vegetation	None <10% cover	Few 10-20% cover	Moderate 20-60% cover	Abundant >60% cover
Herbs	0	0.4	1.2	2.0
Shrubs	0	0.8	2.4	4.0
Small trees 1-5m	0	1.4	4.2	12.0
Medium trees 5-10m	0	2.4	7.2	20.0
Large trees 10-20m	0.8 tC per tree			
Very large trees >20m	2.5 tC per tree			

For the purposes of this study the baseline vegetation carbon content was assumed to be 20.6 tC/ha.

Since most semi-degraded pine-oak forests in the central highlands of Chiapas are in a process of gradual deterioration, it is reasonable to expect further loss of biomass in the baseline scenario, of at least 1 percent per year. This rate of loss could be exceeded in areas where there is a high level of population pressure and ease of access. However, it is recommended that rates of loss of carbon stocks in excess of 1 percent per year should be substantiated using an objectively verifiable methodology such as a regional risk matrix model (RRM) as discussed for Case 7 (avoidance of deforestation).

14.5.2 Carbon Uptake by the Regenerating Forest

Following the first 4 years of establishment, the system will accumulate carbon at 5 to 12 tC ha^{-1} y^{-1} during most of the 30-35 year rotation. Carbon storage for different productivity classes will be approximately as shown in Table 14-3:

Table 14-3
Expected carbon storage from Pine-Oak forest enriched with *Pinus Oocarpa* over 100 years

Productivity	Low	Medium	High
Rotation length (years)	35	35	30
Maximum above ground carbon (tC ha^{-1})	73	98	112
Average above-ground carbon (tC ha^{-1})	44	61	67
Average soil etc. carbon (tC ha^{-1})	99	114	121

14.6 Costs:

14.6.1 Establishment and Maintenance

The cost of initial establishment has been estimated at $290 per hectare followed by annual maintenance costs of around $60 per year for a further 6 to 8 years, depending on the state of the vegetation into which the pine is introduced. From then on any maintenance costs are likely to be covered by the value of fuelwood, fenceposts and other minor forest products.

14.6.2 Land

The net present opportunity cost of land associated with this system is generally near to zero, since the alternative use would be marginal grazing on the degraded forest with perhaps the occasional crop of maize in patches of bare ground. A conservatively low value of $200/ha was chosen for this study.

14.6.3 Potential Income

300 m^3 of pine timber/ha could be produced, at a price of $30/m^3, giving a total income of $9000 /ha at end of rotation plus additional benefits from fuelwood and other products. The volume of timber is estimated from the average reported yield[2].

14.7 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Pine oak is presented in Table 14-4. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 14-5. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 14-5 for the medium productivity case. For the low productivity case, the timber yield at the end of the rotation is 220 m^3/ha, time between harvest is 35 years, and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the low productivity case on several accounting bases in Table 14-6. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 14-6 for the high productivity case. For the high productivity case, the timber yield at the end of the rotation is 320 m^3/ha, time between harvest is 30 years, and other input variables are the same as for the medium productivity case. Costs of CO_2 sink enhancement ($/tonne C) are presented for the high productivity case on several accounting bases in Table 14-7. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 14-7 for the high productivity case.

Costs in Tables 14-5 to 14-7 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis. The same establishment, land, maintenance, and harvesting costs were assumed for medium, low, and high productivity cases in Tables 14-5 to 14-7. This assumption likely resulted in a slight overestimation of costs for the low productivity case and a

Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

slight underestimation of costs for the high productivity case but the general comparison is still considered valid.

Table 14-4
Forestry input variables for Pine-Oak

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
○ Plantation, USA, Douglas Fir
○ Plantation (Taungya), Mexico, Spanish cedar
◉ Restoration, Mexico, Pine-oak
○ Restoration, Southern Africa, Miombo
○ Agro- forestry, Southern India, Mango- tamarind
○ Avoidance of deforestation, Mexico, Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Restoration*
Country:	*Mexico*
Trees:	*Pine-oak*

Establishment cost ($/ha)	**292**
Land cost ($/ha)	**200**
Annual maintenance ($/ha)	**60**
Maintenance (years)	**7**

Timber revenue ($/m^3)	**30**

Timber yield (m^3/ha) :		Time Between Harvests (yrs)
End of rotation	280	35
Thinning 1		
Thinning 2		

Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

Table 14-5
Forestry summary of results for Pine-Oak medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

	Management:	*Restoration*
	Country/Region:	*Mexico*
	Trees:	*Pine-oak*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	20.47
Above & below ground carbon	12.68
Above & below ground & timber product carbon	12.20
Above & below ground carbon & non-CO$_2$ GHGs	13.03
Above ground carbon with timber revenues	3.54
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	2.17

* C Equivalent LC GHG Avoided Basis
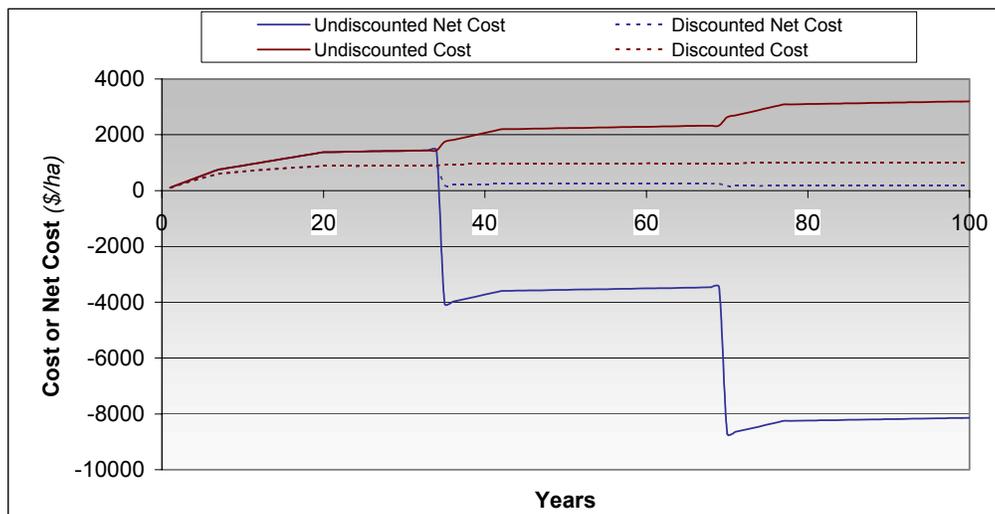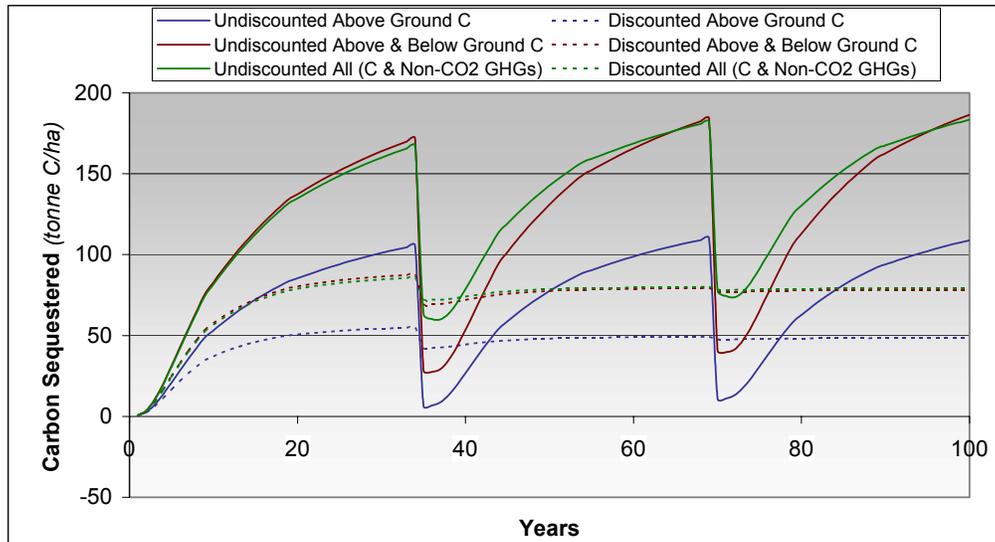
Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

Table 14-6
Forestry summary of results for Pine-Oak low productivity case

Forestry: Summary of Results *(Single System)*
Low Productivity

CO_2 Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Restoration*
Country/Region:	*Mexico*
Trees:	*Pine-oak*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	29.06
Above & below ground carbon	18.32
Above & below ground & timber product carbon	17.55
Above & below ground carbon & non-CO_2 GHGs	19.07
Above ground carbon with timber revenues	9.68
Above & below ground carbon, non-CO_2 GHGs, with timber products & revenues (*All*)*	6.07

* C Equivalent LC GHG Avoided Basis
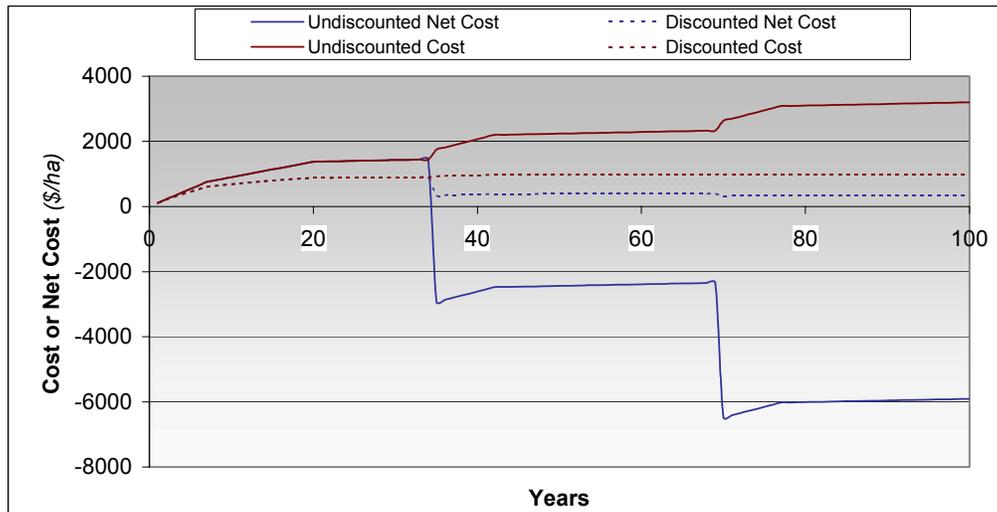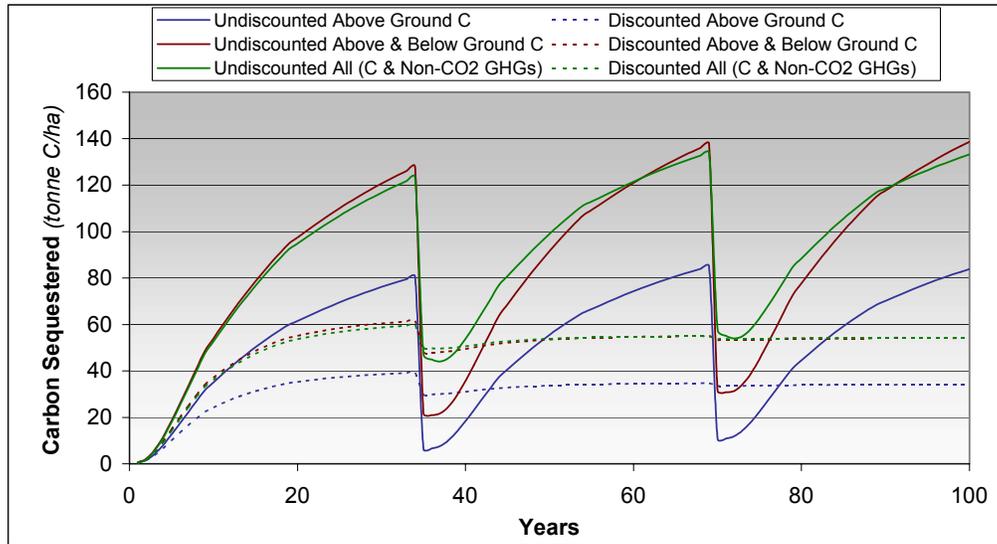
14-8

Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

Table 14-7
Forestry summary of results for Pine-Oak high productivity case

Forestry: Summary of Results *(Single System)*
High Productivity

CO_2 Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Restoration*
Country/Region:	*Mexico*
Trees:	*Pine-oak*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	17.77
Above & below ground carbon	10.86
Above & below ground & timber product carbon	10.33
Above & below ground carbon & non-CO_2 GHGs	11.11
Above ground carbon with timber revenues	(5.00)
Above & below ground carbon, non-CO_2 GHGs, with timber products & revenues (*All*)*	(2.97)

* C Equivalent LC GHG Avoided Basis
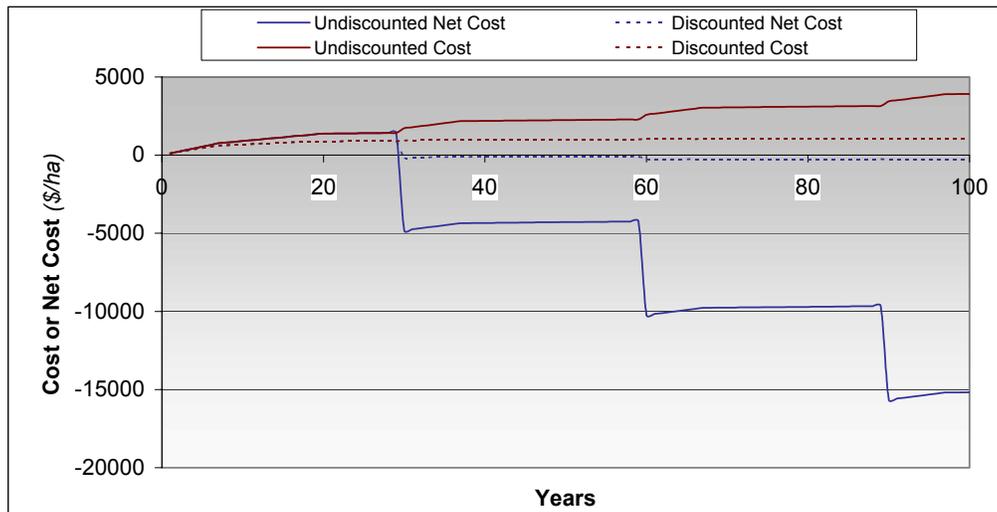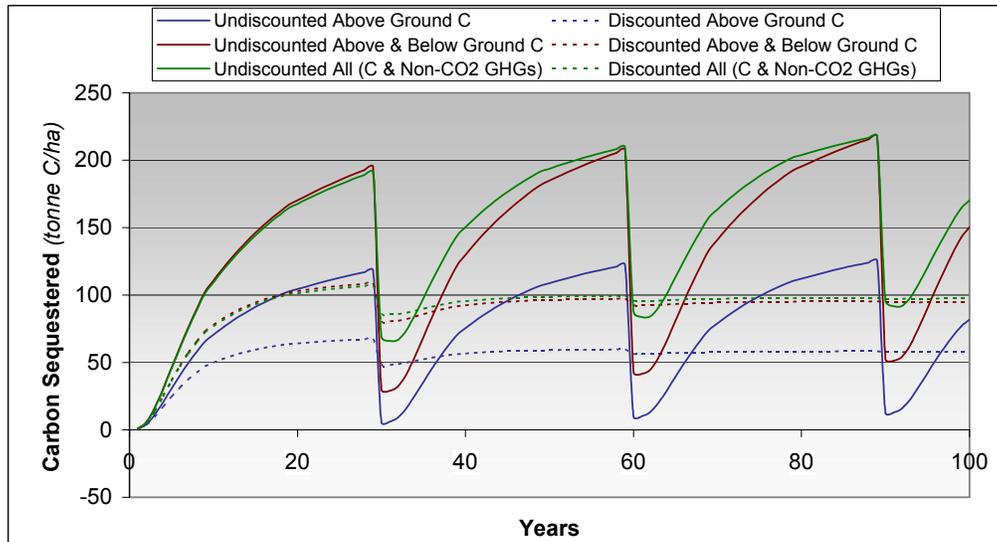
Case 4: Restoration of Degraded Pine-Oak Woodland in Chiapas, Mexico Through Enrichment Planting With Pinus oocarpa

14.8 References

Some of these references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

1   Greaves A. (1982) Pinus oocarpa. [Review Article]. Forestry Abstracts 43(9) 503-526

2   Webb D.B., Wood P.J., Smith J.P. and Henman G.S. (1984) *A Guide to Species Selection for Tropical and Subtropical Plantations*. Tropical Forestry Paper 15, Oxford, UK

3   CABI Forestry Compendium

4   Hellier A., Newton A.C., Ovhoa Gaona S. (1999) Use of indigenous knowledge for rapidly assessing trends in biodiversity: a case study from Chiapas, Mexico. *Biodiversity and Conservation* 8: 869-889

5   ECCM technical note for classifying productivity in the absence of yield class information.

6   de Jong per. comm.

7   Montoya G., Soto L., de Jong B., Nelson K., Farias P., Taylor J. and Tipper R. (1995) Desarrollo forestall sustenable: captura de carbono en las zones tzeltal y tojolabal del estado de Chiapas. Cuadernos de Trabajo 4, Instituto Nacional de Ecología, Mexico

15
CASE 5: RESTORATION OF DEGRADED DRY MIOMBO WOODLAND IN SOUTHERN AFRICA

15.1 Introduction

Miombo woodland is found in central, southern and eastern Africa, and is typified by the dominance of the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia*. It is an ecologically and economically important ecosystem, providing a valuable source of timber, fuelwood and game for a population of around 40 million people. Large areas of miombo have been seriously degraded due to extraction of precious hardwoods, fuelwood and charcoal. The degradation of miombo woodland causes severe problems for local populations, for erosion control and maintaining water quality. Restoration through enrichment planting with native species combined with the development of sustainable agroforestry could provide a sustainable resource for local communities and prevent degradation of the environment, as well as provide carbon sequestration benefits. In many cases restoration of miombo woodlands will be part of a larger community-based program for agricultural and environmental improvement.

15.2 Ecology

Miombo is the term used to describe woodlands of the south subhumid tropical zone in Africa, which are distinguished by the dominance of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia*. Miombo occurs across approximately 2.8 million km^2 in Southern Africa and contains over 8000 species of higher plants. Mean annual rainfall within its range is between 710-1365 mm with mean temperatures of 18-23°C. In most areas, 95 percent of the rainfall occurs in a 5-7 month wet-season. Soils are generally nutrient poor and acidic with low organic matter (<3 percent). In more nutrient rich area or areas with higher rainfall and deeper soils, miombo woodland grades into other vegetation types. It is thought that the presence of root ecto-mycorrhizae possessed by miombo species may allow them to exploit the porous and infertile soils. Dry miombo woodland occurs in areas with <1000 mm annual rainfall, such as central and northern Mozambique. Dry miombo is less floristically diverse than wet miombo and has a lower biomass.

15.3 Management Operations

Typical management operations are described in the following subsections.

Case 5: Restoration of Degraded Dry Miombo Woodland in Southern Africa

15.3.1 Establishment

Establishment involves planting of nursery-grown seedlings consisting of a mosaic of species, possibly supplemented by natural regeneration. Species include *Brachystegia spiciformis, Julbernadia globiflora, Millettia stuhlmanii, Pterocarpus angolensis, Dhalbergia melanoxylon, Afzelia quanzensis, Acacia nigrenscens, Swatzia madascariensis, Combretum imberbe, Khaya nyassicca, Albizzia veriscolour, Erthrophleoum* suavolens and others. Land is game-fenced and firebreaks established. Planting of pioneer species in the initial stages allows quick establishment of the woodland.

15.3.2 Maintenance

Fire is an important factor in miombo woodland. Control of fire, particularly of anthropogenic origin for hunting or to create new grazing areas, will be an important part of management for carbon. Control of herbivores, including damage by elephants, is also important.

15.3.3 Harvesting

Thinnings take place firstly in years 5-7 to produces poles for traditional housing as well as fuelwood. Sustainable timber extraction occurs with harvests of around 30m^3/ha over a 30 year period.

15.3.4 Re-establishment

Natural regeneration of small areas is considered suitable, with planting of nursery-grown seedlings where required.

15.4 Classification of Productivity

There is little information on relative productivity of miombo woodlands though it has been found that above-ground biomass increases with increasing rainfall. Productivity can range from 55 t/ha of above ground biomass in old-growth dry miombo woodland to about 90 t/ha in mature wet miombo. As discussed above, on deeper, more nutrient rich soils, vegetation will grade into evergreen or semi-evergreen forest.

15.5 Carbon Sequestration Potential

15.5.1 Baseline

The following are the initial assumptions for existing stored carbon at the site based on ECCM information.

- Vegetation: 6 tC/ha

- Soils: 5 tC/ha (to 30 cm depth)

15.5.2 Carbon Uptake and Storage in Miombo Woodland

Expected carbon storage is shown in Table 15-1.

Table 15-1
Expected carbon storage from restoration of Miombo woodland over 100 years

Productivity	Low	Medium	High
Rotation length (years)	n.a.	Continuous cover	n.a.
Maximum above ground carbon (tC ha^{-1})	n.a.	43	n.a.
Average above-ground carbon (tC ha^{-1})	n.a.	36	n.a.
Average soil etc. carbon (tC ha^{-1})	n.a.	25	n.a.

15.6 Costs

15.6.1 Establishment and Maintenance

Establishment costs are estimated at approximately $100/ha including nursery establishment and training of local staff in forest management and timber utilisation techniques.

Maintenance costs following establishment will be very low. Activities that are carried out, including selective harvesting and hunting, will generate small net income or benefits.

15.6.2 Land

The opportunity costs of land associated with restoration of the woodland are zero, since there is no change of use and the productivity of the degraded system is virtually zero.

15.6.3 Potential Income

There is potential income from forest products manufactured from sustainable timber harvesting. While the growth rates of miombo are low (around 1 m^3 per hectare per year) some of the species produce very valuable timber (fetching between $500 and $1000/m^3 on international markets). Other major benefits of restoration of miombo woodland are reduction in soil erosion and further environmental degradation, hydrological benefits and provision of a local resource for hunting, house building and fuel.

Case 5: Restoration of Degraded Dry Miombo Woodland in Southern Africa

15.7 Additional Information

It should be noted that most rural populations in the areas where miombo woodland occurs are 90 percent dependent on fuelwood or charcoal for their energy requirements. Significant amounts of wood are exported to towns. If the current rate of miombo degradation and deforestation continues then both urban and rural populations will become dependent upon fossil fuels (typically kerosene) for domestic energy. The CO_2 benefits of avoiding future dependence on fossil fuels have not been included in this study.

15.8 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Miombo is presented in Table 15-2. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 15-3. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 15-3 for the medium productivity case. Data were unavailable for low and high productivity cases for Miombo.

Costs in Table 15-3 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis.

Table 15-2
Forestry input variables for Miombo

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
○ Plantation, USA, Douglas Fir
○ Plantation (Taungya), Mexico, Spanish cedar
○ Restoration, Mexico, Pine-oak
◉ Restoration, Southern Africa, Miombo
○ Agro- forestry, Southern India, Mango- tamarind
○ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Restoration*
Country:	*Southern Africa*
Trees:	*Miombo*

Establishment cost ($/ha)	**100**
Land cost ($/ha)	**0**
Annual maintenance ($/ha)	**40**
Maintenance (years)	**4**
Timber revenue ($/m^3)	**500**

Annually after

Timber yield (m^3/ha) :   Year
 End of rotation
  Thinning 1   1   15
  Thinning 2

Case 5: Restoration of Degraded Dry Miombo Woodland in Southern Africa

Table 15-3
Forestry summary of results for Miombo medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Restoration*
Country/Region:	*Southern Africa*
Trees:	*Miombo*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	22.98
Above & below ground carbon	13.33
Above & below ground & timber product carbon	13.02
Above & below ground carbon & non-CO$_2$ GHGs	14.62
Above ground carbon with timber revenues	(139.74)
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	(86.65)

* C Equivalent LC GHG Avoided Basis
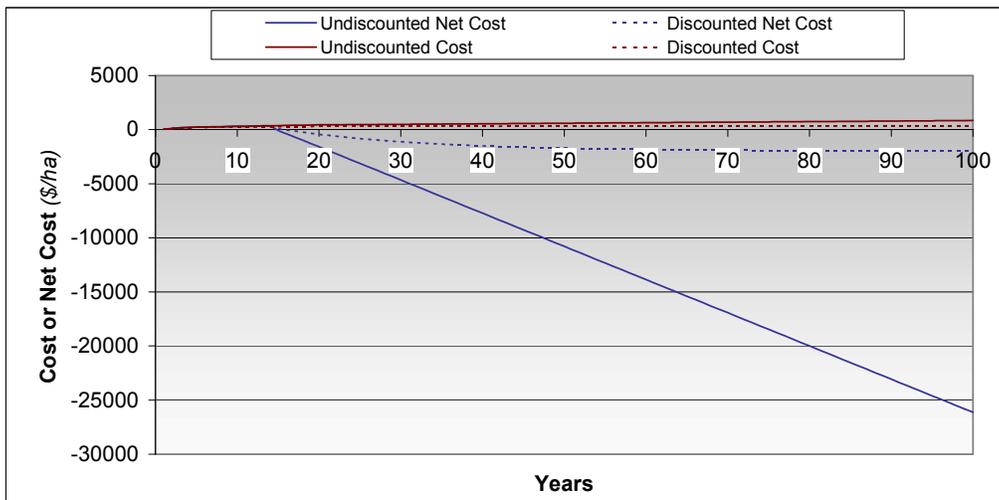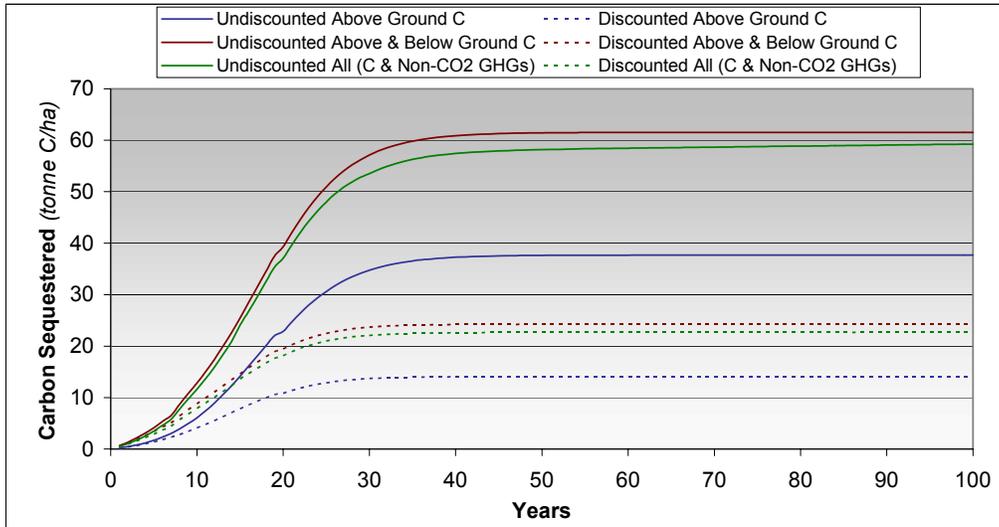
15.9 References

These references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

1   Campbell, B. 1996. *The Miombo in Transition: Woodlands and Welfare in Africa.* Centre for International Forestry Research (CIFOR), Bogor, Indonesia.

2   Desanker, P.V. Frost, P.G.H., Frost, C.O., Justice, C.O. and Scholes, R.J. 1997. *The Miombo Network: Framework for a Terrestrial Transect Study of Land-Use and Land-Cover Change in the Miombo Ecosystems of Central Africa.* IGBP Report 41. The Interational Geosphere-Biosphere Programme (IGBP), Stockholm, Sweden.

3   McGhee, W. personal communication.

4   Schwartz, A. personal communication.

5   White, F. 1983. *The Vegetation of Africa.* Unesco, Switzerland

16

CASE 6: AGRO-FORESTRY: MANGO AND NATIVE FRUIT ORCHARDS IN SEMI-ARID AREAS OF SOUTHERN INDIA

16.1 Introduction

Agroforestry is the combination of tree growing and crop and livestock production within the same farming system, such that the total output is greater than could be achieved by the implementation of a single component. In the extensive dry-land areas of southern India, such as North Kolar District, Karnataka, agro-forestry is a suitable system of land management. Small farmers can grow fruit trees and fast growing fuel wood species as wind breaks on water collection bunds. Depending on the soil type, soil depth, water availability for the particular plot, and management capability of the farming family, various fruit trees may be introduced to supplement income and nutrition. This case involves agro-forestry: Mango and native fruit orchards (Tamarind, Jackfruit, Jamun, Pongemia) in semi-arid areas of southern India

16.2 Ecology

Trees are selected on the basis of multiple attributes, including their contribution to water conservation, soil fertility, fruit quality, fuelwood production and shade effect. Native fruit orchards are a viable option for areas such as the Kolar district of Karnataka in southern India (600-1200 masl), where rainfall is highly seasonal, with 80 percent of the annual rainfall of 800 to 1200 mm falling in a 2-3 month period and where temperatures range from 10ºC to 45ºC. Local varieties of Mango and Tamarind are likely to be the main components of the orchards. Other trees such as Jack Fruit, Jamun, Pongemia, Neem, and *Acacia auriculiformis* may also be introduced as windbreak trees for fuelwood, timber and fodder for browsing by small livestock. Intercropping with groundnuts or beans is carried out for the first 12 years. These species fit well with the existing farming systems, where water management is critical. Villages are encouraged to dig ponds and bunds (low mounds and ditches) for catching the 4 - 5 annual flash floods which bring up to half the annual rainfall on their plots. Once the ponds dry out, farmers become dependent upon bore-wells for water to irrigate their plots. Tree orchards help to reduce the runoff and peak stream flows after sudden downpours and the deep root systems that do not compete strongly with the staple crops, they also provide out-of-season income from fruits that keep families going in the lean months.

Timber extraction and charcoal production have ruined many of the old Tamarind stands in the Kolar district. Farm trees are often in poor form due to indiscriminate lopping for fuelwood but good examples of individual Mango trees and Tamarind "toops" (stands) may still be found.

Case 6: Agro-forestry: Mango and Native Fruit Orchards in Semi-Arid Areas of Southern India

16.3 Classification of Productivity

Shown in Table 16-1 are the important parameters for productivity for the chosen species:

Table 16-1
Productivity factors for mixed orchards of Tamarind and Mango

Productivity	Conditions	Production (mango fruit)
High	600-1200m; deep, well-drained loamy soil, good sub-soil ; temp 10-38ºC, rainfall >1000mm/y, with good rains from June to September followed by a more or less dry spell. The quantum of rainfall is not as important as its distribution.	10 t ha^{-1} (5 y) 20 t ha^{-1} (10 y) 30 t ha^{-1} (20 y)
Medium	Intermediate	8 t ha^{-1} (5 y) 15 t ha^{-1} (10 y) 25 t ha^{-1} (20 y)
Low	Stony soils with temperatures exceeding 40ºC for prolonged periods, rainfall during flowering and fruit-setting (February – April).	5 t ha^{-1} (5 y) 10 t ha^{-1} (10 y) 15 t ha^{-1} (20 y)

16.4 Management Operations

Typical management operations are described in the following subsections.

16.4.1 Establishment

Planting pits are dug and filled with red earth, sand and manure. Irrigation channels are dug and wind-breaks should have been planted one or two years before. Irrigation, training, hoeing, weeding and staking to protect against high winds have to be carried out at regular intervals. Grafted plants are kept free of branching up to at least 75cm height, with as little pruning as possible being done. Inter-cultivation is necessary to control Mango mealy bug in November and December. Mangos grow well even in poor soils due to their deep root system but during the non-bearing period, N P K fertiliser should be applied.

Between the trees in the centre of the plot, legumes, millet and groundnuts are planted in rows up to the 12th year. Thereafter inter-cropping will probably cease. As Tamarind does not allow such annual crops to come up under its shade, Tamarind is placed at the edge and the corners of the field. The suitable hybrid varieties of Mango are Ratnagiri Alfonso, Benisha, H 13, and Mallika. Suitable Hybrid Tamarind varieties are Urigam, and local Red Tamarind varieties. The Jack Fruit and Jamun trees are placed suitably in the centre of a hexagon of Mangos, and the Old

Variety Mangos are planted on the bund between the Neem and Pongemia and left to grow to their natural massive height.

220 Mango trees, 20 Tamarind trees, 20 Jack Fruit, 20 Jamun and 20 old variety Mango are planted per hectare. Pongemia, Neem, and Acacia Auriculiformis are planted as windbreak trees for fuel and fodder at 2.5 m spacing in 2 rows along the bunds.

16.4.2 Harvesting/Replanting

The trees are replaced in the following cycles:

Mango grafted	100% every 40 years
Tamarind	100% every 40 years
Jack	100% every 80 years
Jamun	100% every 30 years
Old Variety Mango	100 years +

Neem, Pongemia and *Acacia Auriculiformis* will be coppiced for fuel wood, and the leaves and twigs cut for mulch.

16.5 Carbon Sequestration Potential

16.5.1 Baseline

The baseline vegetation for most new orchards will be a sparse covering of shrubs and small trees. Estimated above-ground carbon density is around 8 tC ha^{-1}. Soil carbon is estimated to be 20 tC ha^{-1}.

16.5.2 Carbon Uptake and Storage by Orchards

Carbon uptake by the vegetation is constrained by the availability of moisture during much of the year and while groves of old Tamarind trees have been estimated to contain over 300 tC ha^{-1} based on data from the Centre of Ecological Science[4].

Mean carbon storage figures for sites of different productivity levels are not yet available. However, it is estimated that the typical carbon storage over 100 years from establishment will be as shown in Table 16-2.

Case 6: Agro-forestry: Mango and Native Fruit Orchards in Semi-Arid Areas of Southern India

Table 16-2
Expected carbon storage from Mango-Tamarind agro-forestry over 100 y

Productivity	Low	Medium	High
Rotation length (years)	n.a.	Continuous cover	n.a.
Maximum above ground carbon (tC ha^{-1})	n.a.	60	n.a.
Average above-ground carbon (tC ha^{-1})	n.a.	33	n.a.
Average soil etc. carbon (tC ha^{-1})	n.a.	33	n.a.

16.6 Costs

16.6.1 Establishment and Maintenance

It is estimated that the costs of establishment are between $100 and $300 per hectare in the first year.

In addition to the establishment, the mango-tamarind orchard will require considerable labor input, for watering and weed control during the establishment phase. The actual cost will depend upon the water requirement of the growing seedlings and the availability / proximity of a reliable water supply. For sites where there is an existing network of bunds, and water retention facilities, the maintenance costs during the first 5 years will be $100 to $150 per hectare per year, depending on the availability of labor and inputs. In much of southern India the price of farm labor is extremely low – less than $1 per day.

Where the construction of water tanks, boreholes or other water retaining features are required the initial establishment costs could be significantly higher - in the order of $1000 per hectare per year during the first 5 years. However, for the farmers / communities this investment will also see a considerable increase in the value of the land.

16.6.2 Land

The main alternative land use will be cultivation for groundnuts. Yields are sporadic, depending upon the rainfall and the returns per hectare will range from almost zero to $150/year. On improved land (with bunds for water retention and fertiliser input) the returns will be higher. An annual opportunity cost of $60 to $120 per hectare was selected. This corresponds to a land cost of about $900 per hectare (ten times the average opportunity cost) at establishment.

16.6.3 Potential Income

The system is managed primarily for fruit, with mango being the main cash crop. A mixed orchard will produce $200 to $600 per hectare depending on age, productivity class and the

mixture of species. Inter-cropped legumes and groundnuts are also harvested for the first 10 years, or so. Fuelwood, fodder, and some fence-posts are assumed not to make a substantial difference to the total standing biomass or the carbon flows of the plot.

Other products from the orchards will include fodder from the leaves of Neem and cooking oils for Pongemia and Neem seeds.

16.7 Additional Comments

While the carbon uptake and storage potential of forestry / agroforestry systems in semi-arid conditions is relatively low, the costs of establishment and the associated benefits in terms of long term benefits to the rural economy make this an attractive option.

The carbon benefits of these systems can be further enhanced by utilising woody biomass for electricity generation. Many villages in the region referred to are dependent upon electrical or diesel pumps for extracting water from bore-wells. A number of promising examples of bio-fuelled generators and water pumps have been established.

16.8 Summary of Model Inputs and Results

A summary of input variables for the base case (medium productivity) Mango-tamarind is presented in Table 16-3. The cost of CO_2 sink enhancement (\$/tonne C) is presented on several accounting bases in Table 16-4. Cumulative changes in carbon sequestered (tonne C/ha) and costs (\$/ha) are presented below Table 16-4 for the medium productivity case. Data were unavailable for low and high productivity cases for Mango-tamarind. Costs in Table 16-4 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis.

Case 6: Agro-forestry: Mango and Native Fruit Orchards in Semi-Arid Areas of Southern India

Table 16-3
Forestry input variables for Mango-Tamarind

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
○ Plantation, USA, Douglas Fir
○ Plantation (Taungya), Mexico, Spanish cedar
○ Restoration, Mexico, Pine-oak
○ Restoration, Southern Africa, Miombo
◉ Agro- forestry, Southern India, Mango- tamarind
○ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**
Interest Rate	**5.83%**
Tax Rate	**38%**
Discount rate	**6.09%**
Transaction Costs ($/ha)	**5**
Monitoring/ verification ($/ha/y)	**5**

Management:	*Agro- forestry*
Country:	*Southern India*
Trees:	*Mango- tamarind*

Establishment cost ($/ha)	**200**
Land cost ($/ha)	**900**
Annual maintenance ($/ha)	**125**
Maintenance (years)	**5**

Timber revenue ($/m^3)   **400** $/y fruit

Timber yield (m^3/ha) :
  End of rotation
    Thinning 1
    Thinning 2

Table 16-4
Forestry summary of results for Mango-Tamarind medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

Management:	*Agro- forestry*
Country/Region:	*Southern India*
Trees:	*Mango- tamarind*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	176.93
Above & below ground carbon	129.00
Above & below ground & timber product carbon	129.00
Above & below ground carbon & non-CO$_2$ GHGs	154.10
Above ground carbon with timber revenues	(181.20)
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues *(All)**	(157.82)

* C Equivalent LC GHG Avoided Basis

16-7

Case 6: Agro-forestry: Mango and Native Fruit Orchards in Semi-Arid Areas of Southern India

16.9 References / Information Sources

Some of these references are not indicated specifically in the body of the chapter and instead represent background for the information presented in this chapter.

1   Agro-ecological information was compiled from farmers in the North Kolar District, Karnataka

2   Economics of establishment: Anandi Sharan of WSD, Bangalore

3   Management of mango plantations: Fruit Growing, J.S. Bal, Kalyani Publ., New Delhi, 1997

4   Carbon uptake estimates supplied by Dr. Nagraj of Centre of Ecological Science, Bangalore 2000

17
CASE 7: AVOIDANCE OF DEFORESTATION IN CHIAPAS, MEXICO

17.1 Introduction

Deforestation, particularly in tropical regions, is one of the largest sources of anthropogenic greenhouse gas emissions. Carbon emissions from deforestation in the tropics during the 1990s range from 1.1 to 1.7 GtC/y, with a best estimate of 1.6 GtC/y[1]. In tropical countries with large areas of remaining forest, reduction of deforestation has much greater potential climate benefits than other forestry options. Reduction of deforestation also usually produces more complementary benefits, such as maintaining biodiversity. On the other hand, quantifying the direct benefits of a program of avoiding deforestation is much more difficult than quantifying the direct effects of more discrete activities.

The rates and causes of deforestation vary by region and scale. Conversion of forests to pasture and cropland has been the most direct cause of tropical deforestation. Non-sustainable logging has been the leading factor in parts of South-east Asia, whereas excessive harvest of wood fuel has been important only in specific sub-country regions and in some African countries.

The avoidance of deforestation cases in this study are based on information from the Chiapas region of southern Mexico, although conditions are similar is many other Central and South American countries.

17.2 Ecology

Three types of forest, which account for a large proportion of the existing native forest in Chiapas, are included in this case:

- Pine-oak forest
- Moist tropical forest
- Montane cloud forest

Pine-oak forest occurs naturally in temperate to sub-tropical mountain regions. Further details are given in Chapter 14.

Moist tropical forests consist of communities that reach up to 30m high and contain a great diversity of canopy species. They occur mainly at altitudes of <500 m and rainfall of >2000 mm/y.

The canopy of the mountain forest is dominated by various species of oak and can reach up to 40m high. It occurs at altitudes of >1500 m and rainfall of >1000 mm/y.

The forests of Chiapas exhibit important characteristics in common with many regions of Latin America. The Altos or Central Highlands displays land use patterns that can be recognized in highland settings in Guatemala, Peru, Colombia and Ecuador as well as other areas of Mexico. Such areas contain established, traditionally managed agricultural systems and high population densities. The Lowland region, in common with many areas of extensive moist tropical forest in Latin America, is subject to rapid colonization, both by subsistence farmers and ranchers.

17.3 Carbon Sequestration Potential

The carbon sequestration potential depends on the expected rate of deforestation in the baseline, i.e., without any additional forest preservation measures. There are a number of issues associated with setting baselines for projects that purport to avoid emissions by preventing deforestation. The key issues are:

- How can project developers be prevented from skewing the results in their favor (overestimating the probable loss of forest)?

- How can an objective measurement of the risk of emissions be derived?

- How can we the error associated with predicted emissions be measured?

- How can a consistent methodology be applied to different projects within the same region?

In response to these questions, the Edinburgh Centre for Carbon Management (ECCM) has developed a standardized, objective method for setting baselines for deforestation prevention projects, using a risk-assessment approach, which relates the probability of future loss of terrestrial carbon to key driving factors that exist within a particular region[2]. This method, called the Regional Risk Matrix (RRM) method, produces a baseline map that allows any project within the region studied to be given an indicative figure for % loss of above-ground carbon over a specific (approx. 20 year) period into the future. A simplified version of this method is used in this study.

The RRM method consists of the following steps that were applied, to a study area of 2.8 million ha in southern Mexico by ECCM and El Colegio de la Frontera Sur:

1. A series of satellite images of the area, showing vegetation changes over a 20 year period were analyzed: around 15 types of vegetation were identified and mapped, and changes in vegetation cover over a 20 years were calculated and mapped.

2. Estimates of above-ground biomass for each vegetation type were combined with the land use change data to provide estimates of emissions over a 20-year period.

3. Maps of agricultural land use, roads and population densities were digitized for the study area and were compared with the maps of land use change.

4. A number of probability matrices describing the relationship between emissions per unit of above ground biomass and key "driving and predisposing" factors of land use change were derived.

5. These matrices were then used to drive a model of future emissions, based upon the assumption that the land use change processes remain similar. This produced a map of probable future emissions for the next 20 years.

6. The prediction errors of different matrices were measured by comparison against the map of historical emissions (the predicted map was overlain upon the historic map to give a spatially explicit measure of the errors).

Further refinement of the RRM is undertaken in iterations, involving:

7. Division and re-calibration of the matrix for sub-regions, as appropriate to reduce prediction error.

Two of the main driving factors for deforestation are the population density and the distance from a road. Figure 17-1 shows the percentage loss of above ground carbon in 2.8 million ha of Chiapas, Mexico between 1976 and 1996 and Figure 17-2 shows the population densities and distances from roads. The emissions were derived from a series of vegetation maps and biomass estimates. Total emissions during this period were approximately 140 million tC.

Case 7: Avoidance of Deforestation in Chiapas, Mexico
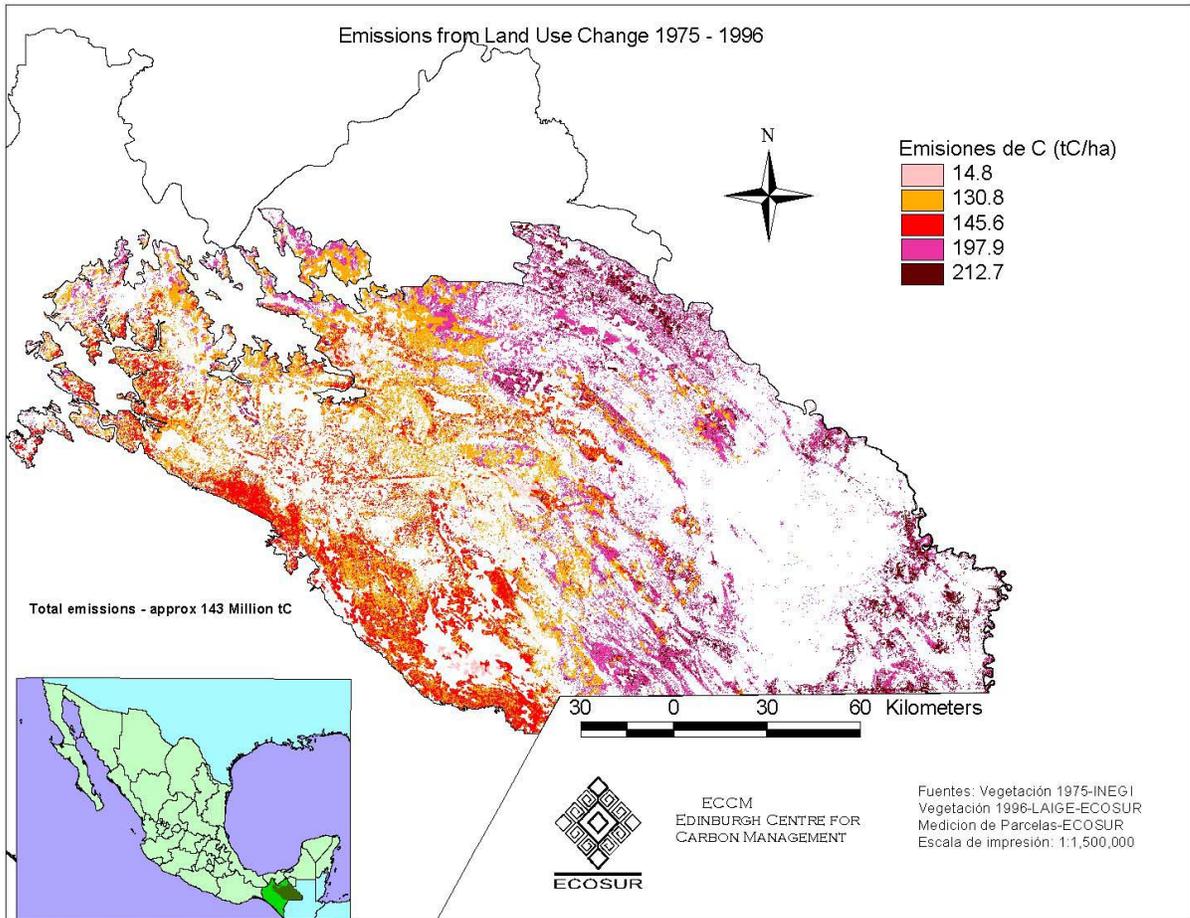
Figure 17-1
Emissions from land use change in Chiapas, Mexico, over 20 years from the mid-1970's.
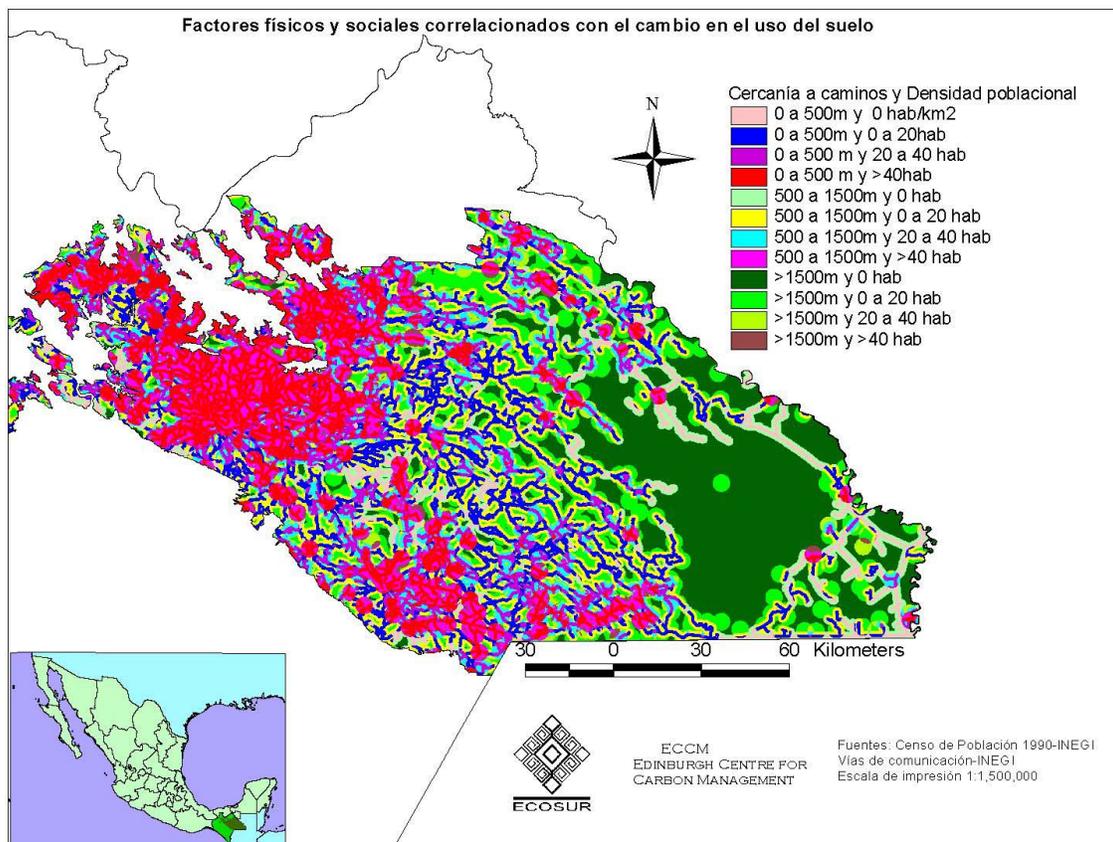
Figure 17-2
Map of two key causal factors in land-use change: Distance to roads and tracks and population density

Note that the red area to the west of the map corresponds to the densely populated central highlands and the green area to the east corresponds to the lowland tropical forests.

The relationship between the quantity of above ground carbon lost between 1976 and 1996 and population density and distance from roads and tracks is summarised in Table 17-1.

Table 17-1
Percentage of above-ground carbon lost from 1976 to 1996.

Population density	Distance to road (m)		
(person/km^2)	500	500-1500	1500
>40	63	55	41
20-40	56	46	37
0-20	46	*35*	25
0	41	28	8

Case 7: Avoidance of Deforestation in Chiapas, Mexico

Predictions of the quantities of carbon that are expected to be lost over the next 20 years for the 2.8 million ha study area are shown in Figure 17-3. The expected emissions over this period are around 90 million tC. The quantities of carbon lost range from 12 to 150 tC/ha. The current matrix models are able to provide baselines with an average site-specific error of +/- 20 percent and an aggregate error for the region as a whole of +/- 5 percent.
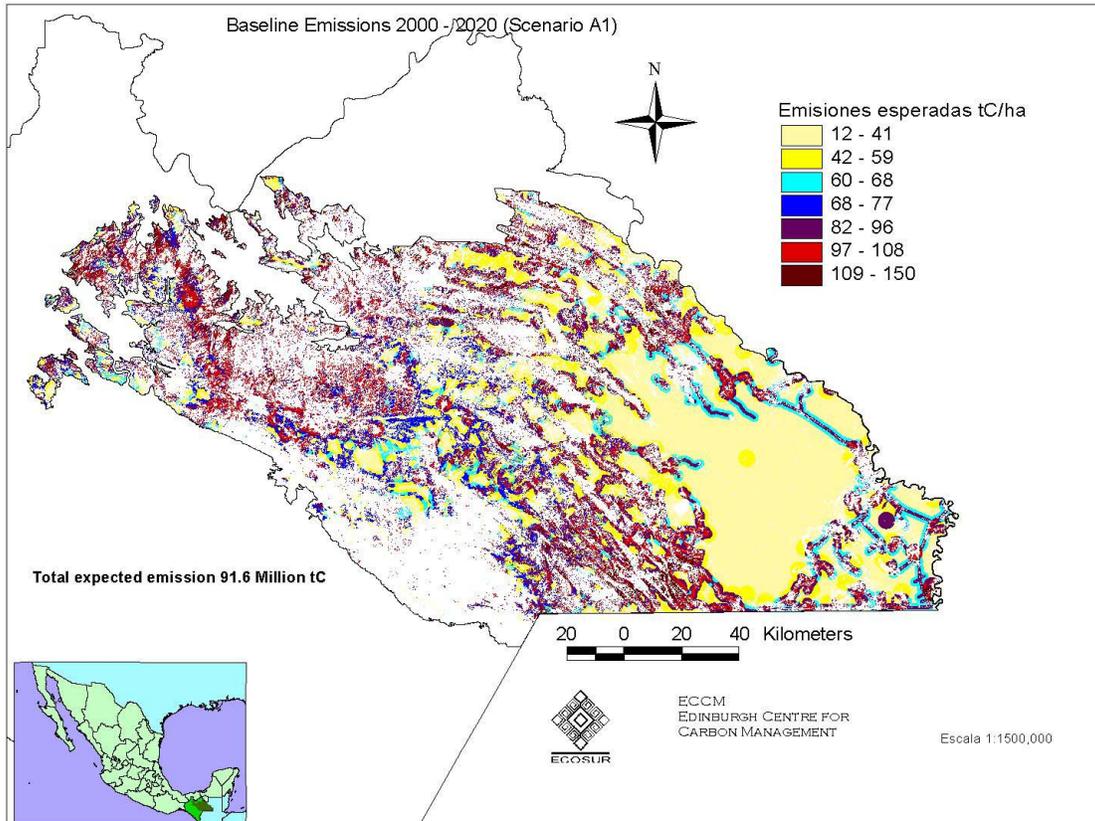
Figure 17-3
Regional baseline for 2000 to 2020, showing expected emissions tc/ha

For the purposes of this study a simplified version of the methodology derived by ECCM has been used. The rate of deforestation is assumed to depend on three factors:

- Base rate
- Vulnerability
- Pressure

Pressure is linked to the population density and vulnerability is linked to the distance to roads and tracks. Each of these parameters can be defined as low, medium or high and the model predicts an annual rate of deforestation. The predicted rates of deforestation are shown in Table 17-2

Table 17-2
Predicted annual rate of deforestation (%).

Base rate	Population pressure	Vulnerability		
		Low	**Medium**	**High**
Low	**Low**	0.39	0.6	0.84
	Medium	0.65	1.00	1.40
	High	0.84	1.30	1.82
Medium	**Low**	1.09	1.68	2.35
	Medium	1.82	2.80	3.92
	High	2.37	3.64	5.10
High	**Low**	1.37	2.10	2.94
	Medium	2.27	*3.50*	4.90
	High	2.96	4.55	6.37

The baseline quantity of carbon stored depends on the type of forest; 180 t/ha for pine-oak forest, 240 t/ha for moist tropical forest, and 350 t/ha for montane cloud forest.

For this study it is assumed that the rate of deforestation will be constant over the next 100 years but it should be recognised that over such long time spans the performances of projects that avoid deforestation are subject to greater uncertainty than afforestation projects. The benefits of afforestation projects depend on the rate of carbon accumulation, which can be predicted with reasonable accuracy provided the forest continues to be maintained. The benefits of projects that avoid deforestation depend mainly on the baseline rate of deforestation, which is very uncertain more than 20 years into the future.

17.4 Costs

17.4.1 Establishment and Maintenance

A large proportion of the forests in Chiapas are legally held by communities rather than individuals or the public sector. Any management regime needs approval and consensus at the local level if it is to succeed. The total cost of establishment, including the socio-technical costs associated with obtaining local consensus, would nevertheless be relatively low and is estimated to be $270/ha. An additional allowance of $25/ha for the first four years is also included.

17.4.2 Land Costs

Accessible pine-oak and mountain forests would have substantial opportunity costs due to the value of charcoal and bromeliads that are currently extracted at significantly higher rates than the

apparent level of sustainable yield. Some areas of the rainforests would have a relatively high opportunity costs associated with the available stocks of high value hardwoods, particularly mahogany. The annual opportunity cost is estimated to be about $300/ha.

17.4.3 Potential Income

Some products for local use such as bromeliads, firewood and tree bark could be extracted on a sustainable basis from preserved forests. As in the other cases in this study, it is assumed that these minor products for local use would not be taken into account in the economic evaluation.

17.5 Summary of Model Inputs and Results

A summary of input variables for the base case (moist tropical forest, medium vulnerability, population pressure and medium productivity) avoidance of deforestation is presented in Table 17-3. The cost of CO_2 sink enhancement ($/tonne C) is presented on several accounting bases in Table 17-4. Cumulative changes in carbon sequestered (tonne C/ha) and costs ($/ha) are presented below Table 17-4. Costs in Table 17-4 were calculated on an NPV basis as described in Chapter 2, and can be compared with costs for CO_2 capture and storage and other sink enhancement options calculated on the same NPV basis.

Table 17-3
Forestry input values for avoidance of deforestation

Forestry: Input Variables

○ Plantation, USA, Loblolly Pine
○ Plantation, USA, Douglas Fir
○ Plantation (Taungya), Mexico, Spanish cedar
○ Restoration, Mexico, Pine-oak
○ Restoration, Southern Africa, Miombo
○ Agro- forestry, Southern India, Mango- tamarind
◉ Avoidance of deforestation, Mexico,Various

Productivity	**Medium**	Base case carbon (tC/ha)	**240**
Interest Rate	**5.83%**	Annual rate of deforestation	**2.8%**
Tax Rate	**38%**		
Discount rate	**6.09%**		
Transaction Costs ($/ha)	**5**		
Monitoring/ verification ($/ha/y)	**5**		

Management: *Avoidance of deforestation*
Country: *Mexico*
Trees: *Various*

Establishment cost ($/ha)	**270**
Land cost ($/ha)	**300**
Annual maintenance ($/ha)	**25**
Maintenance (years)	**4**

Timber revenue ($/m^3)

Timber yield (m^3/ha) :
   End of rotation
     Thinning 1
     Thinning 2

Case 7: Avoidance of Deforestation in Chiapas, Mexico

Table 17-4
Forestry summary of results for Avoidance of Deforestation medium productivity case

Forestry: Summary of Results *(Single System)*
Medium Productivity

CO$_2$ Sink Enhancement, NPV Basis *(years 1-100)*

	Management:	*Avoidance of deforestation*
	Country/Region:	*Mexico*
	Trees:	*Various*

Carbon accounting basis *($/tonne C Equivalent)*

Above ground carbon	9.68
Above & below ground carbon	9.68
Above & below ground & timber product carbon	9.68
Above & below ground carbon & non-CO$_2$ GHGs	9.87
Above ground carbon with timber revenues	9.68
Above & below ground carbon, non-CO$_2$ GHGs, with timber products & revenues (*All*)*	9.87

* C Equivalent LC GHG Avoided Basis

17.6 References

1   IPCC (Intergovernmental Panel on Climate Change), Climate change 2001, the scientific basis, published by Cambridge University Press, 2001, ISBN 0 521 80767

2   Edinburgh Centre for Carbon Management, 2001, forthcoming paper.

18

ECONOMICS OF CO_2 SINK ENHANCEMENT VIA REDUCING TILLAGE ON U.S. CROPLAND—BASIS AND APPROACH

18.1 Introduction

Reducing the amount of tillage and associated improvements in residue management beyond that already achieved account for about one-half of the potential (75-208 million tonnes of carbon/year) for CO_2 sink enhancement in U.S. croplands[1]. The CO_2 sink enhancement in croplands is the result of increased carbon storage in soil organic matter. The remaining one-half of the potential for CO_2 sink enhancement on U.S. croplands is highly fragmented and beyond the scope and resources of this project.

The main purpose of the cropland component of this project is to estimate, from an energy company perspective, the cost of GHG emission offsets ($/tonne carbon equivalent GHG avoided) from reducing tillage on U.S. croplands. This involves estimating the following aspects of reducing tillage over time: (1) levels of CO_2 sink enhancement, (2) changes in GHG emissions other than from CO_2 sink enhancement (e.g., from fuel use for tillage operations and from nitrous oxide emissions), (3) adoption incentives a company would have to pay to get farmers to adopt reduced-tillage practices, (4) transaction costs for aggregating and brokering GHG credits, and (5) monitoring costs for assuring that contractual obligations are fulfilled. A second purpose of this section is to estimate the hectares of reduced-tillage required to offset specified quantities of power plant GHG emissions.

18.2 Tillage-System Definitions

Research, development, demonstration, and deployment of reduced-tillage systems has been a major agricultural initiative over roughly the last forty years. Significant levels of adoption began to occur in the 1970's. In addition to CO_2 sink enhancement, there are many benefits of reducing tillage such as fuel, labor, and equipment savings, improved soil quality, and reduced soil erosion by both water and wind[2]. Reductions in soil erosion are highly correlated with the percent of the soil surface covered by crop residues at the time of planting. For this reason, reduced-tillage systems are commonly characterized by the percent of the soil surface covered by crop residues at the time of planting and are commonly called conservation-tillage systems.

Tillage-system definitions published by the Conservation Tillage Information Center[3] are used in this report. These definitions are as follows:

Conservation Tillage Types (30 percent or more crop residue left on the soil surface after planting):

These types include any tillage and planting system that covers 30 percent or more of the soil surface with crop residue, after planting, to reduce soil erosion by water. Where soil erosion by wind is the primary concern, any system that maintains at least 1,000 pounds per acre of flat, small grain residue equivalent on the surface throughout the critical wind erosion period.

No-till/strip-till—The soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width (strips may involve only residue disturbance or may include soil disturbance). Planting or drilling is accomplished using disc openers, coulter(s), row cleaners, in-row chisels or roto-tillers. Weed control is accomplished primarily with crop protection products (herbicides). Cultivation may be used for emergency weed control. Other common terms used to describe no-till include direct seeding, slot planting, zero-till, row-till, and slot-till.

Ridge-till—The soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width. Planting is completed on the ridge and usually involves the removal of the top of the ridge. Planting is completed with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with crop protection products (frequently using banded application) and/or cultivation. Ridges are rebuilt during row cultivation.

Mulch-till—Full-width tillage involving one or more tillage trips which disturb all of the soil surface and is done prior to and/or during planting. Tillage tools such as chisels, field cultivators, disks, sweeps or blades are used. Weed control is accomplished with crop protection products and/or cultivation.

Other Tillage Types:

Reduced-till (15-30 percent residue)—Full-width tillage involving one or more tillage trips which disturb all of the soil surface and is performed prior to and/or during planting. There is 15-30 percent residue cover after planting or 500 to 1,000 pounds per acre of small grain residue equivalent throughout the critical wind erosion period. Weed control is accomplished with crop protection products and/or row cultivation.

Conventional-till or intensive-till—Full-width tillage which disturbs all of the soil surface and is performed prior to and/or during planting. There is less than 15 percent residue cover after planting, or less than 500 pounds per acre of small grain residue equivalent throughout the critical wind erosion period. Generally involves plowing or intensive (numerous) tillage trips. Weed control is accomplished with crop protection products and/or row cultivation.

The case studies reported later in this report rely heavily on county- and state-level estimates of carbon stored in soils and crop residues as affected by tillage system. These estimates have been published for Iowa[4], Indiana[5], and Nebraska[6] for intensive-till, moderate-till, and no-till systems. In these reports, moderate-till includes mulch-till and ridge-till systems and no-till systems with intermittent intensive-tillage.

18.3 Effects of Tillage-System on the Amount of Carbon Stored in Soil Organic Matter

The production of crop residues (crop stalks and roots) removes CO_2 from the atmosphere and incorporates the CO_2 into crop residues via photosynthesis (Figure 18-1). As the crop residues decompose, they release CO_2 back into the atmosphere. When crop residues decompose at a slower rate than they are added to the soil, the amount of soil organic matter increases and the amount of carbon stored in soil organic matter increases proportionally. A key effect of reducing tillage is that crop residues decompose more slowly but the amount of crop residues added to the soil remains about the same. This results in an increase in the amount of carbon stored in soil organic matter. In addition to increasing the soil organic matter of non-eroded soil, conservation-tillage systems also significantly reduce the potential for soil erosion and loss of CO_2 from eroded soil.
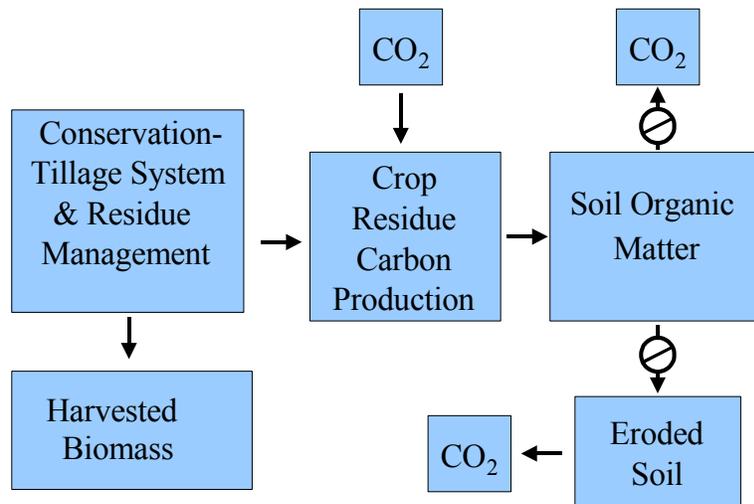
Figure 18-1
Mechanisms by which conservation-tillage systems affect the amount of carbon that remains stored in soil organic matter

Reducing tillage slows the rate of soil organic matter decomposition for several reasons[7]. One key reason is that the soil tends to be more aggregated and soil organic matter contained inside the aggregates is less exposed to soil oxygen, slowing the rate of organic matter decomposition. Another key reason is that crop residues on the soil surface reflect sunlight and result in significantly lower soil temperatures, further slowing the rate of organic matter decomposition. Also, less mixing of crop residues with the soil reduces exposure of the residues to soil moisture and nutrients required for rapid decomposition.

After switching from intensive- to conservation-tillage, the increase in soil organic matter becomes smaller each year and soil organic matter levels eventually build up to a point that the rate of organic matter decomposition equals the rate of crop residue addition. Once this new steady-state is reached, no additional carbon is stored in soil organic matter as a result of reducing tillage. An example of reaching a new steady-state level of soil organic carbon

(ΔSOCs) is illustrated in Figure 18-2. The data points for 0, 10, and 20 years are model predictions from the Iowa Carbon Storage Project[4] and the response curve is from a best-fit quadratic curve for the 1, 10, and 20-year data points. In this example, the predicted number of years (Ys) to reach the new steady-state level of SOC was 29. Results from the Iowa and Indiana Carbon Storage Projects indicate that when intensive-till systems are switched to no-till, Ys in these states will typically be between 25 and 35 years.
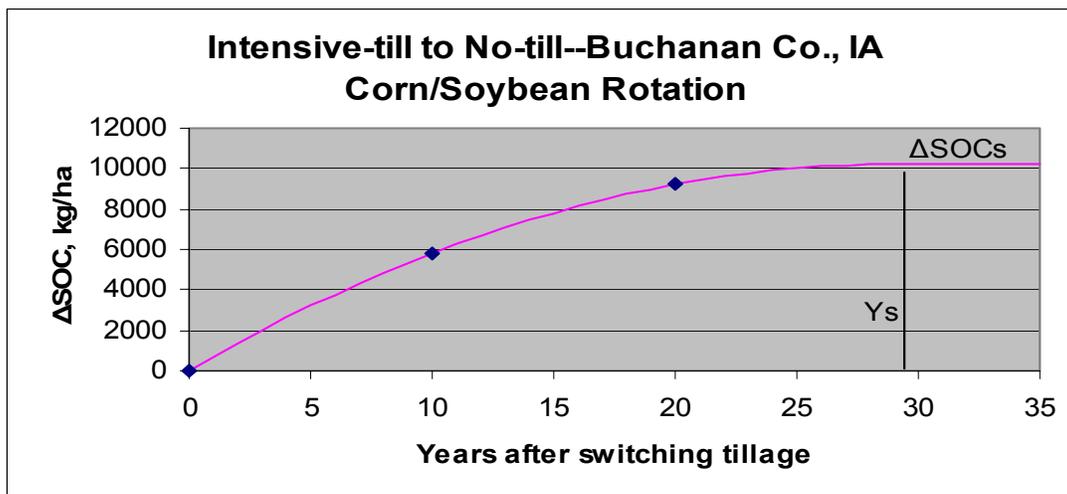
Figure 18-2
Increases in soil organic carbon (SOC) via switching from intensive-till to no-till

The native vegetation for U.S. cropland was primarily grass in the drier areas and trees in the more humid areas. Soil organic matter levels were much higher under native vegetation than they are today after several decades of cultivation. When the grasslands and forests were converted to cropland with intensive tillage systems, soil organic matter levels declined steadily until a new steady-state level was reached. The general decline in SOC for the central Corn Belt is illustrated in Figure 18-3[8]. From the early 1900's until about 1950, SOC levels declined steadily and then remained at a new steady-state level until about 1970. With the advent of conservation-tillage practices in the 1970's, the general SOC levels in the central Corn Belt began to rise. Further adoption of conservation-tillage practices will help to restore part of the SOC that existed under natural vegetation.
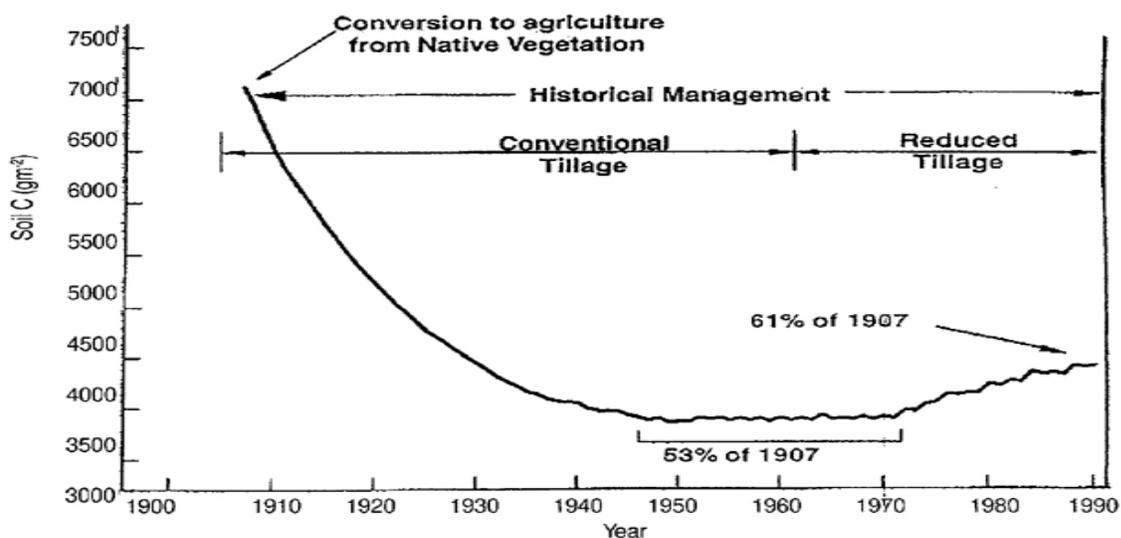
Figure 18-3
Trends in soil organic carbon (SOC) in the central corn belt

18.4 Regions With Greatest Potential for Increasing Soil Organic Carbon

Regions with the greatest potential for increasing SOC via reducing tillage are regions with large amounts of cropland and large per hectare increases in SOC as a result of reducing tillage. Counties with 20,000 or more hectares of cropland are presented in Figure 18-4[9]. These counties meet the criteria of relatively large amounts of cropland. Most of this cropland is east of the Rocky Mountains. Generally, SOC levels increase moving east from the Rocky Mountains through the Great Plains and into the Corn Belt, mainly because of increasing precipitation levels and the associated increase in crop production and amount of crop residues added to the soil[7].

Likewise, the potential per hectare increases in SOC that can occur as a result of reducing tillage will be greater moving east from the Rocky Mountains through the Great Plains and into the Corn Belt, mainly because of increasing precipitation levels and the associated increase in crop production and amount of crop residues added to the soil.
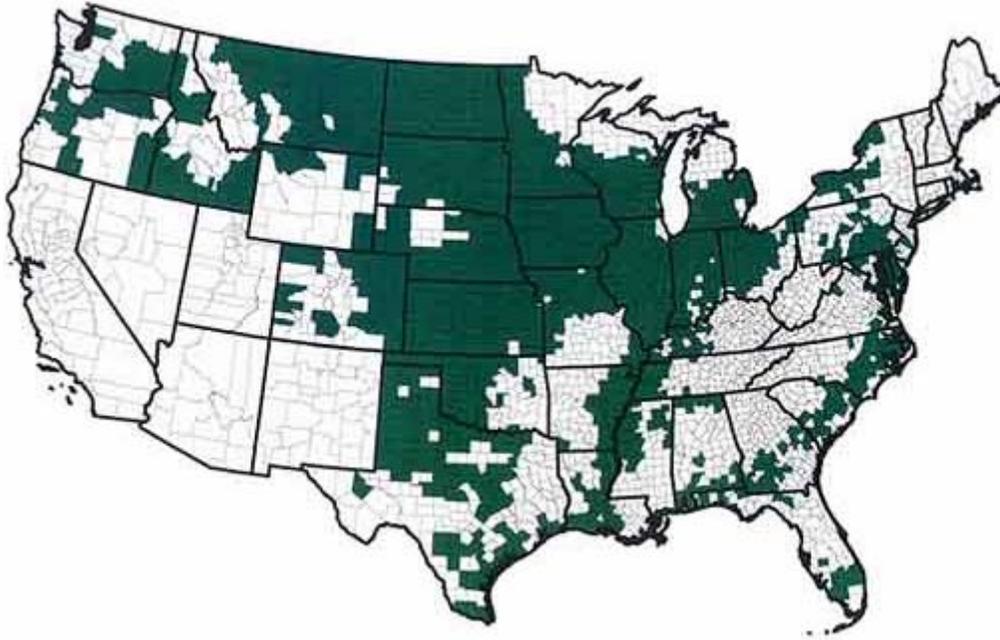
Figure 18-4
Counties with more than 20,000 hectares of cropland

The region comprising roughly the western third of the Great Plains states of North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas and counties on west to the Rocky Mountains produces predominantly dry land small grains (mainly wheat). Crop production levels and associated residue production levels in this region are severely limited by the amount of rainfall. The traditional cropping system in this region is a wheat/fallow rotation. A crop is grown every two years and the land is left fallow in the alternate years to store soil moisture for the next crop. In traditional wheat-fallow systems in this region, crop residues are added back to the soil only every other year and soil organic matter levels are continuing to decline from levels under native vegetation. Switching to no-till wheat/fallow maintains current soil organic matter levels but does not result in a significant increase in soil organic matter. These relationships are presented for an eastern Colorado location in Figure 18-5 which is based on model simulations[10]. Switching to no-till in the traditional wheat/fallow region holds promise for conserving enough additional soil moisture to enable growing two crops out of three years or three crops out of four years, in which case moderate additional increases in soil organic matter levels can be achieved over that with no-till wheat/fallow[11].
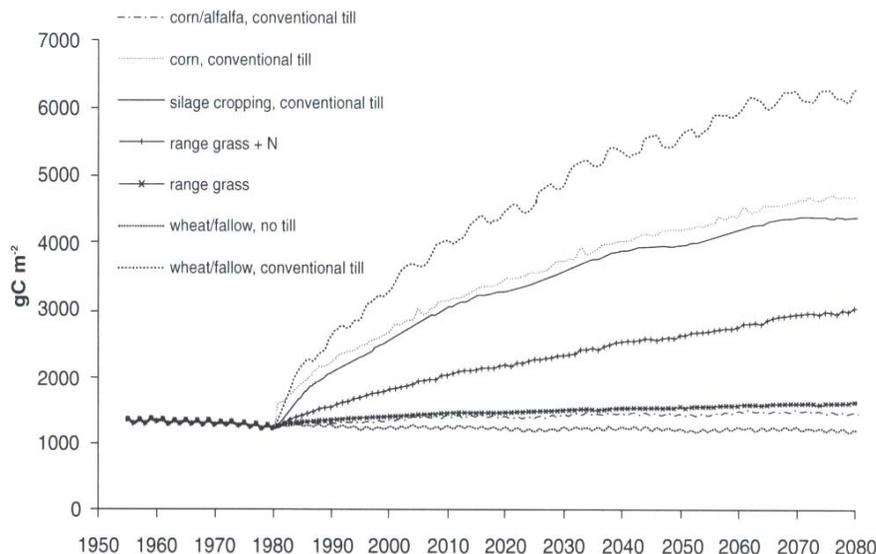
Figure 18-5
Simulated changes in soil organic carbon (SOC) as affected by tillage and cropping systems in eastern Colorado

The silage corn, corn, and corn/alfalfa curves in Figure 18-5 are for irrigated, conventionally-tilled systems in which crop production is not limited by moisture. The large increase in SOC in these cropping systems compared to the curves for dryland wheat illustrates the extremely important impact of crop productivity and crop residue production levels on SOC levels. Even greater increases in SOC could be achieved in the irrigated systems by using conservation tillage instead of conventional tillage.

Roughly the eastern two-thirds of the Great Plains states mentioned above receives enough precipitation to enable growing a crop every year. Therefore, crop residues are added to the soil each year and this region has the potential to achieve greater increases in soil organic matter via reducing tillage than does the region discussed in the previous paragraph.

The Corn Belt states of Iowa, Illinois, Indiana, Ohio, Minnesota, Wisconsin, Michigan, and Missouri receive more rainfall than the Great Plains states and produce significantly more crop residues/hectare than the Great Plains. Most of the cropland in these states is in a corn/soybean rotation. In these states, there is a slightly larger area in corn than soybeans. Most of the "excess" corn area is in continuous corn or is rotated with crops in addition to soybeans (mainly wheat). Typical increases in SOC due to switching from intensive-till to no-till at a central Indiana location are presented in Figure 18-6[10]. Based on acreage and SOC increases per hectare, Corn/soybean rotations in the Corn Belt offer the greatest potential in the United States for increasing SOC via reducing tillage.

Economics of CO2 Sink Enhancement Via Reducing Tillage on U.S. Cropland—Basis and Approach
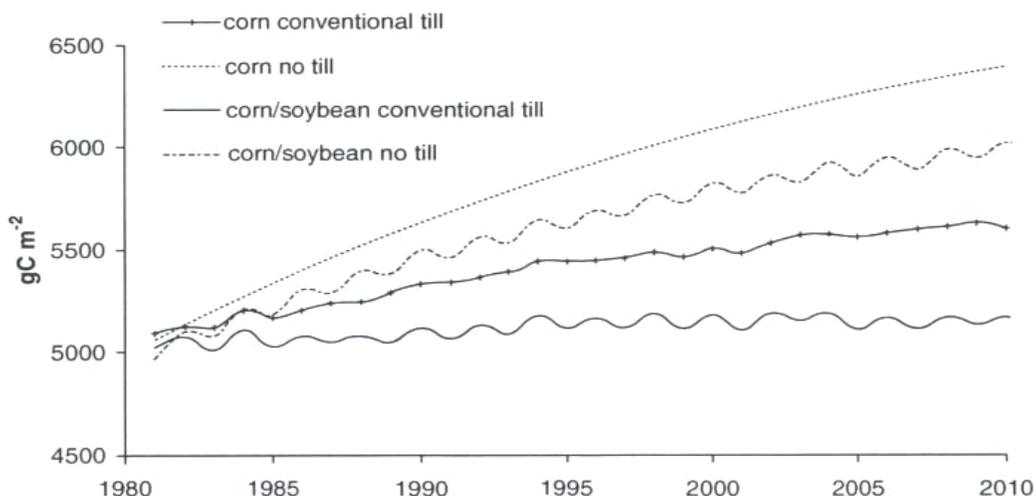
Figure 18-6
Simulated changes in soil organic carbon (SOC) as affected by tillage and cropping systems in central Indiana

Counties with more than 20,000 hectares in the Mississippi corridor to the south of the Corn Belt (Figure 18-4) also have significant potential for increasing SOC via reducing tillage. Cotton and soybeans are major crops in these counties. Crop productivity and amounts of crop residues added to the soil tend to be lower than in the Corn Belt and, due to higher temperatures, the rate of crop residue decomposition tends to be higher than in the Corn Belt. These factors result in less potential on a per hectare basis for increasing SOC via reducing tillage than occurs in the Corn Belt.

18.5 Current Levels of Conservation-Tillage Adoption

18.5.1 Corn and Soybeans in the Corn Belt

The hectares of corn and soybeans and adoption of conservation-tillage in a north-south transect in the eastern Corn Belt are presented in Table 18-1[12]. Two trends are evident in Table 18-1. First, conservation-tillage adoption levels are much higher for soybeans than corn. Adoption levels are higher for soybeans than corn mainly because soybeans are better adapted to conservation-tillage and pose less risk of reduced income to the farmer. Since almost all soybeans are rotated with corn, Table 18-1 implies that there is a significant amount of the cropland in which soybeans are in conservation-tillage and corn is in intensive tillage. For example, in Indiana, 59+15=74 percent of the full season soybeans are in conservation tillage and 21+8=29 percent of the corn is conservation-tillage. This implies that roughly 45 percent

(74-29 percent) of the land in conservation-till soybeans is not in conservation-till corn. The second trend is that conservation-tillage adoption levels increase going from north to south. One of the challenges of conservation tillage is that leaving more crop residues on the soil surface causes soils to warm and dry more slowly in the spring. This can delay planting in the spring or at least slow growth in the spring and increase the risk of yield reductions with conservation tillage. The risk reduces going from north to south as reflected by the conservation-tillage adoption levels.

Table 18-1
Adoption of conservation-tillage practices in the eastern corn belt and mid-south U.S.

			Conservation-till		Intensive-till	
			No-till	Mulch-till	15-30%	0-15%
State	Crop	M hectares	% of hectares			
MI	Corn (FS)	1.1	14	12	20	54
MI	SB (FS)	0.8	39	9	16	36
IN	Corn (FS)	2.3	21	8	19	53
IN	SB (FS)	2.2	59	15	11	15
IN	SB (DC)	0.1	80	13	2	5
KY	Corn (FS)	0.5	56	16	12	16
KY	SB (FS)	0.3	56	15	11	19
KY	SB (DC)	0.2	86	11	2	1
TN	Corn (FS)	0.2	54	11	16	19
TN	SB (FS)	0.3	50	7	18	25
TN	SB (DC)	0.1	85	5	5	5
FS=full season; DC=double crop						

The hectares of corn and soybeans and adoption of conservation-tillage in a north-south transect in the western Corn Belt are presented in Table 18-2[12]. The same trends are evident as were discussed above for Table 18-1.

Table 18-2
Adoption of conservation-tillage practices in the western corn belt

			Conservation-till		Intensive-till	
			No-till	Mulch-till	15-30%	0-15%
State	Crop	M hectares	% of hectares			
MN	Corn (FS)	2.9	2	23	1	74
MN	SB (FS)	2.8	4	42	2	51
IA	Corn (FS)	4.8	18	27	34	21
IA	SB (FS)	4.3	27	50	16	7
MO	Corn (FS)	1.1	24	11	24	41
MO	SB (FS)	1.9	37	16	17	30
MO	SB (DC)	0.2	58	9	11	21
FS=full season; DC=double crop						

18.5.2 Small Grains

Adoption of conservation-tillage practices in the major small grain producing states in year 2000 is presented in Table 18-3[12]. A majority of the small grains are still intensively tilled. In the traditional stubble-mulch wheat-fallow systems, seven or more tillage operations are performed during the fallow period between wheat crops. Sweep undercutters and rod weeders are commonly used in these systems. These implements don't invert the soil and leave more crop residues on the soil surface than disks or chisel plows, but after seven or more operations during the fallow period, less than 30 percent residue cover is left in most of the traditional wheat-fallow systems.

Table 18-3
Adoption of conservation-tillage practices in major small grain states in year 2000

			Conservation-till		Intensive-till	
			No-till	Mulch-till	15-30%	0-15%
State	Crop	M hectares	% of hectares			
WA	SSSG	0.4	17	20	34	29
	FSSG	0.8	7	19	40	34
MT	SSSG	3.4	9	34	32	25
	FSSM	0.8	15	38	32	14
ND	SSSG	5.4	10	16	28	43
	FSSG	0.6	8	10	22	60
SD	SSSG	0.8	16	15	34	35
	FSSG	0.6	19	10	42	29
NE	FSSG	0.6	7	14	18	60
KS	FSSG	4.4	6	15	25	53
CO	FSSG	1.5	4	35	28	34
OK	FSSG	2.4	5	18	25	51
TX	FSSG	2.7	3	28	26	42

SSSG=spring seeded small grains; FSSG=fall seeded small grains.

18.5.3 Cotton

Adoption of conservation-tillage practices in the major cotton producing states in year 2000 is presented in Table 18-4[12]. Until recently, adoption of conservation-tillage in cotton has been slow. With the advent of herbicide resistant cotton, adoption of no-till cotton has occurred more rapidly in some states such as Alabama and Tennessee.

Table 18-4
Adoption of conservation-p in major cotton states in year 2000

			Conservation-till		Intensive-till	
			No-till	Mulch-till	15-30%	0-15%
State	Crop	M hectares	% of hectares			
MO	Cotton	0.1	5	3	3	66
AK	Cotton	0.4	4	1	7	84
LA	Cotton	4.8	18	27	34	21
TN	Cotton	0.2	45	1	7	47
MS	Cotton	0.8	7	4	18	70
AL	Cotton	0.2	35	4	2	11
TX	Cotton	2.8	1	2	10	86

18.6 GHG Effects in Addition to Carbon Storage in Soil Organic Matter

Reducing tillage has several important effects on GHG emissions in addition to increasing the amount of carbon stored in soil organic matter. These include changes in GHG emissions from the following:

- Fuel use for field operations

- Machinery manufacturing, transportation, and repair

- Nitrogen (N) fertilizer use

- Herbicide use

- Nitrous oxide (N_2O) emissions from soil

These changes in GHG emissions due to reducing tillage continue indefinitely, even after a steady-state level of SOC has been attained. The net effect of the changes in these emissions and the increase in SOC due to reducing tillage is referred to in the case studies as avoided GHG emissions. Avoided GHG emissions will be estimated for a 100-year planning horizon. An overview of factors affecting GHG emissions by means other than carbon storage in SOM is presented below. More details are provided in the case studies.

18.6.1 Fuel Use

Reducing the number and intensity of tillage operations reduces fuel use and the associated CO_2 emitted from fuel use.

18.6.2 Machinery Required

Reducing tillage reduces the number of implements and tractors and the size of tractors required. This reduces emissions from machinery manufacture, transportation, and repair.

18.6.3 N Fertilizer Use

Reducing tillage increases the potential for N losses from the soil and for N tie-up in soil organic matter, but this potential is not necessarily realized if N is managed well. If greater N losses and/or more N tie-up do occur, more N fertilizer is required to produce a crop. Production of N fertilizer requires large quantities of fossil fuel to provide hydrogen and process energy for production of anhydrous ammonia and downstream N fertilizers such as urea and urea-ammonium nitrate solutions. Additional energy is required to store, distribute, and apply N fertilizer. Therefore, any increase in N fertilizer use translates to significant increases in CO_2 emissions. The amount of N fertilizer recommended for conservation-till systems is generally the same as for intensive-till systems in the Corn Belt. However, N rate recommendations are higher for conservation-till systems in some other regions. More details will be provided in the case studies.

18.6.4 Herbicide Use

Herbicide manufacture and use require some fossil energy but not nearly as much as required for N fertilizer manufacture and use. Reducing tillage results in somewhat more herbicide use but the increase in herbicide use is becoming minimal. As herbicide prices decrease and herbicide tolerate crops become more widespread, intensive-till and conservation-till systems rely on herbicide use to about the same extent. The main difference is that virtually all no-till systems use a burn-down contact herbicide before planting whereas intensive-till systems don't use a burndown herbicide before planting.

18.6.5 N$_2$O Emissions From Soil

Increases in N_2O emissions can have a large impact on the overall amount of GHG avoided by reducing tillage. Small differences in N_2O emissions can be important because N_2O is 296 times more potent (weight basis) than CO_2 as a GHG. Reducing tillage increases the potential for increased N_2O emissions from the soil, but this potential is not necessarily realized if these systems are well managed. Emission of N_2O from soils results from both denitrification and nitrification (more details about these processes in the next paragraph). In general, the amount of N_2O emitted increases with the amount of N fertilizer applied; this must be considered when reducing tillage increases the amount of N fertilizer required. However, even when more N fertilizer is not applied with reduced tillage, more N_2O may be emitted when tillage is reduced. This is because, in some cases, soil conditions with reduced tillage are more conducive to N_2O emissions from denitrification and nitrification. Therefore, both the amount of N fertilizer applied and soil factors must be considered in estimating the effects of reducing tillage on N_2O emissions.

Denitrification is a microbial process in which nitrate nitrogen is converted to gases, mainly N_2 and N_2O, under limited oxygen conditions[13]. Nitrous oxide is usually a minor portion of the N lost via denitrification. In addition to a supply of nitrate and low oxygen conditions, a source of biologically available carbon is required as an energy source for the denitrifying microbes. Low oxygen conditions occur in soil mainly when soils are excessively wet and soil pores contain sufficient water to restrict movement of air into the soil; this can result in a depletion of soil oxygen levels as oxygen is used to support plant and microbial growth. In some cases, excessively wet conditions and more biologically available carbon occur more extensively in conservation-till than intensive-till systems, leading to more N_2O emissions with conservation-till[14]. More specifics will be provided in the case studies.

Nitrification is the microbial conversion of ammonium to nitrate. Most N fertilizers are applied in an ammonium form and N from soil organic matter is released as ammonium. In cropland, most of the N supplied from fertilizers and from soil organic matter is ultimately present as ammonium and then converted to nitrate via nitrification. Nitrification is a less important source of N_2O than is denitrification and effects of reducing tillage on N_2O emissions from nitrification are less well understood than the effects of reducing tillage on N_2O emissions from denitrification[13].

18.7 Costs of Reducing Tillage as a Means of Offsetting Utility GHG Emissions

The costs of reducing tillage as a means of offsetting energy company GHG emissions are of three types: (1) adoption incentives an energy company would have to pay to get farmers to switch from intensive-tillage to conservation-tillage practices on additional land, (2) transaction costs for aggregating and brokering GHG credits, and (3) monitoring costs to assure that contractual obligations are fulfilled.

In general, crop production costs are less for conservation-tillage systems than for intensive-tillage systems and average yields are not significantly affected by tillage system (See Appendix E for more details). This means that, in general, farmers' long-term incomes are not greatly affected by switching from intensive till to conservation till. The big economic difference when switching to conservation-tillage is greater yield variability and greater risk of reduced income in a given year[15]. Therefore, the main cost of achieving increased adoption of conservation tillage is an adoption incentive to compensate the farmer for accepting increased risk, especially in the first few years after adoption of reduced tillage. The increased risk with conservation-tillage systems is usually greatest during the first few years after switching to conservation tillage[16]. This is partly because farmers have to learn how to adapt conservation-tillage systems to their specific soils, climate, and financial resources and partly because benefits of improved soil quality from conservation tillage may not be significant until several years after switching to conservation tillage. Once significant soil quality improvements have occurred, they usually translate into higher crop yields. In most cases, the higher crop yields will provide sufficient economic incentive to continue the reduced-tillage practices without an external incentive. However, in some cases, farmers may have to be compensated for a lower average income over

the long term; in these cases, adoption incentives will compensate for lost average income in addition to increased risk.

In addition to adoption incentives, other costs of CO_2 sink enhancement via reducing tillage are transaction costs for aggregating and brokering CO_2 credits and monitoring costs to verify that contractual obligations are fulfilled. These costs are not well defined because of lack of actual implementation projects. Costs will be based on related experiences such as in forestry sink enhancement projects.

A key question is how long adoption incentives will have to be paid to a farmer to get him to maintain the switch to conservation tillage. There are not definitive answers to this question. As indicated in Figures 18-2, 18-5, and 18-6, after switching from intensive-till to conservation-till, the annual increases in SOC decrease with time and eventually become zero, usually within 20 to 40 years after switching to conservation tillage. Will adoption incentives be required for the entire 20 to 40 years that SOC is increasing, or even longer? Since the greatest financial risk to the farmer occurs in the early years after switching to conservation tillage, it is likely that incentive payments will only be necessary for the first 5 to 20 years after switching tillage. After that time, higher crop yields with conservation tillage are expected to provide adequate incentive to continue conservation-tillage practices. Our analyses in the case studies will assume a range of 5 to 20 years for adoption incentive payments.

Another key question is how to handle situations in which a farmer must intensively till occasionally (e.g., in one or two years out of 20) to overcome some production problem that develops such as the need to incorporate lime or severe rutting of fields because of harvesting when the soils were too wet. This project uses a 100-year planning horizon for the economic analyses. With this length of planning horizon, we assume that if intensive tillage is used occasionally, the SOC level will have time to rebound to the steady-state level under conservation tillage before the end of the 100-year planning horizon.

Another key question is how to estimate costs of CO_2 abatement from an energy company perspective if farmers were to permanently switch back to intensive tillage after adoption incentives are no longer paid (as discussed above, this is not expected to be the usual case). As discussed in Section 2.4, we use an approach that accounts for the timing of both CO_2 abatement and CO_2 abatement costs. This approach was selected to enable comparison of CO_2 storage and sink enhancement options that vary greatly in the timing and permanence of CO_2 abatement and timing of CO_2 abatement costs. We treat removals and emissions/leaks of CO_2 as separate events. The basic idea is that when a company removes or pays for removal of a ton of CO_2, the company receives the going price of CO_2. When a ton of CO_2 is released, the owner of this CO_2 (in this case the company) must then purchase a credit from elsewhere at the going price. With this approach, a breakeven CO_2 price (\$/tonne of CO_2) is calculated as the price at which the sum of discounted CO_2 revenues (both positive and negative) equals the sum of discounted costs of CO_2 sink enhancement. This breakeven price is the long-term cost of CO_2 abatement. See Section 2.4 for calculating costs of storing captured CO_2 for more details on calculating the breakeven CO_2 price.

Economics of CO2 Sink Enhancement Via Reducing Tillage on U.S. Cropland—Basis and Approach

A 6.09 percent after-tax discount rate was used in calculating breakeven CO_2 prices for CO_2 sink enhancement via reducing tillage on U.S. croplands. This is the same discount rate (constant dollar basis) as used for calculating costs of storing captured CO_2, and is applicable for calculating CO_2 abatement costs from an energy company perspective. An energy company likely would use the same financial parameters for evaluating GHG abatement investments regardless of whether the investments involve CO_2 capture and storage or CO_2 sink enhancement.

18.8 Cropland Case Studies Included in This Project

The following cropland case studies are included in this project, the goal being to both (1) include cases representing the greatest amount of avoided GHG emissions that could be achieved by reducing tillage and (2) illustrate the range of amounts per hectare and costs of avoided GHG emissions that could be achieved by reducing tillage.

1. Chapter19: Corn/soybean rotations in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N_2O emissions.

2. Chapter 20: Continuous corn cropping systems in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N_2O emissions.

3. Chapter 21: Wheat/fallow rotations in the western Great Plains being converted from intensive-till to no-till. This case includes variations in the amount of SOC sequestered and amount of N_2O emissions due to reducing tillage.

4. Chapter 22: Intensive-till cotton to no-till cotton in the southeastern U.S. This case includes variations in the amount of SOC sequestered and amount of N_2O emissions due to reducing tillage.

18.9 References

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19
CORN/SOYBEAN ROTATIONS IN THE U.S. CORN BELT

19.1 Introduction

As indicated in Chapter 18, corn/soybean rotations in the Corn Belt represent the largest potential for increasing SOC via reducing tillage in the United States. This is primarily because of the large land area in corn/soybean rotations. Also, corn and soybean yields, crop residue levels, and potential for per hectare increases in SOC are larger than for regions beyond the Corn Belt that use corn/soybean rotations. Base-case results for corn/soybean rotations are presented in Section 19.2. The base cases assume good N fertilizer management. Effects of poor N fertilizer management on amounts and costs of GHG credits from corn/soybean rotations are presented in Section 19.3.

19.2 Corn/Soybean Rotation (Base Cases)

A summary of effects of switching from intensive-till to no- or moderate-till on SOC, GHG emissions, and costs of avoided GHG emissions is presented in Table 19-1 for corn/soybean rotations in Indiana and Iowa. The bases for the results in Table 19-1 are discussed in the following sections using output from the corn/soybean spreadsheet model developed for this project.

The results in Table 19-1 are presented at a state level because, even with the relatively large land area of corn/soybean rotations in the Corn Belt states, additional adoption of conservation-tillage will be required on a state scale to avoid the same quantity of GHG emissions as avoided in the CO_2 capture and storage cases assessed in this project. For example, converting the base-case 425 MW (net) integrated gasification combined cycle (IGCC) power plant to capture 90 percent of the CO_2 produced and storing the captured CO_2 via enhanced oil recovery (EOR) avoids 0.45 million tonnes CE of GHG per year on a life-cycle basis during the 20-year life time of the plant (see earlier section on EOR). This translates to 9.1 million tonnes CE of GHG avoided during the 20 year life of the plant. Converting from intensive-till to no-till in Iowa avoids 9.9 tonnes CE GHG emissions per hectare during the 100-year planning horizon used in this project (Table 19-1). This means that 9,100,000/9.9=919,000 hectares of intensive-till cropland converted to no-till will be required to equal the avoided GHG in the IGCC-EOR case. This amount of cropland (0.92 million hectares) is slightly less than the amount of intensively tilled soybeans in Iowa and about one-third of the intensively tilled corn in Iowa (Table 18-2).

Table 19-1
Effects of switching from intensive-till to no- or moderate-till on SOC, GHG Emissions, and costs of life-cycle (LC) avoided GHG emissions--Indiana and Iowa state averages for Corn/Soybean rotation

State	Indiana	Indiana	Iowa	Iowa
Switching from intensive-till to:	No-till	Moderate-till	No-till	Moderate-till
Quadratic SOC response curve				
ΔSOCs, kg C/ha	7221	5159	9794	6520
E (slope factor)	53.1	37	68.3	45.6
Years to new steady state (Ys)	27	28	29	29
Average annual increase in SOC (years 1 to Ys), kg C/ha/yr	267	184	338	225
GHG emissions from tillage-system inputs and N_2O (years 1-100), kg CE/ha/y:				
Δ Fuel use	-22.3	-16.9	-22.3	-16.9
Δ Machinery maint., trans., and repair	-4	-3	-4	-3
Δ N fertilizer use	0	0	0	0
Δ Herbicide use	3	0.8	3	0.8
Δ Total GHG emissions from inputs	-23.3	-19.1	-23.3	-19.1
Δ N_2O emissions from soil	30.3	30.3	30.3	30.3
Δ Total GHG emissions	7.0	11.2	7.0	11.2
Average LC GHG avoided (kg CE/ha/y)				
Years 1 to Ys	260	173	331	214
Years Ys to 100	-7	-11	-7	-11
Total LC GHG avoided (years 1-100), tonne CE/ha	6.5	4.0	9.9	5.4
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	4.3	2.9	5.7	3.7
Costs, $/ha/y				
Transaction (year 1)	5	5	5	5
Adoption incentive (years 1-20)	25	12.5	25	12.5
Monitoring (years 1-100)	1	1	1	1
Total costs (years 1-100), $/ha	605	355	605	355
NPV Total costs (years 1-100), $/ha	306	163	306	163
Cost (NPV basis), $/tonne CE LC GHG avoided	72	56	54	44

19.2.1 Increases in Soil Organic Carbon

The increases in SOC due to switching from intensive-till to no-till or moderate-till (Table 19-1) are based on state- and county-level assessments for Iowa[1] and Indiana[2]. Iowa and Indiana form a representative east-west transect across the mid-section of the Corn Belt states. Similar assessments are not available for the other Corn Belt states. The Iowa and Indiana assessments provide county-level estimates of increases in SOC for 10 and 20 years after switching corn/soybean rotations from intensive-till to no-till or moderate-till. These results were provided for several combinations of soil texture and internal drainage [non-hydric (i.e., well drained) or hydric (i.e., poorly drained)]. State-level estimates of increases in SOC were provided for 10 years after switching from intensive-till to no-till or moderate-till on both non-hydric and hydric soils. SOC response curves for counties representing the range and mean of SOC responses in Indiana and Iowa are presented in Appendix F. An interpolation procedure described in Appendix F was used to develop state-level SOC response curves for switching from intensive-till to no-till and moderate-till in Indiana and Iowa. Graphs of the four SOC response curves represented in Table 19-1 are presented in Figure 19-1.
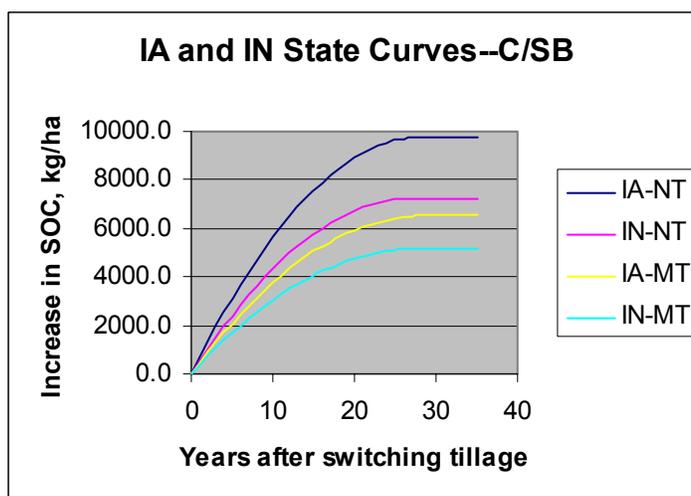
Figure 19-1
State SOC response curves for switching from intensive-till to no-till (NT) or moderate-till (MT) in Iowa and Indiana

After completing county-level carbon storage estimates first in Iowa[1] and then in Indiana[2], results in Indiana were judged to be most representative of the Corn Belt (personal communication, John Brenner, NRCS). Eve et al.[3] used the IPCC method of estimating first-approximation regional increases in SOC due to reducing tillage. The IPCC method assumes a 20-year linear increase in SOC. Using the IPCC method, switching from intensive tillage to no tillage in the Corn Belt resulted in an estimated weighted mean increase in SOC of 480 kg C/ha/yr for a 20-year period. This estimated increase in SOC should be representative for a corn/soybean rotation since it is the predominant cropping system in the Corn Belt. A best-fit linear/plateau curve for the Indiana state curve (intensive till to no till) in Figure 19-1 gave a linear SOC increase of 400 kg C/ha/yr until the plateau was reached after 18 years. This is very similar to the IPCC estimate of 480 kg/ha/yr for a 20-year period, further supporting use of the Indiana state curves as being more representative of the Corn Belt than are the Iowa state curves.

West and Post[4] summarized increases in SOC in the United States due to switching corn/soybean rotations from intensive tillage to no tillage for a period of 10 to 15 years; they estimated a mean increase in SOC of 900 kg C/ha/yr. This is much higher than the estimates by either Eve et al.[3] using IPCC methodology or Brenner et al.[1] on which the curves in Figure 19-1 are based. The higher values from West and Post[4] appear to be due at least partially to the fact that most of the studies they summarized are for a shorter time period (10-15 years) after switching to no tillage, thereby reflecting a steeper portion of the SOC response curve.

Example spreadsheet inputs for calculating increases in SOC due to switching from intensive-till to no-till in Indiana (first column of Table 19-1) are presented in Table 19-2.

Table 19-2
Example process and economic input variables for switching from intensive-till to no-till for corn/soybean rotation in Indiana

Cropland: Two-Year Corn/Soybean Rotation
(Changes Due to Switching from Intensive-Till to No-Till)

Indiana

Process and Economic Input Variables

Process

Alternative Tillage System: **No-till**

Calculation Method for Sequestering Soil Organic Carbon (SOC)
Quadratic Plateau ●
Linear Plateau ○

Efficiency or Slope Index (E)	**53.1**	
SOC Increase to New Steady State (ΔSOCs)	**7221.0**	kg/ha
Years until New Steady State (Ys)	27	years

No-till time period	**100**	years
SOC Release Rate after no-till time period	**1500**	kg C/ha/yr

Economic

		Cost $/ha/yr
Transaction Costs	(years 1 – **1**)	**5.00**
Farmer Adoption Incentive to Reduce Tillage	(years 1 – **20**)	**25.00**
Monitoring Costs	(years 1 – **100**)	**1.00**

Discount rate **6.09%**

19.2.2 Costs

Example cost inputs are presented in Table 19-2. Experience with conservation-tillage adoption programs indicates that an adoption incentive of at least $25/ha/year for corn/soybean rotations will be required to achieve additional adoption from intensive-till of no-till in the Corn Belt (personal communication, Dan Towery, Conservation Tillage Information Center). For example, the Environmental Quality Incentives Program (EQIP) in Illinois is providing an incentive of $50/ha/yr for switching corn from intensive tillage to no tillage and is providing no incentive for switching soybeans from intensive tillage to no tillage. This results in an average incentive of $25/ha/yr for corn/soybean rotations. Conservation-tillage adoption incentives are estimated in Appendix E and ranged from $20 to 25/ha/year for switching from intensive-till to no-till corn/soybean rotations. A value of $25/ha/year was used for the case studies in this chapter. As a first approximation, we assume an adoption incentive of $12.50/ha/yr will be required to achieve additional adoption of corn/soybean rotations from intensive-till to moderate till. Transaction costs are based on experience with forestry projects and are estimated at $5/ha. Monitoring costs are assumed to be less than for forestry ($5/ha), assuming that cropland monitoring will be based mainly on monitoring practices that have been correlated with changes in SOC rather than direct measurements of SOC in each field. Monitoring costs of $1/ha/year were assumed.

19.2.3 GHG Effects in Addition to Carbon Storage in Soil Organic Matter

19.2.3.1 Fuel Use

Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in a corn/soybean rotation are presented in Table 19-3. Fuel usage rates are from Langemeier and Taylor[5]. Reductions in fuel use and associated carbon emissions by switching from intensive-till to moderate-till in a corn/soybean rotation are presented in Table 19-4.

Corn/Soybean Rotations in the U.S. Corn Belt

Table 19-3
Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in a corn/soybean rotation

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Fuel Use for tillage, planting, and herbicide operations

Corn Portion				*Soybean Portion*			
		Annual Fuel Use				Annual Fuel Use	
	gal./acre	L/ha	kg C/ha		gal./acre	L/ha	kg C/ha
Intensive-till:				*Intensive-till:*			
Moldboard plow	1.68	15.71	13.3	Disk corn stalks	0.45	4.21	3.6
Disk	0.55	5.14	4.4	Moldboard plow	1.68	15.71	13.3
Field cultivate	0.60	5.61	4.8	Disk	0.55	5.14	4.4
Plant	0.50	4.68	4.0	Field cultivate	0.60	5.61	4.8
Cultivate	0.45	4.21	3.6	Plant	0.50	4.68	4.0
Total	3.78	35.34	30.0	Total	3.78	35.34	30.0
No-till:				*No-till:*			
Burndown herbicide application	0.10	0.94	0.8	Burndown herbicide application	0.10	0.94	0.8
Plant	0.50	4.68	4.0	Shred Corn Stalks	0.75	7.01	6.0
	0.00			Plant	0.50	4.68	4.0
Total	0.60	5.61	4.8	Total	1.35	12.62	10.7
Tillage-system difference			-25.2	Tillage-system difference			-19.3

Mean annual tillage-system difference *(years 1- 100)* **-22.3 kg C/ha**

Energy Savings Embodied in Machinery Manufacturing,
Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-22.3 kg C/ha
Annual machinery MTR savings	18% of fuel savings

Annual machinery MTR saving from reducing tillage *(years 1- 100)* **-4.0 kg C/ha**

19.2.3.2 Machinery Manufacture, Transportation, and Repair

Reductions in machinery manufacture, transportation, and repair (MTR) and associated carbon emissions by switching from intensive-till to no-till or moderate-till in a corn/soybean rotation were calculated as 18 percent of the fuel savings (Tables 19-3 and 19-4). The 18 percent factor is based on ratios of tillage-system fuel use and machinery MTR in a national analysis of tillage-system effects on GHG emissions[6].

Table 19-4
Reductions in fuel use and associated carbon emissions by switching from intensive-till to moderate-till in a corn/soybean rotation

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Fuel Use for tillage, planting, and herbicide operations

Corn Portion					*Soybean Portion*			
		Annual Fuel Use					Annual Fuel Use	
	gal./acre	L/ha	kg C/ha			gal./acre	L/ha	kg C/ha
Intensive-till:					*Intensive-till:*			
Moldboard plow	1.68	15.71	13.3		Disk corn stalks	0.45	4.21	3.6
Disk	0.55	5.14	4.4		Moldboard plow	1.68	15.71	13.3
Field cultivate	0.60	5.61	4.8		Disk	0.55	5.14	4.4
Plant	0.50	4.68	4.0		Field cultivate	0.60	5.61	4.8
Cultivate	0.45	4.21	3.6		Plant	0.50	4.68	4.0
Total	3.78	35.34	30.0		Total	3.78	35.34	30.0
Moderate-till:					*Moderate-till:*			
Disk	0.55	5.14	4.4		Disk	0.55	5.14	4.4
Field Cultivate	0.60	5.61	4.8		Field Cultivate	0.60	5.61	4.8
Plant	0.50	4.68	4.0		Plant	0.50	4.68	4.0
Total	1.65	15.43	13.1		Total	1.65	15.43	13.1
Tillage-system difference			-16.9		Tillage-system difference			-16.9

Mean annual tillage-system difference *(years 1- 100)*   -16.9 kg C/ha

Energy Savings Embodied in Machinery Manufacturing, Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-16.9 kg C/ha
Annual machinery MTR savings	18% of fuel savings

Annual machinery MTR saving from reducing tillage *(years 1- 100)*   -3.0 kg C/ha

19.2.3.3 Nitrogen Fertilizer Use

N fertilizers generally are not applied on soybeans because they are legumes. When inadequate soil N is available to legumes, they convert N_2 from the atmosphere into forms available for plant nutrition, a process known as biological N fixation. Therefore, reducing tillage has no impact on the amount of N fertilizer used in the soybean portion of a corn/soybean rotation.

In addition to not requiring N fertilizer, soybeans generally leave more readily available N for the next crop than does corn. In the Corn Belt, it is common to reduce N fertilizer recommendations for corn following soybeans by about 30 kg N/ha relative to recommendations for corn following corn[7]. This credit is not adjusted for tillage system.

In contrast to soybeans, corn generally requires significant quantities of N fertilizer for economically optimum production. There are several mechanisms by which more N can be lost from the soil when tillage is reduced, especially when N is poorly managed[8,9]. Reducing tillage conserves soil moisture. Higher soil moisture levels increase the potential for N leaching losses

via downward movement with soil water, especially in highly permeable soils. No-till soils tend to develop more macro-pores that potentially can cause greater N leaching losses, especially when N is applied on the soil surface and N fertilizer moves directly into macro-pore openings at the soil surface. Higher soil moisture levels also increase the potential for N losses via denitrification, especially with wet conditions in soils with poor internal drainage (see Chapter 18 discussion of denitrification in the section about N_2O losses via denitrification). More readily available organic matter near the soil surface in conservation-tillage systems also increases the potential for denitrification, especially when N is applied on the soil surface. The potential for denitrification can be greatly reduced by injecting N below the crop residues that are concentrated near the soil surface in conservation-till systems. The potential for both denitrification and leaching losses can be significantly reduced by applying N close to the time of crop need. When urea-containing fertilizers are applied on the soil surface without immediate incorporation, the potential for ammonia volatilization losses is much greater in conservation-till systems and especially in no-till systems. This problem is virtually eliminated when urea-containing fertilizers are injected into the soil. In summary, the potential for N losses is greater with conservation tillage than with intensive tillage when N is poorly managed. With conservation tillage, it is more important that N be applied close to the time of crop need and that the N be injected below the decomposing crop residues.

Minimizing contact of N fertilizers with crop residues is especially critical in conservation-tillage systems[10]. In the Corn Belt, most of the N is applied as anhydrous ammonia and by necessity is injected well below the soil surface. Injection reduces the potential for denitrification and N tie-up in organic matter in conservation-tillage systems. In contrast to urea or urea-ammonium nitrate solution, ammonia volatilization from anhydrous ammonia generally is not a significant problem and is not likely to differ by tillage system. With timely application of anhydrous ammonia, N leaching is not likely to be significantly greater in conservation-tillage systems than intensive-tillage systems. Outside the Corn Belt, anhydrous ammonia is not the dominant form of N fertilizer and surface applications of N fertilizer are more common. In some of these cases N rate recommendations are higher for conservation-till systems, especially no-till. An example is in Kentucky in which N rate recommendations are increased about 25 kg/ha for no-till corn on soils that are not well drained[11].

In addition to N losses, the amount of N released from crop residues and soil organic matter affects the amount of N fertilizer required. In general, N mineralization (conversion from organic to inorganic N) is slower with conversation tillage than with intensive tillage, especially with cool wet conditions in the spring. When soil organic matter levels increase, more N as well as C is sequestered in the organic matter. Soil C:N ratios usually stabilize at about 11:1. This implies that if the SOC level increases 338 kg/ha/yr due to reducing tillage (see Iowa No-till example in Table 19-1), then the amount of N tied up in soil organic matter should increase by about 30 kg N/ha/yr. In some cases, the added N tied up in soil organic matter with conservation tillage may be N that would have been lost had it not been tied up. In that case, the amount of N fertilizer required is not affected by N tie-up in organic matter. Also, it should be noted that if conservation-tillage corn residues mineralize less N to become available to the subsequent soybean crop, the soybean N-fixation mechanism likely makes up for most or all of that deficit.

Nitrogen rate recommendations generally are adjusted for yield levels expected to be achieved in a given cropping system. For individual farms and years, tillage system can significantly affect yields. However, averaged over a broad area (e.g., a state) and several years, tillage system is expected to have little impact on yields and associated N fertilizer rates.

In summary, the issue of amount of N fertilizer required by differing tillage systems is relevant for only the corn portion of a corn/soybean rotation and the soybean N fixation mechanism probably largely compensates for any reduced mineralization of soil organic matter following the corn crop. The principles discussed above indicate that when N is injected well below the decomposing crop residues and is applied close to when the crop needs the N, then the amount of N fertilizer required for Corn in the Corn Belt should not be significantly affected by tillage system. However, with poorly managed N, more N fertilizer will be required with conservation tillage than with intensive tillage.

The N fertilizer recommendations for Michigan, Ohio, and Indiana have been integrated into one system[7] and are representative of the Corn Belt. The recommended N rate is not adjusted for tillage system. However, the following adjustments are made for tillage system:

1. For soils with greater than 30 percent residue cover, the majority of applied N should be either:

    a. Injected below the soil surface
    b. Dribbled if using N solutions
    c. Or broadcast only if the material contains no urea

2. No-till corn planted into cold, wet soils should receive some of the recommended N at planting banded near the row (20 to 40 kg N/ha)

The National Agricultural Statistical Service reported the following average N rates for corn in the 10 major corn states as affected by tillage system and manure application (Table 19-5). Significantly less N fertilizer per hectare and more manure were applied in intensive-till systems involving plowing than in the other tillage systems reported. The lower mean N fertilizer rate for intensive-till systems involving plowing appears to be due to more manure being used in these systems, not because this tillage system requires less N fertilizer per se. Less N fertilizer is recommended on fields receiving manure, regardless of tillage system[12].

Table 19-5
Mean N rates for corn in the ten major U.S. corn producing states--1995[13]

	Intensive-till with plow	Intensive-till without plow	Mulch-till	No-till
N rate, kg/ha	108	148	150	150
% of fields with N fertilizer	93	98	97	98
% of fields with manure	38	15	14	8

In this corn/soybean rotation case study, it was assumed that N rate is not affected by tillage system. This is because N rate recommendations are not adjusted for tillage system in the Corn Belt and the mean of actual N rates for corn after correcting for manure application, don't differ by tillage system.

Effects of applying more N fertilizer with no-till than with intensive-till, a case that is applicable when N fertilizer is poorly managed, is presented in Section 19-3.

19.2.3.4 Herbicide Use

The mean annual herbicide rates for intensive-till and no-till corn/soybean rotations were estimated from West and Marland[6] as 1.92 and 2.56 kg active ingredient (a.i.)/ha, respectively. West and Marland[6] estimated 4.70 kg C emitted/kg herbicide a.i. used. With these factors, carbon emissions were 3.0 kg C/ha/yr more for no-till than intensive-till. The mean annual herbicide rate for moderate-till corn/soybean rotations was estimated from West and Marland[6] as 2.09 kg a.i./ha. Multiplying (2.09-1.92 kg a.i./ha) by 4.70 kg C emitted/kg herbicide gave 0.8 kg C/ha/yr more for moderate-till than no-till. Example spreadsheet output is presented in Table 19-6.

Table 19-6
Example spreadsheet output for estimating herbicide carbon equivalent emissions for corn/soybean rotation

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Annual Herbicide Use X Tillage System

	Mean annual herbicide rate kg a.i./ha	kg C/kg herbicide (a.i.)	kg C/ha/yr
Intensive-till corn/soybean rotation	**1.92**		
No-till corn/soybean rotation	**2.56**		
Difference (years 1- 100)	0.64	4.70	**3.0**

19.2.3.5 N$_2$O Emissions from Soil

Background on N$_2$O emissions from soil was provided earlier, indicating that N$_2$O emissions are dependent on both soil conditions and amount of N fertilizer applied. In this Corn Belt corn/soybean rotation case, the amount of N fertilizer applied does not change with tillage system, but soil conditions do change as discussed earlier. Robertson et al.[14] measured effects of switching from intensive-till to no-till in a corn/wheat/soybean rotation on a well drained soil in Michigan. The same N rate was used for both tillage systems and anhydrous ammonia was the primary N source. Switching to no-till increased N$_2$O emissions from 141 to 152 kg CE/ha/yr. Del Grosso et al.[15] modeled N$_2$O emissions as affected by switching corn/soybean rotations from intensive-till to no-till on a well drained soil in Indiana. The same N fertilizer rate was assumed

for both tillage systems. A specific placement (e.g., knifing or broadcast) of the N fertilizer was not indicated but broadcast placement is assumed. With these assumptions, N_2O emissions were slightly lower with no-till than intensive-till in both a corn/soybean rotation and continuous corn. Mummey et al.[16] modeled N_2O emissions for intensive-till and no-till systems at 1035 sites for corn and 655 sites for soybeans. These sites represented the range of soil and environmental conditions for these crops in the United States. This modeling effort indicated that in the north central U.S. the mean N_2O-N emissions were 3.04 kg/ha for intensive-till and 3.28 kg/ha for no-till. Taking the difference (0.24 kg N_2O-N/ha) times 126.4 kg N_2O CE/kg N_2O-N gives 30.3 kg N_2O CE/ha/yr. This is a larger increase in N_2O emissions due to switching to no-till than was found by Robertson et al.[14] and Del Grosso et al.[15], but the latter two studies were on well drained soils whereas the Mummey et al.[16] study covered a range of soil and environmental conditions. On the other hand, Mummey et al.[16] did not account for possible reductions in denitrification and N_2O emissions with knifed N fertilizer applications that are common with anhydrous ammonia in the Corn Belt. The Mummey et al.[16] estimates of increased N_2O emissions due to switching from intensive-till to no-till in the north central U.S. were used as inputs to generate results in Table 19.1 for the corn/soybean Corn Belt case study (base scenario). Example spreadsheet output is presented in Table 19-7.

Table 19-7
Example spreadsheet output for carbon equivalent emissions from changes in N_2O emissions for corn/soybean rotation when changing from intensive-till to no-till

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Annual Changes in N_2O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till corn/soybean rotation	3.04		
No-till corn/soybean rotation	3.28		
Difference (*years 1- 100*)	0.24	126.4	30.3

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till corn/soybean rotation	75.0		
No-till corn/soybean rotation	75.0		
Difference (*years 1- 100*)	0.0	2.65	0.0

	Total Difference (*years 1- 100*)	30.3

19.2.3.6 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions is presented in Table 19-8. This output corresponds to the first column in Table 19-1.

Table 19-8
Example spreadsheet output summarizing changes in GHG emissions for corn/soybean rotation when changing from intensive-till to no-till

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions			kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years 1 - 27)*			-267
CO_2 Emissions from Tillage-System Inputs: *(years 1 - 100)*			
Fuel			-22.3
Machinery MTR			-4.0
N fertilizer			0.0
Herbicides			3.0
Total			-23.3
N_2O Emissions from Soil *(years 1 - 100)*			30.3

Avoided GHG Emissions		*Annual Average*	
		kg CE/ha/yr	tonne CE/ha/yr
	(years 1 - 27)	260.4	**0.260**
	(years 28 - 100)	-7.1	**-0.007**

19.2.4 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 19-9. This output corresponds to the first column in Table 19-1.

Table 19-9
Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis for corn/soybean rotation when changing from intensive-till to no-till

<div align="center">

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Summary

</div>

Process Description

Calculation Method for Sequestering SOC -	*Quadratic Plateau*		No-till time period	100	years
Average SOC Sequestered	267	kg C/ha/yr	Release Rate after No-till	1.5	tonne CE/ha/yr
Time until Steady State	27	years			

Economic

	Cost	LC Avoided CE	
	($/ha/yr)	*(tonne/ha/yr)*	*($/tonne LC avoided CE)*
Average Annual Costs *(years 1 - 1)*	31.00	0.545	56.93
(years 2 - 20)	26.00	0.349	74.44
(years 21 - 27)	1.00	0.095	10.48
(years 28 - 100)	1.00	-0.007	-141.45
	($/ha)	*(tonne/ha)*	*($/tonne LC avoided CE)*
CO_2 Sink Enhancement, NPV Basis *(years 1 - 100)*	305.75	4.27	71.68
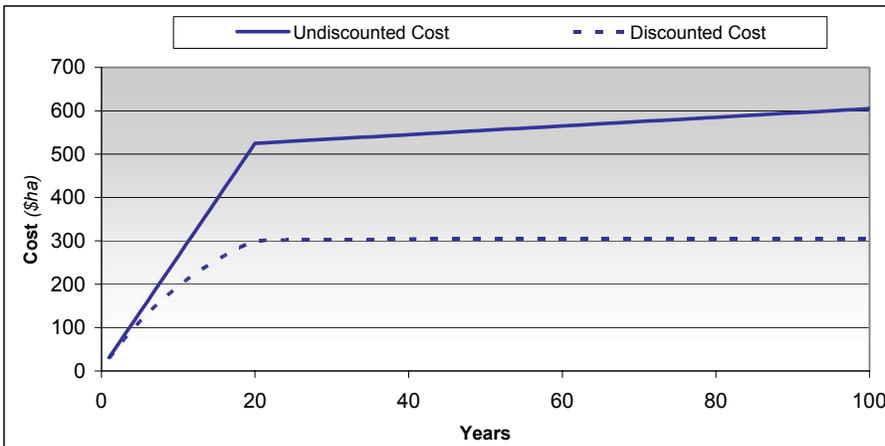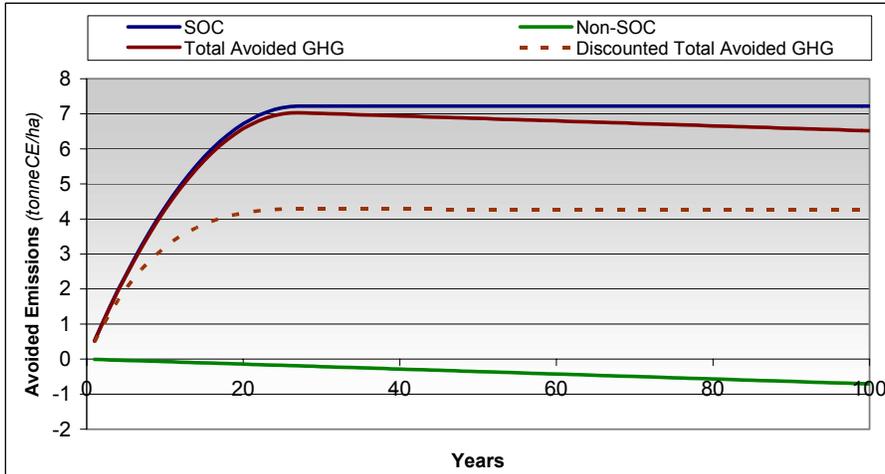
19.2.5 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 19-10. This sensitivity output presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 1500 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 19-10
Corn/soybean rotation sensitivity summary

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Quadratic Plateau*
Efficiency Index (Slope Factor)	53.1
SOC Increase to New Steady State (kg/ha)	7221
Time Until Steady State (years)	27
SOC Release Rate after no-till time period (tonne C/ha/yr)	1.5
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$25.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

Update Values

CO$_2$ Sink Enhancement Costs (100 year summation)

No-till Time Period (years)	Farmer Adoption Incentive Time Period (years)	NPV Basis LC avoided basis ($/tonne C equivalent)
5	5	358.50
10	10	193.75
15	15	146.75
20	20	126.53
100	5	29.57
100	10	47.90
100	15	61.53
100	20	71.68

19.3 Corn/Soybean Rotations (Poor N Management Scenario)

This case is the same as the Indiana no-till base case in the last section except that poorer N management (broadcast application of urea) is assumed for the corn portion of the rotation, resulting in more N fertilizer being required with no-till corn than intensive-till corn. Using more N fertilizer increases GHG emissions associated with N fertilizer use and also increases N_2O emissions in alternating years when corn is grown. This case assumes 150 kg N/ha for intensive-till and 175 kg N/ha or 200 kg/ha for no-till. These N rates fall within the recommended rates for intensive-till and no-till corn in Kentucky[11].

Table 19-11
Effects of switching from intensive-till using 150 kg N/ha to no- till using 175 or 200 kg N/ha on GHG emissions and costs of life-cycle (LC) avoided GHG emissions—Indiana Corn/Soybean rotations

Switching from intensive-till to:	No-till	No-till	No-till
N rate, kg/ha	150	175	200
Quadratic SOC response curve			
ΔSOCs, kg C/ha	7221	7221	7221
E (slope factor)	53.1	53.1	53.1
Years to new steady state (Ys)	27	27	27
Average annual increase in SOC (years 1 to Ys), kg C/ha/yr	267	267	267
GHG emissions from tillage-system inputs and N_2O (years 1-100), kg CE/ha/y:			
Δ Fuel use	-22.3	-22.3	-22.3
Δ Machinery maintenance, trans., and repair	-4	-4	-4
Δ N fertilizer use	0	14.4	28.7
Δ Herbicide use	3	3	3
Δ Total GHG emissions from inputs	-23.3	-8.9	5.4
Δ N_2O emissions from soil	30.3	63.5	96.6
Δ Total GHG emissions	7.0	54.5	102
Average LC GHG avoided (kg CE/ha/y)			
Years 1 to Ys	260	213	165
Years Ys to 100	-7	-55	-102
Total LC GHG avoided (years 1-100), tonne CE/ha	6.5	1.8	-3.0
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	4.3	3.5	2.7
Costs, $/ha/y			
Transaction (year 1)	5	5	5
Adoption incentive (years 1-20)	25	25	25
Monitoring (years 1-100)	1	1	1
Total costs (years 1-100), $/ha	605	605	605
NPV Total costs (years 1-100), $/ha	306	306	306
Cost (NPV basis), $/tonne CE LC GHG avoided	72	88	113

A summary of results is presented in Table 19-11. Increasing the N rate every other year for corn by 25 kg N/ha increased the cost of avoided GHG from $72 to $88/tonne CE LC avoided. Increasing the N rate for corn by 50 kg N/ha increased the cost of avoided GHG from $72/tonne CE LC avoided to $113/tonne CE LC avoided on an NPV basis. These increased costs are due to less avoidance of GHG emissions per dollar invested in adoption incentives and transaction and monitoring costs. Adding an additional 50 kg N/ha every other year for corn nearly doubled the cost per tonne CE LC avoided on an NVP basis and resulted in a negative avoidance of GHG emissions on a nondiscounted basis after 100 years (a decrease from 6.5 to -3.0 tonnes CE LC avoided). This emphasizes the importance of efficient N fertilizer management in cropping systems designed to reduce GHG emissions. Details of the effects of increased N fertilizer use on GHG emissions from N fertilizer manufacture, transportation, storage, and application and on N_2O emissions are presented in the next two sections.

19.3.1 Nitrogen Fertilizer Use

Carbon emissions associated with important combinations of N source and placement are presented in Table 19-12. Emissions from N fertilizer use include manufacture[17] and transportation and storage[18]. Emissions from N fertilizer application are from Langemeier and Taylor[5]. The manufacturing numbers assume that all energy is from natural gas, but a small undermined amount of energy is from electricity. The transportation, storage, and application numbers assume the energy is from diesel fuel.

Table 19-12
Corn/soybean carbon emissions associated with important combinations of N source and placement

Cropland: Two-Year Corn/Soybean Rotation
Indiana
N Fertilizer Use X Crop and Tillage System

		Corn Portion						Soybean Portion			
	Annual N fertilizer use			N Appln.	Total			Annual N fertilizer use		N Appln.	Total
Source/Placement	kg N/ha	kg C/kg N	kg C/ha	kg C/ha	kg C/ha	Source/Placement	kg N/ha	kg C/kg N	kg C/ha	kg C/ha	kg C/ha
Intensive-till:						*Intensive-till:*					
Anhydrous ammonia/knifed	0.0	0.838	0.0	0	0.0	Anhydrous ammonia/knifed	0.0	0.838	0.0	0.0	0.0
Urea/broadcast	150.0	1.148	172.2	1.6	173.8	Urea/broadcast	0.0	1.148	0.0	0.0	0.0
UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0	UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0
UAN solution/knifed	0.0	1.012	0.0	0.0	0.0	UAN solution/knifed	0.0	1.012	0.0	0.0	0.0
Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0	Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0
Total	150.0		172.2	1.6	173.8	Total	0.0		0.0	0.0	0.0
No-till:						*No-till:*					
Anhydrous ammonia/knifed	0.0	0.838	0.0	0	0.0	Anhydrous ammonia/knifed	0.0	0.838	0.0	0.0	0.0
Urea/broadcast	175.0	1.148	200.9	1.6	202.5	Urea/broadcast	0.0	1.148	0.0	0.0	0.0
UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0	UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0
UAN solution/knifed	0.0	1.012	0.0	0.0	0.0	UAN solution/knifed	0.0	1.012	0.0	0.0	0.0
Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0	Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0
Total	175.0		200.9	1.6	202.5	Total	0.0		0.0	0.0	0.0
Tillage-system difference	25.0		28.7		28.7	Tillage-system difference	0.0		0.0	0.0	0.0

	Annual N fertilizer use kg N/ha	N Appln. kg C/ha	Total kg C/ha
Mean annual tillage-system difference (years 1- 100)	12.5	14.4	**14.4**

This case assumes that no N fertilizer is applied for soybeans and urea is broadcast for corn in both the intensive-till and no-till systems and that 150 kg N/ha and 175 kg N/ha are required for

intensive-till and no-till corn , respectively. This resulted in an average annual increase in N fertilizer use of 12.5 kg N/ha.

The increase in N fertilizer use with no-till was assumed to increase N_2O emissions from soils in accordance with the IPCC default N_2O emission factor for commercial N fertilizer use[19]. The IPCC factor assumes the following:

- Direct N_2O-N emissions = 1.25 percent of applied N

- Indirect N_2O-N emissions from:
  Volatilized NH_3 and NOx = 0.1 percent of applied N
  Leached N = 0.75 percent of applied N

- Total N_2O-N emission = 2.1 percent of applied N
  (i.e., 0.021 kg N_2O-N/kg applied N)

The IPCC factor is converted to a carbon equivalent (CE) radiative forcing basis as follows:

- 1.57 N_2O/N_2O-N

- 296 CO_2 equivalent/N_2O

- 0.272 C equivalent (CE)/CO_2 equivalent

- 1.57 x 296 x .272 CE/N_2O-N
  (126.4 CE/N_2O-N)

Therefore, 1 kg applied N = 0.021 x 126.4 kg CE from N_2O
                = 2.65 kg CE from N_2O

The overall increase in N_2O emissions due to both switching from intensive-till to no-till and increasing N fertilizer use was calculated as shown in Table 19-13. Increased N_2O emissions due to tillage-related changes in soil properties and micro-climate (without changes in N fertilizer rate) are based on the same assumptions as in the previous case in which N fertilizer rate didn't change with tillage system.

Table 19-13
Corn/soybean overall increase in N_2O emissions due to both switching from intensive-till to no-till and increasing N fertilizer use

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Annual Changes in N_2O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till corn/soybean rotation	**3.04**		
No-till corn/soybean rotation	**3.28**		
Difference *(years 1- 100)*	0.24	126.4	30.3

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till corn/soybean rotation	87.5		
No-till corn/soybean rotation	75.0		
Difference *(years 1- 100)*	12.5	2.65	33.1

Total Difference *(years 1- 100)*   **63.5**

19.3.2 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till and increasing N fertilizer use by 25 kg N/ha is presented in Table 19-14. These results correspond to the second column in Table 19-11. Over the course of the 100-year planning horizon, the added N fertilizer use and associated increase in N_2O emissions substantially reduced the amount of GHG emissions avoided (Table 19-15).

Table 19-14
Corn/soybean example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till and increasing N fertilizer use

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

				kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years*	*1*	*- 27*	*)*	-267
CO_2 Emissions from Tillage-System Inputs:	*(years*	*1*	*- 100)*	
Fuel				-22.3
Machinery MTR				-4.0
N fertilizer				14.4
Herbicides				3.0
Total				-8.9
N_2O Emissions from Soil	*(years*	*1*	*- 100)*	63.5

Avoided GHG Emissions

				Annual Average	
				kg CE/ha/yr	tonne CE/ha/yr
(years	*1*	*- 27*	*)*	212.9	**0.213**
(years	*28*	*- 100*	*)*	-54.5	**-0.055**

19.3.3 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 19-15. This output corresponds to the second column in Table 19-11.

Table 19-15
Corn/soybean example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis when changing from intensive-till to no-till and increasing N fertilizer use

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Summary

Process Description

Calculation Method for Sequestering SOC -	*Quadratic Plateau*		No-till time period	100	years
Average SOC Sequestered	267	kg C/ha/yr	Release Rate after No-till	1.5	tonne CE/ha/yr
Time until Steady State	27	years			

Economic

		Cost	LC Avoided CE	
		($/ha/yr)	*(tonne/ha/yr)*	*($/tonne LC avoided CE)*
Average Annual Costs *(years 1 - 1)*		31.00	0.530	58.47
(years 2 - 20)		26.00	0.335	77.63
(years 21 - 27)		1.00	0.081	12.33
(years 28 - 100)		1.00	-0.055	-18.33
		($/ha)	*(tonne/ha)*	*($/tonne LC avoided CE)*
CO_2 Sink Enhancement, NPV Basis *(years 1 - 100)*		305.75	3.49	87.66
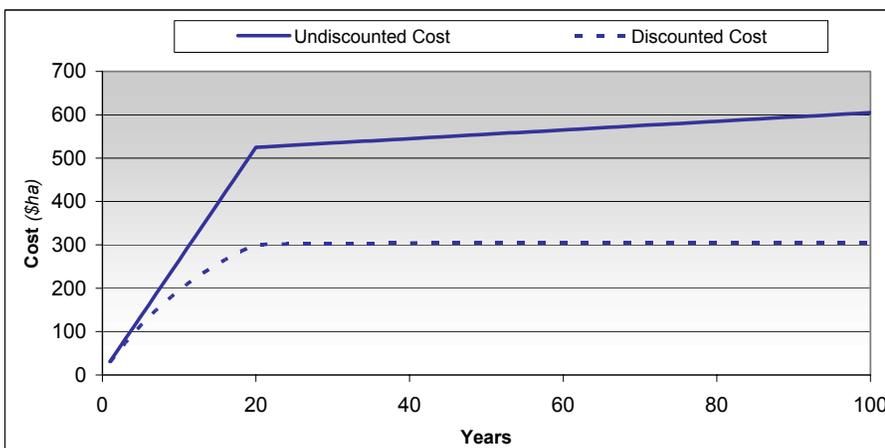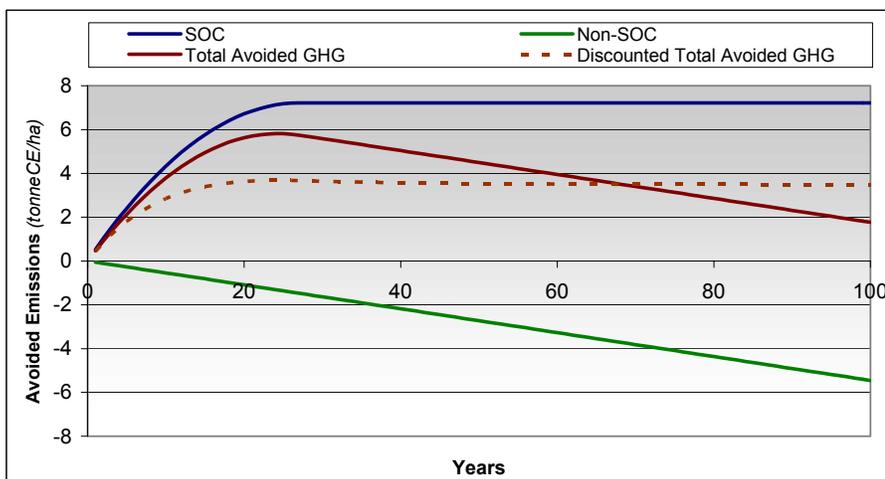
19.3.4 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 19-16. This output corresponds to the second column in Table 19-11 and presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 1500 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 19-16
Corn/soybean example spreadsheet sensitivity summary output when changing from intensive-till to no-till and increasing N fertilizer use

Cropland: Two-Year Corn/Soybean Rotation
Indiana
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Quadratic Plateau*
Efficiency Index (Slope Factor)	53.1
SOC Increase to New Steady State (kg/ha)	7221
Time Until Steady State (years)	27
SOC Release Rate after no-till time period (tonne C/ha/yr)	1.5
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$25.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

Update Values

CO_2 Sink Enhancement Costs *(100 year summation)*

No-till Time Period *(years)*	Farmer Adoption Incentive Time Period *(years)*	**NPV Basis** LC avoided basis *($/tonne C equivalent)*
5	5	827.87
10	10	289.15
15	15	197.32
20	20	162.98
100	5	36.16
100	10	58.57
100	15	75.25
100	20	87.66

Examples of the large effects of N rate and N_2O emissions on amount of GHG emissions avoided and cost per tonne of GHG avoided are presented in Table 19-17. The scenarios in Table 19-17 are for switching from intensive-till to no-till in a corn/soybean rotation in the Corn Belt. No significant change in N_2O emissions due switching from intensive-till to no-till is a possibility with good N management, especially on well-drained soils. The increases in N rate and N_2O emissions in Table 19-17 due to switching from intensive-till to no-till are possibilities with poor N management. Amounts of GHG avoided range from 9.6 tonnes CE LC GHG avoided/ha with a best-case N rate and N_2O scenario to -3.0 tonnes CE LC GHG avoided/ha for a worst-case scenario. Costs on an NPV basis range from \$64/tonne CE LC GHG avoided with a best-case N rate and N_2O scenario to \$113/tonne CE LC GHG avoided for a worst-case scenario. Differences between the best-case and worst-case scenarios regarding amount of GHG avoided are very large because the annual effects are manifested over the entire 100-year planning horizon. In order for reducing tillage on corn/soybean rotations to be a viable option for avoiding GHG emissions, N fertilizer will have to be managed efficiently so that the amount of N fertilizer used and the N_2O emissions are not significantly increased.

Table 19-17
Effects of increases in N rate and N_2O emissions on amounts and costs of avoided GHG via switching from intensive-till to no-till in a Corn/Soybean rotation

ΔN rate		ΔN$_2$O	Years 1-100	NPV basis, years 1-100	
kg N/ha/yr	kg/CE/ha/yr	kg/CE/ha/yr	tonne CE LC GHG avoided/ha	tonne CE LC GHG avoided/ha	\$/tonne CE LC GHG avoided[1]
0	0	0	9.6	4.8	64 [2]
0	0	30.3	6.5	4.3	72 [3]
25	14.4	63.5	1.8	3.5	88 [4]
50	28.8	96.6	-3.0	2.7	113 [5]

[1] Assumes incentive payments for 20 years.

[2] Base case except for no change in N_2O emissions due to switching to no-till.

[3] Base case (see first column, Table 19-11).

[4] Base case except for an increase in N rate due to switching from to no-till (see second column, Table 19-11).

[5] Base case except for an additional increase in N rate due to switching from to no-till (see third column, Table 19-11).

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20
CONTINUOUS CORN IN THE U.S. CORN BELT

20.1 Introduction

As indicated in Chapter 18, continuous corn is produced on a much smaller land area in the United States than is corn rotated with soybeans. However, the amount of carbon sequestered per hectare is significantly larger for continuous corn than for corn/soybean rotations and a larger adoption incentive is required for continuous corn than for a corn/soybean rotation. Base-case results for continuous corn are presented in Section 20.2. The base cases assume good N fertilizer management. Effects of poor N fertilizer management on amounts and costs of GHG credits from continuous corn are presented in Section 20.3. Effects of N fertilizer management are greater for continuous corn than for corn/soybean rotations because N fertilizer is used every year for continuous corn and only every other year for corn/soybean rotations.

20.2 Continuous Corn (Base Cases)

A summary of effects of switching from intensive-till to no- or moderate-till on SOC, GHG emissions, and costs of avoided GHG emissions is presented in Table 20-1 for continuous corn in Indiana and Iowa. The bases for the results in Table 20-1 are discussed in the following sections using output from the continuous corn spreadsheet model developed for this project.

Table 20-1
Effects of switching from intensive-till to no- or moderate-till on SOC, GHG emissions, and costs of life-cycle (LC) avoided GHG emissions--Indiana and Iowa state averages for Continuous Corn

State	Indiana	Indiana	Iowa	Iowa
		Moderate-		Moderate-
Switching from intensive-till to:	No-till	till	No-till	till
Quadratic SOC response curve				
ΔSOCs, kg C/ha	13104	10174	1335 5	5619
E (slope factor)	92.0	72.5	92.3	35.3
Years to new steady state (Ys)	28	28	29	32
Average annual increase in SOC (years 1 to Ys), kg C/ha/yr	468	363	461	176
GHG emissions from tillage-system inputs and N_2O (years 1-100), kg CE/ha/y:				
Δ Fuel use	-22.9	-20.5	-22.9	-20.5
Δ Machinery maint., trans., and repair	-4	-4	-4	-4
Δ N fertilizer use	0	0	0	0
Δ Herbicide use	4	1.2	4	1.2
Δ Total GHG emissions from inputs	-22.7	-23.0	-22.7	-23.0
Δ N_2O emissions from soil	30.3	30.3	30.3	30.3
Δ Total GHG emissions	7.6	7.3	7.6	7.3
Average LC GHG avoided (kg CE/ha/y)				
Years 1 to Ys	460	356	453	168
Years Ys to 100	-8	-7	-8	-7
Total LC GHG avoided (years 1-100), tonne CE/ha	12.3	9.4	12.6	4.9
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	7.7	6.0	7.8	3.1
Costs, $/ha/y				
Transaction (year 1)	5	5	5	5
Adoption incentive (years 1-20)	50	25	50	25
Monitoring (years 1-100)	1	1	1	1
Total costs (years 1-100), $/ha	1105	605	1105	605
NPV Total costs (years 1-100), $/ha	590	306	590	306
Cost (NPV basis), $/tonne CE LC GHG avoided	77	51	76	100

20.2.1 Increases in Soil Organic Carbon

The increases in SOC due to switching from intensive-till to no-till or moderate-till (Table 20-1) are based on state- and county-level assessments for Iowa[1] and Indiana[2]. Iowa and Indiana form a representative east-west transect across the mid-section of the Corn Belt states. Similar assessments are not available for the other Corn Belt states. The Iowa and Indiana assessments provide county-level estimates of increases in SOC for 10 and 20 years after switching corn/soybean rotations from intensive-till to no-till or moderate-till. These results were provided for several combinations of soil texture and internal drainage [non-hydric (i.e., well drained) or hydric (i.e., poorly drained)]. State-level estimates of increases in SOC were provided for 10 years after switching from intensive-till to no-till or moderate-till on both non-hydric and hydric soils. SOC response curves for counties representing the range and mean of SOC responses in Indiana and Iowa are presented in Appendix F. An interpolation procedure described in Appendix F was used to develop state-level SOC response curves for switching from intensive-till to no-till and moderate-till in Indiana and Iowa. Graphs of the four SOC response curves represented in Table 20-1 are presented in Figure 20-1. After completing county-level carbon storage estimates first in Iowa[1] and then in Indiana[2], results from Indiana were judged to be most representative of the Corn Belt (personal communication, John Brenner, NRCS).
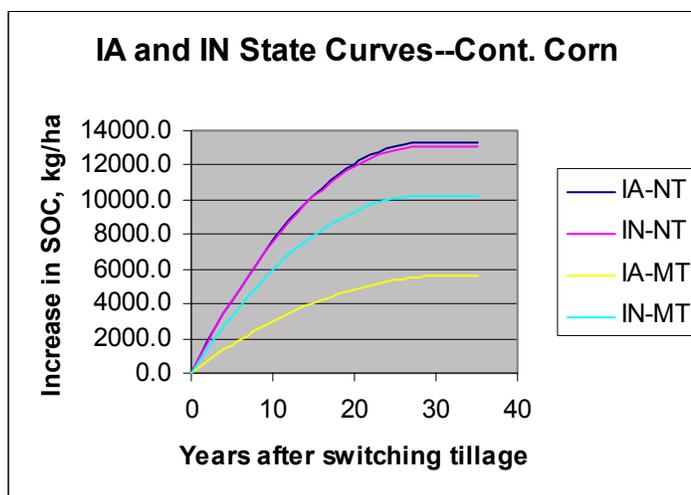
Figure 20-1
State SOC response curves for switching from intensive-till to no-till (NT) or moderate-till (MT) in Iowa and Indiana

Example spreadsheet inputs for calculating increases in SOC due to switching from intensive-till to no-till in Indiana (first column of Table 20-1) are presented in Table 20-2.

Table 20-2
Example process and economic input variables for switching from intensive-till to no-till for continuous corn in Indiana

Cropland: Continuous Corn
(Changes Due to Switching from Intensive-Till to No-Till)

Indiana

Process and Economic Input Variables

Process

Alternative Tillage System: **No-till**

Calculation Method for Sequestering Soil Organic Carbon (SOC)
Quadratic Plateau ◉
Linear Plateau ○

Efficiency or Slope Index (E)	**92.0**
SOC Increase to New Steady State (ΔSOCs)	**13103.5**
Years until New Steady State (Ys)	28 years

No-till time period	**100** years
SOC Release Rate after no-till time period	**1500** kg C/ha/yr

Economic

		Cost $/ha/yr
Transaction Costs	(years 1 - **1**)	**5.00**
Farmer Adoption Incentive to Reduce Tillage	(years 1 - **20**)	**50.00**
Monitoring Costs	(years 1 - **100**)	**1.00**

Discount rate **6.09%**

20.2.2 Costs

Example cost inputs are presented in Table 20-2. Experience with conservation-tillage adoption programs indicates that an adoption incentive of at least $50/ha/year for continuous corn will be required to achieve additional adoption from intensive-till of no-till in the Corn Belt (personal communication, Dan Towery, Conservation Tillage Information Center). For example, the Environmental Quality Incentives Program (EQIP) in Illinois is providing an incentive of $50/ha/yr for switching corn from intensive tillage to no tillage and is providing no incentive for switching soybeans from intensive tillage to no tillage. Conservation-tillage adoption incentives are estimated in Appendix E and ranged from $66 to 100/ha/year for switching from intensive-till to no-till continuous corn. Risks of lower and more variable yields associated with no-till continuous corn have been lowered somewhat in recent years via improvements in technology and experience with no-till. As a first approximation, we assume an adoption incentive of $50/ha/yr will be required to achieve additional adoption of continuous corn from intensive-till to no-till and that an adoption incentive of $25/ha/yr will be required to achieve additional adoption of continuous corn from intensive-till to moderate-till. Transaction costs are based on experience with forestry projects and are estimated at $5/ha. Monitoring costs are assumed to be less than for forestry ($5/ha), assuming that cropland monitoring will be based mainly on monitoring practices that have been correlated with changes in SOC rather than direct measurements of SOC in each field. Monitoring costs of $1/ha/year were assumed.

20.2.3 GHG Effects in Addition to Carbon Storage in Soil Organic Matter

20.2.3.1 Fuel Use

Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in a corn/soybean rotation are presented in Table 20-3. Fuel usage rates are from Langemeier and Taylor[3]. Reductions in fuel use and associated carbon emissions by switching from intensive-till to moderate-till for continuous corn are presented in Table 20-4. Fuel usage rates are from Langemeier and Taylor[3].

Continuous Corn in the U.S. Corn Belt

Table 20-3
Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in continuous corn

Cropland: Continuous Corn
Indiana
Fuel Use for tillage, planting, and herbicide operations

		Annual Fuel Use		
		gal./acre	L/ha	kg C/ha
Intensive-till:				
Disk corn stalks		0.45	4.21	3.6
Moldboard plow		1.68	15.71	13.3
Disk		0.55	5.14	4.4
Field cultivate		0.60	5.61	4.8
Plant		0.50	4.68	4.0
Cultivate		0.45	4.21	3.6
	Total	4.23	39.55	33.6
No-till:				
Burndown herbicide application		0.10	0.94	0.8
Shred Corn Stalks		0.75	7.01	6.0
Plant		0.50	4.68	4.0
	Total	1.35	12.62	10.7

Tillage-system difference (years 1- 100)   -22.9 kg C/ha

Energy Savings Embodied in Machinery Manufacturing, Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-22.9 kg C/ha
Annual machinery MTR savings	18% of fuel savings

Annual machinery MTR saving from reducing tillage (years 1- 100)   -4.1   kg C/ha

20.2.3.2 Machinery Manufacture, Transportation, and Repair

Reductions in machinery manufacture, transportation, and repair (MTR) and associated carbon emissions by switching from intensive-till to no-till or moderate-till for continuous corn were calculated as 18 percent of the fuel savings (Tables 20-3 and 20-4). The 18 percent factor is based on ratios of tillage-system fuel use and machinery MTR in a national analysis of tillage-system effects on GHG emissions[4].

Table 20-4
Reductions in fuel use and associated carbon emissions by switching from intensive-till to moderate-till in continuous corn

Cropland: Continuous Corn
Indiana
Fuel Use for tillage, planting, and herbicide operations

	Annual Fuel Use		
	gal./acre	L/ha	kg C/ha
Intensive-till:			
Disk corn stalks	0.45	4.21	3.6
Moldboard plow	1.68	15.71	13.3
Disk	0.55	5.14	4.4
Field cultivate	0.60	5.61	4.8
Plant	0.50	4.68	4.0
Cultivate	0.45	4.21	3.6
Total	4.23	39.55	33.6
Moderate-till:			
Disk	0.55	5.14	4.4
Field Cultivate	0.60	5.61	4.8
Plant	0.50	4.68	4.0
Total	1.65	15.43	13.1

Tillage-system difference *(years 1- 100)*   -20.5 kg C/ha

Energy Savings Embodied in Machinery Manufacturing, Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-20.5 kg C/ha	
Annual machinery MTR savings	18% of fuel savings	

Annual machinery MTR saving from reducing tillage *(years 1- 100)*   -3.7   kg C/ha

20.2.3.3 N Fertilizer Use

Effects of reducing tillage on the amount of N fertilizer required for corn was discussed in Section 19.2.3.3. The conclusion was that when N is injected well below the decomposing crop residues and is applied close to when the crop needs the N, then the amount of N fertilizer required for Corn in the Corn Belt should not be significantly affected by tillage system. However, with poorly managed N, more N fertilizer will be required with conservation tillage than with intensive tillage. The base case for continuous corn summarized in Table 20-1 assumes that the amount of N fertilizer used in not affected by tillage system. Effects of applying more N fertilizer with no-till than with intensive-till, a case that is applicable when N fertilizer is poorly managed, is presented in Section 20-3.

20.2.3.4 Herbicide Use

The mean annual herbicide rates for intensive-till and no-till continuous corn were estimated from West and Marland[4] as 2.71 and 3.63 kg active ingredient (a.i.)/ha, respectively. West and Marland[4] estimated 4.70 kg C emitted/kg herbicide a.i. used. With these factors, carbon emissions were 4.3 kg C/ha/yr more for no-till than intensive-till. The mean annual herbicide rate for moderate-till corn/soybean rotations was estimated from West and Marland[4] as 2.96 kg a.i./ha. Multiplying (2.96-2.71 kg a.i./ha) by 4.70 kg C emitted/kg herbicide gave 1.2 kg C/ha/yr more for moderate-till than no-till. Example spreadsheet output is presented in Table 20-5.

Table 20-5
Example spreadsheet output for estimating herbicide carbon equivalent emissions for continuous corn

Cropland: Continuous Corn
Indiana
═══ Annual Herbicide Use X Tillage System ═══

	Mean annual herbicide rate kg a.i./ha	kg C/kg herbicide (a.i.)	kg C/ha/yr
Intensive-till continuous corn	**2.71**		
No-till continuous corn	**3.63**		
Difference (years 1- 100)	0.92	4.70	**4.3**

20.2.3.5 N_2O Emissions from Soil

Background on N_2O emissions from soil was provided earlier, indicating that N_2O emissions are dependent on both soil conditions and amount of N fertilizer applied. In this Corn Belt continuous corn case, the amount of N fertilizer applied does not change with tillage system, but soil conditions do change as discussed earlier. Robertson et al.[5] measured effects of switching from intensive-till to no-till in a corn/wheat/soybean rotation on a well drained soil in Michigan. The same N rate was used for both tillage systems and anhydrous ammonia was the primary N source. Switching to no-till increased N_2O emissions from 141 to 152 kg CE/ha/yr. Del Grosso et al.[6] modeled N_2O emissions as affected by switching corn/soybean rotations from intensive-till to no-till on a well drained soil in Indiana. The same N fertilizer rate was assumed for both tillage systems. A specific placement (e.g., knifing or broadcast) of the N fertilizer was not indicated. With these assumptions, N_2O emissions were slightly lower with no-till than intensive-till in both a corn/soybean rotation and continuous corn. Mummey et al.[7] modeled N_2O emissions for intensive-till and no-till systems at 1035 sites for corn and 655 sites for soybeans. These sites represented the range of soil and environmental conditions for these crops in the United States. This modeling effort indicated that in the north central U.S. the mean N_2O-N emissions were 3.04 kg/ha for intensive-till and 3.28 kg/ha for no-till. Taking the difference (0.24 kg N_2O-N/ha) times 126.4 kg N_2O CE/kg N_2O-N gives 30.3 kg N_2O CE/ha/yr. This is a larger increase in N_2O emissions due to switching to no-till than was found by Robertson et al.[5]

and Del Grosso et al.[6], but the latter two studies were on well drained soils whereas the Mummey et al.[7] study covered a range of soil and environmental conditions. On the other hand, Mummey et al.[7] did not account for possible reductions in denitrification and N_2O emissions with knifed N fertilizer applications that are common with anhydrous ammonia in the Corn Belt. The Mummey et al.[7] estimates of increased N_2O emissions due to switching from intensive-till to no-till in the north central U.S. were used as inputs to generate results in Table 20.1 for the continuous corn Corn Belt base case. Example spreadsheet output is presented in Table 20-6.

Table 20-6
Example spreadsheet output for carbon equivalent emissions from changes in N_2O emissions for continuous corn when changing from intensive-till to no-till

Cropland: Continuous Corn
Indiana
Annual Changes in N_2O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till continuous corn	3.04		
No-till continuous corn	3.28		
Difference (*years 1- 100*)	0.24	126.4	30.3

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till continuous corn	150.0		
No-till continuous corn	150.0		
Difference (*years 1- 100*)	0.0	2.65	0.0

Total Difference (*years 1- 100*)   **30.3**

20.2.3.6 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions is presented in Table 20-7. This output corresponds to the first column in Table 20-1.

Table 20-7
Example spreadsheet output summarizing changes in GHG emissions for continuous corn when changing from intensive-till to no-till

Cropland: Continuous Corn
Indiana
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

	kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years 1 - 28)*	-468
CO_2 Emissions from Tillage-System Inputs: *(years 1 - 100)*	
Fuel	-22.9
Machinery MTR	-4.1
N fertilizer	0.0
Herbicides	4.3
Total	-22.7
N_2O Emissions from Soil *(years 1 - 100)*	30.3

Avoided GHG Emissions

	Annual Average	
	kg CE/ha/yr	tonne CE/ha/yr
(years 1 - 28)	460.2	**0.460**
(years 29 - 100)	-7.7	**-0.008**

20.2.4 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 20-8. This output corresponds to the first column in Table 20-1.

Table 20-8
Costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis for continuous corn when changing from intensive-till to no-till

Cropland: Continuous Corn
Indiana
Summary

Process Description

Calculation Method for Sequestering SOC - *Quadratic Plateau*   No-till time period   100   years
Average SOC Sequestered   468   kg C/ha/yr   Release Rate after No-til   1.5   tonne CE/ha/yr
Time until Steady State   28   years

Economic

	Cost $/ha/yr	LC Avoided CE tonne/ha/yr	$/tonne LC avoided CE
Average Annual Costs (years 1 - 1)	56.00	0.927	60.44
(years 2 - 20)	51.00	0.604	84.50
(years 21 - 28)	1.00	0.168	5.97
(years 29 - 100)	1.00	-0.008	-130.16
	($/ha)	(tonne/ha)	($/tonne LC avoided CE)
CO₂ Sink Enhancement, NPV Basis (years 1 - 100)	590.42	7.67	76.95

Continuous Corn in the U.S. Corn Belt
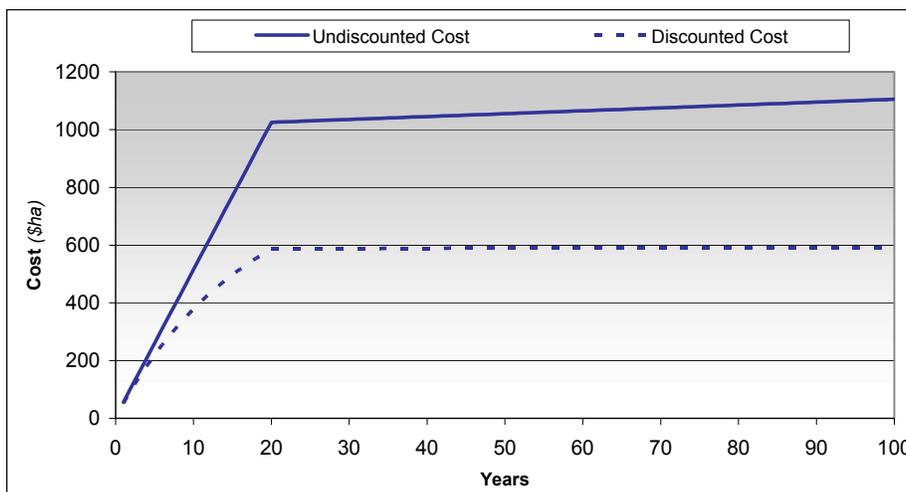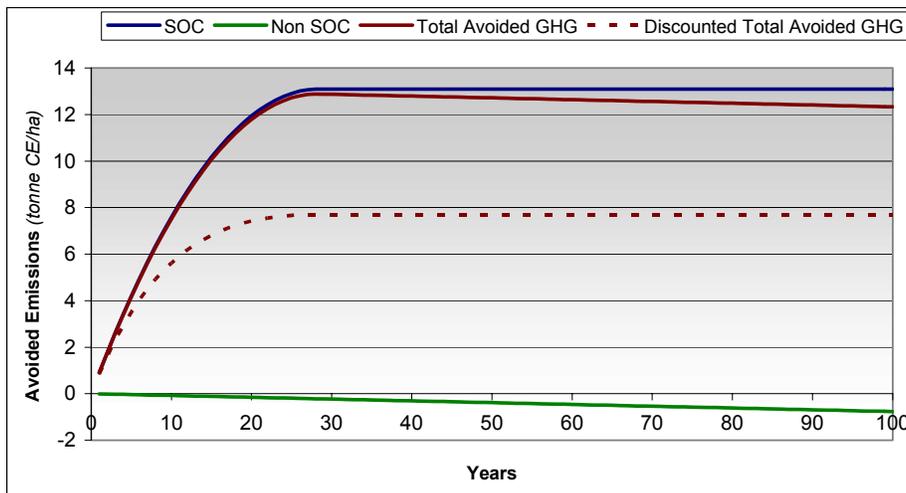
20.2.5 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 20-9. This sensitivity output presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 1500 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 20-9
Continuous corn sensitivity summary

Cropland: Continuous Corn
Indiana
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Quadratic Plateau*
Efficiency Index (Slope Factor)	92
SOC Increase to New Steady State (kg/ha)	13103.5
Time Until Steady State (years)	28
SOC Release Rate after no-till time period (tonne C/ha/yr)	1.5
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$50.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

CO_2 Sink Enhancement Costs *(years 1-100)*

No-till Time Period *(years)*	Farmer Adoption Incentive Time Period *(years)*	**NPV Basis** LC avoided GHG basis *($/tonne C equivalent)*
5	5	320.60
10	10	142.87
15	15	145.55
20	20	128.82
100	5	30.13
100	10	50.51
100	15	65.67
100	20	76.95

20.3 Continuous Corn (Poor N Management Scenario)

This case is the same as the Indiana no-till base case in the last section except that poorer N management (broadcast application of urea) is assumed, resulting in more N fertilizer being required with no-till corn than intensive-till corn. Using more N fertilizer increases GHG emissions associated with N fertilizer use and also increases N_2O emissions. This case assumes 150 kg N/ha for intensive-till and 175 kg N/ha or 200 kg/ha for no-till. These N rates fall within the recommended rates for intensive-till and no-till corn in Kentucky[8].

Table 20-10
Effects of switching from intensive-till Using 150 kg N/ha to no- till Using 175 or 200 kg N/ha on GHG emissions and costs of life-cycle (LC) avoided GHG emissions—Indiana Continuous Corn

Switching from intensive-till to:	No-till	No-till	No-till
N rate, kg/ha	150	175	200
Quadratic SOC response curve			
ΔSOCs, kg C/ha	13104	13104	13104
E (slope factor)	92.0	92.0	92.0
Years to new steady state (Ys)	28	28	28
Average annual increase in SOC (years 1 to Ys), kg C/ha/yr			
	468	468	468
GHG emissions from tillage-system inputs and N_2O (years 1-100), kg CE/ha/y:			
Δ Fuel use	-22.9	-22.9	-22.9
Δ Machinery maintenance, trans., and repair	-4	-4	-4
Δ N fertilizer use	0	21.0	57.4
Δ Herbicide use	4	4	4
Δ Total GHG emissions from inputs	-22.7	6.0	34.7
Δ N_2O emissions from soil	30.3	96.6	162.3
Δ Total GHG emissions	7.6	102.6	197.0
Average LC GHG avoided (kg CE/ha/y)			
Years 1 to Ys	460	365	270
Years Ys to 100	-8	-103	-198
Total LC GHG avoided (years 1-100), tonne CE/ha	12.3	2.8	-6.7
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	7.7	6.1	4.6
Costs, $/ha/y			
Transaction (year 1)	5	5	5
Adoption incentive (years 1-20)	50	50	50
Monitoring (years 1-100)	1	1	1
Total costs (years 1-100), $/ha	1105	1105	1105
NPV Total costs (years 1-100), $/ha	590	590	590
Cost (NPV basis), $/tonne CE LC GHG avoided	77	97	129

A summary of results is presented in Table 20-10. Increasing the N rate every year for corn by 25 kg N/ha increased the cost of avoided GHG from $77 to $97/tonne CE LC avoided. Increasing the N rate for corn by 50 kg N/ha increased the cost of avoided GHG from $77/tonne CE LC avoided to $129/tonne CE LC avoided. These increased costs are due to less avoidance of GHG emissions per dollar invested in adoption incentives and transaction and monitoring costs. Adding an additional 50 kg N/ha every year for corn nearly doubled the cost per tonne CE LC avoided on an NPV basis and resulted in a negative avoidance of GHG emissions on a nondiscounted basis after 100 years (a decrease from 12.3 to -6.7 tonnes CE LC avoided). This emphasizes the importance of efficient N fertilizer management in cropping systems designed to reduce GHG emissions. Details of the effects of increased N fertilizer use on GHG emissions from N fertilizer manufacture, transportation, storage, and application and on N_2O emissions are presented in the next two sections.

20.3.1 N Fertilizer Use

Carbon emissions associated with important combinations of N source and placement are presented in Table 20-11. Emissions from N fertilizer use include manufacture[9] and transportation and storage[10]. Emissions from N fertilizer application are from Langemeier and Taylor[3]. The manufacturing numbers assume that all energy is from natural gas, but a small undermined amount of energy is from electricity. The transportation, storage, and application numbers assume the energy is from diesel fuel.

Table 20-11
Continuous corn carbon emissions associated with important combinations of N source and placement

Cropland: Continuous Corn
Indiana
N Fertilizer Use X Crop and Tillage System

Source/Placement	Annual N fertilizer use kg N/ha	kg C/kg N	kg C/ha	N Appln. kg C/ha	Total kg C/ha
Intensive-till:					
Anhydrous ammonia/knifed	0.0	0.838	0.0	0	0.0
Urea/broadcast	150.0	1.148	172.2	1.6	173.8
UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0
UAN solution/knifed	0.0	1.012	0.0	0.0	0.0
Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0
Total	150.0		172.2	1.6	173.8
No-till:					
Anhydrous ammonia/knifed	0.0	0.838	0.0	0	0.0
Urea/broadcast	175.0	1.148	200.9	1.6	202.5
UAN solution/broadcast	0.0	1.012	0.0	0.0	0.0
UAN solution/knifed	0.0	1.012	0.0	0.0	0.0
Ammonium nitrate/broadcast	0.0	1.021	0.0	0.0	0.0
Total	175.0		200.9	1.6	202.5
Tillage-system difference (*years 1- 100*)	25.0		28.7		**28.7**

Continuous Corn in the U.S. Corn Belt

This case assumes that urea is broadcast for corn in both the intensive-till and no-till systems and that 150 kg N/ha and 175 kg N/ha are required for intensive-till and no-till corn , respectively. This resulted in an annual increase in N fertilizer use of 25 kg N/ha.

The increase in N fertilizer use with no-till was assumed to increase N_2O emissions from soils in accordance with the IPCC default N_2O emission factor for commercial N fertilizer use[11]. The IPCC factor assumes the following:

- Direct N_2O-N emissions = 1.25 percent of applied N

- Indirect N_2O-N emissions from:
  Volatilized NH_3 and NOx = 0.1 percent of applied N
  Leached N = 0.75 percent of applied N

- Total N_2O-N emission = 2.1 percent of applied N
  (i.e., 0.021 kg N_2O-N/kg applied N)

The IPCC factor is converted to a carbon equivalent (CE) radiative forcing basis as follows:

- 1.57 N_2O/N_2O-N

- 296 CO_2 equivalent/N_2O

- 0.272 C equivalent (CE)/CO_2 equivalent

- 1.57 x 296 x .272 CE/N_2O-N
  (126.4 CE/N_2O-N)

Therefore, 1 kg applied N = 0.021 x 126.4 kg CE from N_2O
                                          = 2.65 kg CE from N_2O

The overall increase in N_2O emissions due to both switching from intensive-till to no-till and increasing N fertilizer use was calculated as shown in Table 20-12. Increased N_2O emissions due to tillage-related changes in soil properties and micro-climate (without changes in N fertilizer rate) are based on the same assumptions as in the previous case in which N fertilizer rate didn't change with tillage system.

Table 20-12
Continuous corn overall increase in N₂O emissions due to both switching from intensive-till to no-till and increasing N fertilizer use

Cropland: Continuous Corn
Indiana
Annual Changes in N₂O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till continuous corn	**3.04**		
No-till continuous corn	**3.28**		
Difference (years 1- 100)	0.24	126.4	30.3

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till continuous corn	150.0		
No-till continuous corn	175.0		
Difference (years 1- 100)	25.0	2.65	66.3

	Total Difference (years 1- 100)		**96.6**

20.3.2 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till and increasing N fertilizer use by 25 kg N/ha is presented in Table 20-13. These results correspond to the second column in Table 20-10. Over the course of the 100-year planning horizon, the added N fertilizer use and associated increase in N₂O emissions substantially reduced the amount of GHG emissions avoided (Table 20-14).

Table 20-13
Continuous sorn example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till and increasing N fertilizer use

Cropland: Continuous Corn
Indiana
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

	kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years 1 - 28)*	-468
CO_2 Emissions from Tillage-System Inputs: *(years 1 - 100)*	
Fuel	-22.9
Machinery MTR	-4.1
N fertilizer	28.7
Herbicides	4.3
Total	6.0
N_2O Emissions from Soil *(years 1 - 100)*	96.6

Avoided GHG Emissions

	Annual Average	
	kg CE/ha/yr	tonne CE/ha/yr
(years 1 - 28)	365.2	**0.365**
(years 29 - 100)	-102.6	**-0.103**

20.3.3 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 20-14. This output corresponds to the second column in Table 20-10.

Table 20-14

Continuous corn costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis when changing from intensive-till to no-till and increasing N fertilizer use

Cropland: Continuous Corn
Indiana
Summary

Process Description

Calculation Method for Sequestering SOC - *Quadratic Plateau*			No-till time period	100	years
Average SOC Sequestered	468	kg C/ha/yr	Release Rate after No-til	1.5	tonne CE/ha/yr
Time until Steady State	28	years			

Economic

	Cost $/ha/yr	LC Avoided CE tonne/ha/yr	$/tonne LC avoided CE
Average Annual Costs (*years* 1 - 1)	56.00	0.898	62.37
(*years* 2 - 20)	51.00	0.575	88.72
(*years* 21 - 28)	1.00	0.139	7.20
(*years* 29 - 100)	1.00	-0.103	-9.74
	($/ha)	(tonne/ha)	($/tonne LC avoided CE)
CO_2 Sink Enhancement, NPV Basis (*years* 1 - 100)	590.42	6.12	96.51
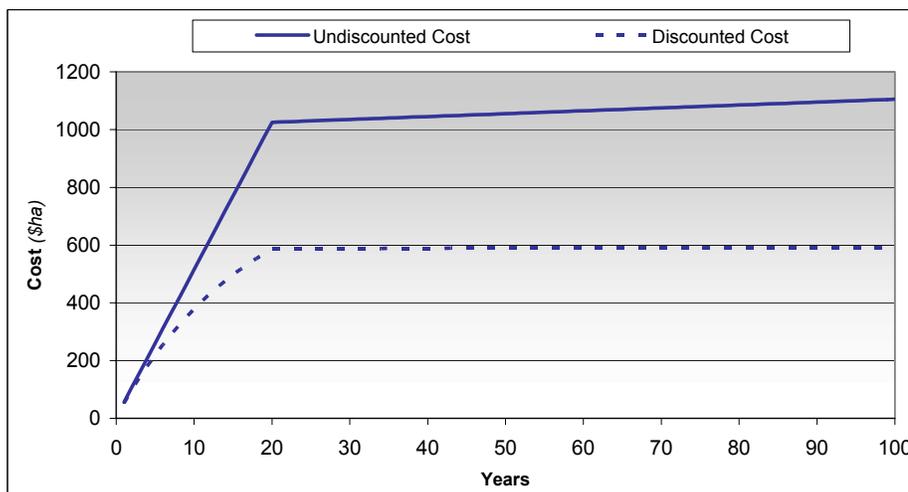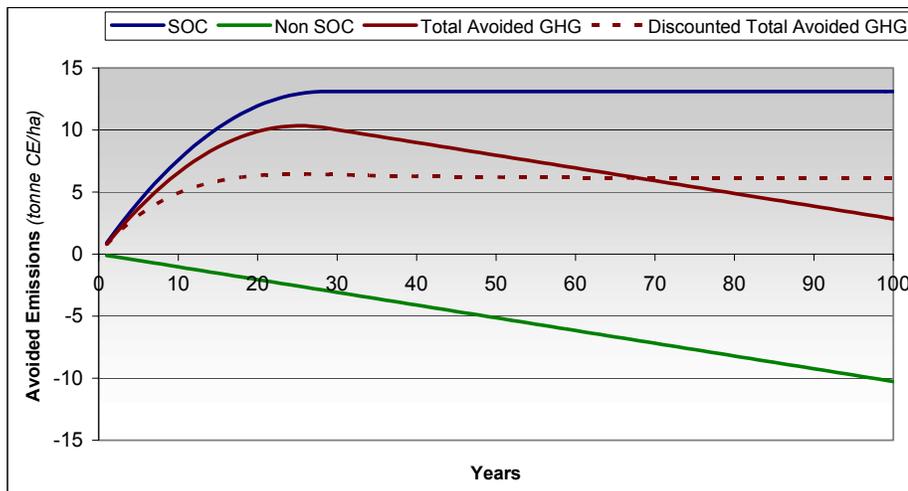
20.3.4 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 20-15. This output corresponds to the second column in Table 20-10 and presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 1500 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 20-15
Continuous corn example spreadsheet sensitivity summary output when changing from intensive-till to no-till and increasing N fertilizer use

Cropland: Continuous Corn
Indiana
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Quadratic Plateau*
Efficiency Index (Slope Factor)	92
SOC Increase to New Steady State (kg/ha)	13103.5
Time Until Steady State (years)	28
SOC Release Rate after no-till time period (tonne C/ha/yr)	1.5
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$50.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

CO_2 Sink Enhancement Costs *(years 1-100)*

No-till Time Period *(years)*	Farmer Adoption Incentive Time Period *(years)*	**NPV Basis** LC avoided GHG basis *($/tonne C equivalent)*
5	5	717.68
10	10	192.17
15	15	197.99
20	20	168.59
100	5	37.79
100	10	63.35
100	15	82.36
100	20	96.51

Continuous Corn in the U.S. Corn Belt

Examples of the large effects of N rate and N_2O emissions on amount of GHG emissions avoided and cost per tonne of GHG avoided are presented in Table 20-16. The scenarios in Table 20-16 are for switching from intensive-till to no-till continuous corn in the Corn Belt. No significant change in N_2O emissions due switching from intensive-till to no-till is a possibility with good N management, especially on well-drained soils. The increases in N rate and N_2O emissions in Table 20-16 due to switching from intensive-till to no-till are possibilities with poor N management. Amounts of GHG avoided range from 15.4 tonnes CE LC GHG avoided/ha with a best-case N rate and N_2O scenario to -6.7 tonnes CE LC GHG avoided/ha for a worst-case scenario. Costs on an NPV basis range from \$72/tonne CE LC GHG avoided with a best-case N rate and N_2O scenario to \$129/tonne CE LC GHG avoided for a worst-case scenario. Differences between the best-case and worst-case scenarios regarding amount of GHG avoided are very large because the annual effects are manifested over the entire 100-year planning horizon. In order for reducing tillage on continuous corn to be a viable option for avoiding GHG emissions, N fertilizer will have to be managed efficiently so that the amount of N fertilizer used and the N_2O emissions are not significantly increased.

Table 20-16
Effects of increases in N rate and N_2O emissions on amounts and costs of avoided GHG via switching from intensive-till to no-Continuous Corn

ΔN rate		ΔN$_2$O	Years 1-100	NPV basis, years 1-100	
kg N/ha/yr	kg/CE/ha/yr	kg/CE/ha/yr	tonne CE LC GHG avoided/ha	tonne CE LC GHG avoided/ha	\$/tonne CE LC GHG avoided[1]
0	0	0	15.4	8.2	72 [2]
0	0	30	12.3	7.7	77 [3]
25	29	97	2.8	6.7	97 [4]
50	58	163	-6.7	4.7	129 [5]

[1] Assumes incentive payments for 20 years.

[2] Base case except for no change in N_2O emissions due to switching to no-till.

[3] Base case (see first column, Table 20-10).

[4] Base case except for an increase in N rate due to switching from to no-till (see second column, Table 20-10).

[5] Base case except for an additional increase in N rate due to switching from to no-till (see third column, Table 20-10).

20.4 References

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21
WHEAT/FALLOW IN THE WESTERN GREAT PLAINS

21.1 Introduction

As indicated in Chapter 18, wheat/fallow systems represent a large land area in the western Great Plains, but the amount of additional carbon sequestered per hectare via reducing tillage is much lower than for con/soybean rotations or continuous corn in the Corn Belt. On the other hand, reducing tillage on wheat/fallow rotations either reduces N_2O emissions or has no significant effect on N_2O emissions and a smaller adoption incentive is required to get farmers to switch from intensive-till to no-till. The net effect is that CO_2 abatement costs per tonne CE LC avoided are not greatly different than for corn/soybean rotations or continuous corn. The base cases (Section 21.2) assume typical levels of carbon sequestration and a small decrease in N_2O emissions due to reducing tillage and the sensitivity cases (Section 21.3) assume typical levels of carbon sequestration and no change in N_2O emissions due to reducing tillage.

21.2 Wheat/Fallow (Base Cases)

A summary of effects of switching from intensive-till to no-till on SOC, GHG emissions, and costs of avoided GHG emissions is presented in Table 21-1 for wheat/fallow systems in the western Great Plains. The bases for the results in Table 21-1 are discussed in the following sections using output from the wheat/fallow spreadsheet model developed for this project. Base cases assuming a reduction in N_2O emissions due to reducing tillage are presented in the first two columns of Table 21-1.

21.2.1 Increases in Soil Organic Carbon

Using the same SOC model for wheat/fallow rotations in Nebraska[1] as for corn/soybean rotations and continuous corn in Iowa[2] and Indiana[3], switching from intensive-till to no-till was predicted to increase SOC an average of 240 kg C/ha/year in Nebraska for the first 10 years after switching from intensive-till to no-till. A Nebraska state average was only provided for the first ten years after switching to no-till but county averages were provided for 10 and 20 years after switching to no-till. For example, the average SOC increase in Kimball County on the western edge of Nebraska was estimated at 140 kg C/ha/year for the first 20 years after switching to no-till. Another approach for estimating regional increases in SOC due to switching from intensive-till to no-till is to use coefficients formulated by the IPCC[4]. These coefficients are for the first 20 years after switching from intensive-till to no-till. Using IPPC coefficients for the Mountain region which is representative of the drier western portion of the Great Plains with predominantly wheat/fallow rotations, switching from intensive-till to no-till resulted in an

estimated weighted-mean increase in SOC of 200 kg C/ha/year. In contrast, a summary of wheat/fallow studies in the Great Plains indicated that switching from intensive-till to no-till resulted in negligible or no increases in SOC[5]. A model simulation[6] indicated that switching from intensive-till to no-till on wheat/fallow systems in eastern Colorado stabilized SOC levels that otherwise were declining over time with intensive-till. Because of the variation in regional estimates of effects of reducing tillage on SOC levels, results are presented in Table 21-1 assuming increases of both 200 and 100 kg C/ha/year for a 20-year period due to switching from intensive-till to no-till in wheat/fallow systems; an increase of 200 kg C/ha/year was chosen as the base case for cost comparisons with other CO_2 sink enhancement or storage options.

Table 21-1
Effects of switching from intensive-till to no-till on SOC, GHG emissions, and costs of life-cycle (LC) avoided GHG emissions—Wheat/Fallow in the western great plains

| Linear SOC response curve	Base-case Δ N_2O		Zero Δ N_2O	
kg C/ha/yr	200	100	200	100
Years to new steady state (Ys)	20	20	20	20
GHG emissions from tillage-system inputs and N_2O (years 1-100), kg CE/ha/y:				
Δ Fuel use	-10.3	-10.3	-10.3	-10.3
Δ Machinery maintenance, trans., and repair	-1.9	-1.9	-1.9	-1.9
Δ N fertilizer use	0	0	0	0
Δ Herbicide use	11.7	11.7	11.7	11.7
Δ Total GHG emissions from inputs	-0.5	-0.5	-0.5	-0.5
Δ N_2O emissions from soil	**-25.3**	**-25.3**	**0**	**0**
Δ Total GHG emissions	-25.8	-25.8	-0.5	-0.5
Average LC GHG avoided (kg CE/ha/y)				
Years 1 to Ys	226	126	201	101
Years Ys to 100	26	26	-1	-1
Total LC GHG avoided (years 1-100), tonne CE/ha	6.6	4.6	4.1	2.1
NPV Total LC GHG avoided (years 1-100), tonne CE/ha	2.7	1.6	2.3	1.2
Costs, $/ha/y				
Transaction (year 1)	5	5	5	5
Adoption incentive (years 1-20)	15	15	15	15
Monitoring (years 1-100)	1	1	1	1
Total costs (years 1-100), $/ha	405	405	405	405
NPV Total costs (years 1-100), $/ha	195	195	195	195
Cost (NPV basis), $/tonne CE LC GHG avoided	71	123	84	167

Example spreadsheet inputs for calculating base-case increases in SOC due to switching from intensive-till to no-till in wheat/fallow systems in the western Great Plains (first column of Table 21-1) are presented in Table 21-2.

Table 21-2
Example process and economic input variables for switching from intensive-till to no-till for wheat/fallow rotation

Cropland: Two-Year Wheat / Fallow Rotation
(Changes Due to Switching from Intensive-Till to No-Till)

Western Great Plains

Process and Economic Input Variables

Process

Alternative Tillage System: **No-till**

Calculation Method for Sequestering Soil Organic Carbon (SOC)
Quadratic Plateau ○
Linear Plateau ◉
    SOC Sequestered until Steady State   **200** kg C/ha/yr
    Years until New Steady State   **20** years

No-till time period   **100** years
SOC Release Rate after no-till time period   **70** kg C/ha/yr

Economic

		Cost $/ha/yr
Transaction Costs	(years 1 - **1**)	**5.00**
Farmer Adoption Incentive to Reduce Tillage	(years 1 - **20**)	**15.00**
Monitoring Costs	(years 1 - **100**)	**1.00**

Discount rate   **6.09%**

21.2.2 Costs

A theoretical basis for estimating conservation-tillage adoption incentives is overviewed in Appendix E and an adoption incentive of $15/ha/year is estimated for switching from intensive-till to no-till in wheat/fallow rotations in the western Great Plains. Transaction costs are based on experience with forestry projects and are estimated at $5/ha. Monitoring costs are assumed to be less than for forestry ($5/ha), assuming that cropland monitoring will be based mainly on monitoring practices that have been correlated with changes in SOC rather than direct measurements of SOC in each field. Monitoring costs of $1/ha/year were assumed.

21.2.3 GHG Effects in Addition to Carbon Storage in Soil Organic Matter

21.2.3.1 Fuel Use

Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in a wheat/fallow rotation are presented in Table 21-3. Fuel usage rates are from Langemeier and Taylor[7].

Table 21-3
Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in a wheat/fallow rotation

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Fuel Use for tillage, planting, and herbicide operations

Wheat Portion				Fallow Portion			
	Annual Fuel Use				Annual Fuel Use		
	gal./acre	L/ha	kg C/ha		gal./acre	L/ha	kg C/ha
Intensive-till:				*Intensive-till:*			
Plant	**0.50**	4.68	4.0	Sweep Plow - 4	**2.40**	22.44	19.1
Spray - 1	**0.10**	0.94	0.8	Rod Weeder - 2	**0.60**	5.61	4.8
Total	0.60	5.61	4.8	Total	3.00	28.05	23.8
No-till:				*No-till:*			
Plant	**0.50**	4.68	4.0	Spray - 3	**0.30**	2.81	2.4
Spray - 2	**0.20**	1.87	1.6	Total	0.30	2.81	2.4
Total	0.70	6.55	5.6				
Tillage-system difference			0.8	Tillage-system difference			-21.4

Mean annual tillage-system difference (years 1- 100)   -10.3 kg C/ha

Energy Savings Embodied in Machinery Manufacturing, Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-10.3 kg C/ha
Annual machinery MTR savings	**18%** of fuel savings

Annual machinery MTR saving from reducing tillage (years 1- 100)   -1.9 kg C/ha

21.2.3.2 Machinery Manufacture, Transportation, and Repair

Reductions in machinery manufacture, transportation, and repair (MTR) and associated carbon emissions by switching from intensive-till to no-till wheat/fallow rotations were calculated as 18 percent of the fuel savings (Tables 21-3). The 18 percent factor is based on ratios of tillage-system fuel use and machinery MTR in a national analysis of tillage-system effects on GHG emissions[8].

21.2.3.3 N Fertilizer Use

In drier climates such as the western Great Plains, reducing tillage has less potential for affecting the amount of N fertilizer required. Switching from intensive-till to no-till in wheat/fallow systems in the western Great Plains is assumed to have no effect on the amount of N fertilizer required.

21.2.3.4 Herbicide Use

In wheat/fallow systems, a switch from intensive-till to no-till involves substituting contact herbicide for tillage operations during the fallow period. A herbicide rate of 3.0 kg active ingredient/ha during the fallow period is assumed[9]. This translates to an average of 1.5 kg active ingredient/ha/year averaged over the entire wheat/fallow rotation. An estimate of 7.80 kg C emitted/kg contact herbicide was used (personal communication, T.O. West, Oak Ridge National Laboratory). Example spreadsheet output is presented in Table 21-4.

Table 21-4
Example spreadsheet output for estimating herbicide carbon equivalent emissions for wheat/fallow rotation

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Annual Herbicide Use X Tillage System

	Mean annual herbicide rate kg a.i./ha	kg C/kg herbicide (a.i.)	kg C/ha/yr
Intensive-till wheat/fallow rotation	0.00		
No-till wheat/fallow rotation	1.50		
Difference (years 1- 100)	1.50	7.80	11.7

21.2.3.5 N_2O Emissions from Soil

Background on N_2O emissions from soil was provided earlier, indicating that N_2O emissions are dependent on both soil conditions and amount of N fertilizer applied. In this western Great Plains wheat/fallow case, the amount of N fertilizer applied does not change with tillage system, but soil conditions do change as discussed Chapter 18. Del Grosso et al.[6] modeled N_2O emissions as affected by switching wheat/fallow rotations from intensive-till to no-till on a well drained soil in eastern Colorado. The same N fertilizer rate was assumed for both tillage systems. A specific placement (e.g., knifing or broadcast) of the N fertilizer was not indicated. With these assumptions, N_2O emissions were slightly lower with no-till than intensive-till. Mummey et al.[10] modeled N_2O emissions for intensive-till and no-till wheat systems at 467 sites. These sites represented the range of soil and environmental conditions for wheat in the United States and wheat/fallow systems represent a significant portion of the wheat producing area. This modeling effort estimated mean N_2O-N emissions of 4.8 kg/ha/year for intensive-till and

4.6 kg/ha/year for no-till. Taking the difference (-0.2 kg N_2O-N/ha/year) times 126.4 kg N_2O CE/kg N_2O-N gives -25.3 kg N_2O CE/ha/year. This estimate was used for the base cases in Table 21-1. Example spreadsheet output is presented in Table 21-5.

Table 21-5
Example spreadsheet output for carbon equivalent emissions from changes in N_2O emissions for wheat/fallow rotation when changing from intensive-till to no-till

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Annual Changes in N_2O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till wheat/fallow rotation	4.80		
No-till wheat/fallow rotation	4.60		
Difference (*years 1- 100*)	-0.20	126.4	-25.3

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till wheat/fallow rotation	35.0		
No-till wheat/fallow rotation	35.0		
Difference (*years 1- 100*)	0.0	2.65	0.0

	Total Difference (*years 1- 100*)	**-25.3**

21.2.3.6 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions is presented in Table 21-6. This output corresponds to the first column in Table 21-1.

Table 21-6
Example spreadsheet output summarizing changes in GHG emissions for wheat/fallow rotation when changing from intensive-till to no-till

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

	kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years 1 - 20)*	-200
CO_2 Emissions from Tillage-System Inputs: *(years 1 - 100)*	
Fuel	-10.3
Machinery MTR	-1.9
N fertilizer	0.0
Herbicides	11.7
Total	-0.5
N_2O Emissions from Soil *(years 1 - 100)*	-25.3

Avoided GHG Emissions

	Annual Average	
	kg CE/ha/yr	tonne CE/ha/yr
(years 1 - 20)	225.8	**0.226**
(years 21 - 100)	25.8	**0.026**

21.2.4 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 21-7. This output corresponds to the first column in Table 21-1.

**Table 21-7
Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a
carbon equivalent (CE) basis for wheat/fallow rotation when changing from intensive-till to
no-till**

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Summary

Process Description

Calculation Method for Sequestering SOC -	*Linear Plateau*		No-till time period	100	years
Average SOC Sequestered	200	kg C/ha/yr	Release Rate after No-till	0.07	tonne CE/ha/yr
Time until Steady State	20	years			

Economic

	Cost	LC Avoided CE	
	($/ha/yr)	*(tonne/ha/yr)*	*($/tonne LC avoided CE)*
Average Annual Costs *(years 1 - 1)*	21.00	0.226	93.02
(years 2 - 20)	16.00	0.226	70.87
(years 21 - 100)	1.00	0.026	38.82
	($/ha)	*(tonne/ha)*	*($/tonne LC avoided CE)*
CO$_2$ Sink Enhancement, NPV Basis *(years 1 - 100)*	191.89	2.70	71.09
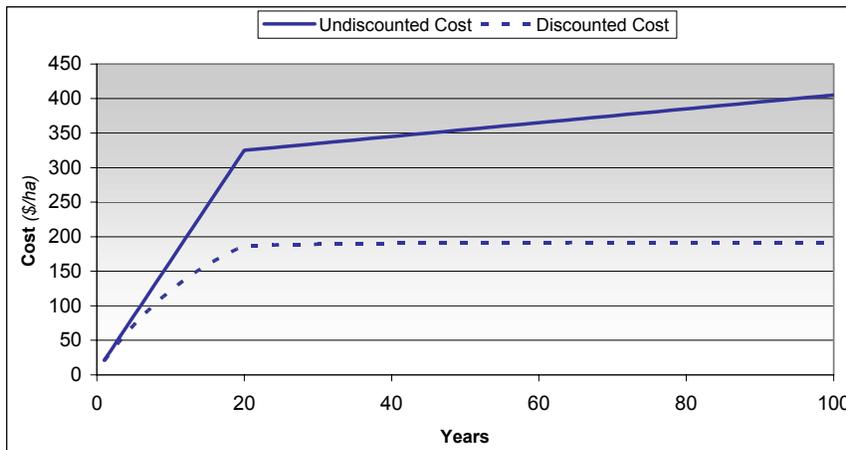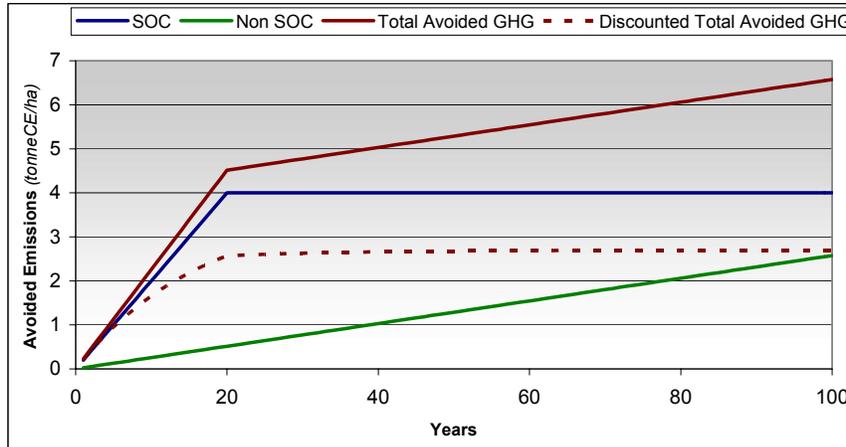
21.2.5 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 21-8. This sensitivity output presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 70 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 21-8
Wheat/fallow rotation sensitivity summary

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Linear Plateau*
SOC Sequestered until Steady State (kg C/ha/yr)	200
Time Until Steady State (years)	20
SOC Release Rate after no-till time period (tonne C/ha/yr)	0.07
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$15.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

Update
Values

CO$_2$ Sink Enhancement Costs (100 year summation)

No-till Time Period (years)	Farmer Adoption Incentive Time Period (years)	**NPV Basis** LC avoided basis (*$/tonne C equivalent*)
5	5	182.45
10	10	115.36
15	15	95.15
20	20	86.04
100	5	31.17
100	10	48.54
100	15	61.47
100	20	71.09

21.3 Wheat/Fallow (Sensitivity Cases with No Tillage Effect on N_2O Emissions)

These cases are the same as the western Great Plains wheat/fallow base cases in Section 21.2 except that no change in N_2O emissions is assumed as a result of reducing tillage. These cases correspond to columns 3 and 4 of Table 21-1. Assuming no decrease in N_2O emissions due to switching from intensive-till to no-till results in somewhat higher costs of CO_2 abatement ($84 vs. $71/tonne CE LC avoided in the 200 kg SOC/ha/year case and $167 vs. $123/tonne CE LC avoided in the 100 kg SOC/ha/year case). The bases for the results in columns 3 and 4 in Table 21-1 are discussed in the following sections using output from the wheat/fallow spreadsheet model developed for this project.

21.3.1 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till wheat/fallow systems with no change in N_2O emissions is presented in Table 21-9. These results correspond to the third column in Table 21-1.

Table 21-9
Wheat/fallow example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till with no change in N_2O emissions

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

				kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered	*(years*	*1 - 20*	*)*	-200
CO_2 Emissions from Tillage-System Inputs:	*(years*	*1 - 100*	*)*	
Fuel				-10.3
Machinery MTR				-1.9
N fertilizer				0.0
Herbicides				11.7
Total				-0.5
N_2O Emissions from Soil	*(years*	*1 - 100*	*)*	0.0

Avoided GHG Emissions

				Annual Average	
				kg CE/ha/yr	tonne CE/ha/yr
	(years	*1 - 20*	*)*	200.5	**0.200**
	(years	*21 - 100*	*)*	0.5	**0.000**

21.3.2 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 21-10. This output corresponds to the third column in Table 21-1.

21.3.3 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 21-11. This output corresponds to the third column in Table 21-1 and presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 70 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 21-10
Wheat/fallow costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis when changing from intensive-till to no-till with no change in N_2O emissions

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Summary

Process Description

Calculation Method for Sequestering SOC -	*Linear Plateau*		No-till time period	100	years
Average SOC Sequestered	200	kg C/ha/yr	Release Rate after No-till	0.07	tonne CE/ha/yr
Time until Steady State	20	years			

Economic

	Cost ($/ha/yr)	LC Avoided CE (tonne/ha/yr)	($/tonne LC avoided CE)
Average Annual Costs *(years 1 - 1)*	21.00	0.200	104.75
(years 2 - 20)	16.00	0.200	79.81
(years 21 - 100)	1.00	0.000	2095.90
	($/ha)	*(tonne/ha)*	*($/tonne LC avoided CE)*
CO_2 Sink Enhancement, NPV Basis *(years 1 - 100)*	191.89	2.29	83.97
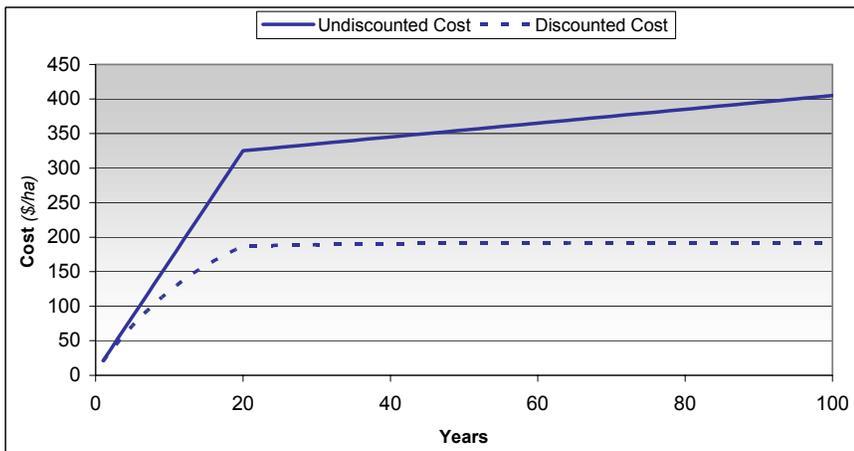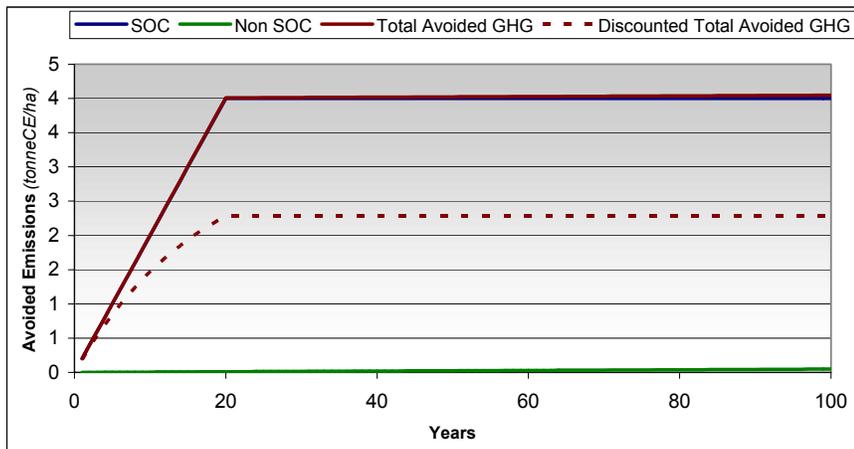
Table 21-11
Wheat/fallow example spreadsheet sensitivity summary output when changing from intensive-till to no-till with no change in N$_2$O emissions

Cropland: Two-Year Wheat / Fallow Rotation
Western Great Plains
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO$_2$	*Linear Plateau*
SOC Sequestered until Steady State (kg C/ha/yr)	200
Time Until Steady State (years)	20
SOC Release Rate after no-till time period (tonne C/ha/yr)	0.07
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$15.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

5 years
10 years
15 years
20 years

Push the adjacent button to update the sensitivity summary costs below.

Update Values

CO$_2$ Sink Enhancement Costs *(100 year summation)*

No-till Time Period (years)	Farmer Adoption Incentive Time Period (years)	**NPV Basis** LC avoided basis ($/tonne C equivalent)
5	5	182.45
10	10	115.36
15	15	95.15
20	20	86.04
100	5	31.17
100	10	48.54
100	15	61.47
100	20	71.09

21.4 References

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22
COTTON IN THE SOUTHEASTERN UNITED STATES

22.1 Introduction

Cotton is grown primarily in the southeastern United States. Switching from intensive-till to no-till cotton results in somewhat greater increases in SOC than in wheat/fallow systems, primarily because with cotton there is no fallow period and cotton residues are added to the soil each year. However, primarily because of the warmer more humid climate in the southeast, switching from intensive-till to no-till cotton results in significant increases in N_2O emissions in contrast to the slight decreases in N_2O emissions for wheat/fallow. A larger adoption incentive is required to get farmers to switch from intensive-till to no-till cotton than is the case for wheat/fallow. The net effect of the above factors is that CO_2 abatement costs per tonne CE LC avoided are significantly greater for cotton than for wheat/fallow. The base cases (Section 22.2) assume typical levels of carbon sequestration and a large increase in N_2O emissions due to reducing tillage and the sensitivity cases (Section 22.3) assume typical levels of carbon sequestration and no change in N_2O emissions due to reducing tillage.

22.2 Cotton (Base Cases)

A summary of effects of switching from intensive-till to no-till on SOC, GHG emissions, and costs of avoided GHG emissions is presented in Table 22-1 for cotton in the southeast. The bases for the results in Table 22-1 are discussed in the following sections using output from the cotton spreadsheet model developed for this project. Base cases assuming an increase in N_2O emissions due to reducing tillage are presented in the first two columns of Table 22-1.

22.2.1 Increases in Soil Organic Carbon

A summary of cotton studies in the southeastern U.S. indicated that switching from intensive-till to no-till resulted in an average increase in SOC of about 300 kg/ha/year for the first 10 to 15 years after switching from intensive-till to no-till[1].   Using IPPC coefficients for the southeastern U.S., switching from intensive-till to no-till resulted in an estimated weighted-mean increase in SOC of 200 kg C/ha/year for the first 20 years after switching from intensive-till to no-till[2]. Cotton is a significant component of the cropping systems in the southeastern U.S. Using IPPC coefficients for the Mississippi Delta region of the United States which also includes a significant land area in cotton, switching from intensive-till to no-till resulted in an estimated weighted-mean increase in SOC of 520 kg C/ha/year for the first 20 years after switching from intensive-till to no-till[2]. Because of the variation in regional estimates of effects of reducing tillage on SOC levels, results are presented in Table 22-1 assuming increases of both 300 and

150 kg C/ha/year for a 20-year period due to switching from intensive-till to no-till in cotton systems; an increase of 300 kg C/ha/year was chosen as the base case for cost comparisons with other CO_2 sink enhancement or storage options.

Table 22-1
Effects of switching from intensive-till to no-till on SOC, GHG emissions, and costs of life-cycle (LC) avoided GHG emissions—Cotton in the southeastern United States

Linear SOC response curve	Base-case Δ N₂O		Zero Δ N₂O	
kg C/ha/yr	300	150	300	150
Years to new steady state (Ys)	20	20	20	20
GHG emissions from tillage-system inputs and N₂O (years 1-100), kg CE/ha/y:				
Δ Fuel use	-23.8	-23.8	-23.8	-23.8
Δ Machinery maint., trans., and repair	-4.3	-4.3	-4.3	-4.3
Δ N fertilizer use	0.0	0.0	0.0	0.0
Δ Herbicide use	0.0	0.0	0.0	0.0
Δ Total GHG emissions from inputs	-28.1	-28.1	-28.1	-28.1
Δ N₂O emissions from soil	**63.2**	**63.2**	**0**	**0**
Δ Total GHG emissions	35.1	35.1	-28.1	-28.1
Average LC GHG avoided (kg CE/ha/y)				
Years 1 to Ys	265	115	328	178
Years Ys to 100	-35.1	-35.1	28.1	28.1
Total LC GHG avoided (years 1-100),				
tonne CE/ha	1.0	-1.3	7.3	5.1
NPV Total LC GHG avoided (years 1-100),				
tonne CE/ha	2.3	0.9	3.4	1.9
Costs, $/ha/y				
Transaction (year 1)	5	5	5	5
Adoption incentive (years 1-20)	25	25	25	15
Monitoring (years 1-100)	1	1	1	1
Total costs (years 1-100), $/ha	605	605	605	605
NPV Total costs (years 1-100), $/ha	306	306	306	306
Cost (NPV basis), $/tonne CE LC GHG avoided	132	350	91	160

Example spreadsheet inputs for calculating base-case increases in SOC due to switching from intensive-till to no-till in cotton in the southeastern U.S. (first column of Table 22-1) are presented in Table 22-2.

Table 22-2
Example process and economic input variables for switching from intensive-till to no-till for cotton

Cropland: Cotton
(Changes Due to Switching from Intensive-Till to No-Till)

Southeastern United States
Process and Economic Input Variables

Process

Alternative Tillage System: **No-till**

Calculation Method for Sequestering Soil Organic Carbon (SOC)
Quadratic Plateau ○
Linear Plateau ◉

SOC Sequestered until Steady State	**300**	kg C/ha/yr
Years until New Steady State	**15**	years
No-till time period	**100**	years
SOC Release Rate after no-till time period	**100**	kg C/ha/yr

Economic

		Cost $/ha/yr
Transaction Costs	(years 1–**1**)	**5.00**
Farmer Adoption Incentive to Reduce Tillage	(years 1–**20**)	**25.00**
Monitoring Costs	(years 1–**100**)	**1.00**

Discount rate **6.09%**

22.2.2 Costs

A theoretical basis for estimating conservation-tillage adoption incentives is overviewed in Appendix E and an adoption incentive of $25/ha/year is estimated for switching from intensive-till to no-till cotton in the southeastern U.S. Transaction costs are based on experience with forestry projects and are estimated at $5/ha. Monitoring costs are assumed to be less than for forestry ($5/ha), assuming that cropland monitoring will be based mainly on monitoring practices that have been correlated with changes in SOC rather than direct measurements of SOC in each field. Monitoring costs of $1/ha/year were assumed.

22.2.3 GHG Effects in Addition to Carbon Storage in Soil Organic Matter

22.2.3.1 Fuel Use

Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till in cotton are presented in Table 22-3. Fuel usage rates are from Langemeier and Taylor[3].

Table 22-3
Reductions in fuel use and associated carbon emissions by switching from intensive-till to no-till for cotton

Cropland: Cotton
Southeastern United States
Fuel Use for tillage, planting, and herbicide operations

| | Annual Fuel Use | | |
	gal./acre	L/ha	kg C/ha
Intensive-till:			
Chisel plow	0.60	5.61	4.8
Disk	0.55	5.14	4.4
Cultimulcher	0.60	5.61	4.8
Sprayer - 7	0.70	6.55	5.6
Plant	0.50	4.68	4.0
Cultivate - 3	1.35	12.62	10.7
Total	4.30	40.21	34.1
No-till:			
Chop stalks	0.75		
Burndown	0.10	0.94	0.8
Plant	0.50	4.68	4.0
Sprayer - 7	0.70	6.55	5.6
Total	2.05	12.16	10.3

Tillage-system difference (years 1- 100)   -23.8 kg C/ha

Energy Savings Embodied in Machinery Manufacturing, Transportation, & Repair (MTR)

Annual fuel saving from reducing tillage	-23.8 kg C/ha
Annual machinery MTR savings	18% of fuel savings

Annual machinery MTR saving from reducing tillage (years 1- 100)   -4.3 kg C/ha

22.2.3.2 Machinery Manufacture, Transportation, and Repair

Reductions in machinery manufacture, transportation, and repair (MTR) and associated carbon emissions by switching from intensive-till to no-till cotton were calculated as 18 percent of the fuel savings (Tables 22-3). The 18 percent factor is based on ratios of tillage-system fuel use and machinery MTR in a national analysis of tillage-system effects on GHG emissions[4].

22.2.3.3 N Fertilizer Use

N rate recommendations for cotton generally are not adjusted for tillage system in the southeastern U.S. Switching from intensive-till to no-till cotton is assumed to have no effect on the amount of N fertilizer required.

22.2.3.4 Herbicide Use

With the advent of herbicide resistant cotton, herbicide use doesn't differ significantly with intensive-till and no-till cotton. Intensive-till and no-till cotton were assumed to involve the same herbicide usage as presented in Table 22-4.

Table 22-4
Example spreadsheet output for estimating herbicide carbon equivalent emissions for cotton

Cropland: Cotton
Southeastern United States
Annual Herbicide Use X Tillage System

	Mean annual herbicide rate kg a.i./ha	kg C/kg herbicide (a.i.)	kg C/ha/yr
Intensive-till cotton	**2.71**		
No-till cotton	**2.71**		
Difference (years 1- 100)	0.00	4.70	**0.0**

22.2.3.5 N$_2$O Emissions from Soil

Background on N$_2$O emissions from soil was provided earlier, indicating that N$_2$O emissions are dependent on both soil conditions and amount of N fertilizer applied. In cotton, the amount of N fertilizer applied does not change with tillage system, but soil conditions do change as discussed Chapter 18. The relatively warm, humid climate in the southeastern U.S. is relatively conducive to N$_2$O emissions. Mummey et al.[5] modeled N$_2$O emissions for intensive-till and no-till cotton at 160 sites. These sites represented the range of soil and environmental conditions for cotton in the United States. This modeling effort estimated mean N$_2$O-N emissions of 6.5 kg/ha/year for

intensive-till and 7.0 kg/ha/year for no-till. Taking the difference (0.5 kg N_2O-N/ha/year) times 126.4 kg N_2O CE/kg N_2O-N gives 63.2 kg N_2O CE/ha/year. This estimate was used for the base cases in Table 22-1. Example spreadsheet output is presented in Table 22-5.

Table 22-5
Example spreadsheet output for carbon equivalent emissions from changes in N_2O emissions for cotton when changing from intensive-till to no-till

Cropland: Cotton
Southeastern United States
Annual Changes in N_2O Emissions

Due to Tillage-Related Changes in Soil Properties & Micro-Climate

	Annual kg N_2O-N/ha	kg N_2O CE/kg N_2O-N	kg N_2O CE/ha/yr
Intensive-till cotton	6.50		
No-till cotton	7.00		
Difference (years 1- 100)	0.50	126.4	63.2

Associated with Changes in N Application Rate

	Mean annual N rate kg N/ha	IPCC emission factor kg N_2O CE /kg N applied	kg N_2O CE/ha/yr
Intensive-till cotton	60.0		
No-till cotton	60.0		
Difference (years 1- 100)	0.0	2.65	0.0

Total Difference (years 1- 100) **63.2**

22.2.3.6 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions is presented in Table 22-6. This output corresponds to the first column in Table 22-1.

Table 22-6
Example spreadsheet output summarizing changes in GHG emissions for cotton when changing from intensive-till to no-till

Cropland: Cotton
Southeastern United States
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

		kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years 1 - 15)*		-300
CO_2 Emissions from Tillage-System Inputs: *(years 1 - 100)*		
Fuel		-23.8
Machinery MTR		-4.3
N fertilizer		0.0
Herbicides		0.0
Total		-28.1
N_2O Emissions from Soil *(years 1 - 100)*		63.2

Avoided GHG Emissions

|	*Annual Average*	
	kg CE/ha/yr	tonne CE/ha/yr
(years 1 - 15)	264.9	**0.265**
(years 16 - 100)	-35.1	**-0.035**

22.2.4 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 22-7. This output corresponds to the first column in Table 22-1.

Cotton in the Southeastern United States

Table 22-7
Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis for cotton when changing from intensive-till to no-till

Cropland: Cotton
Southeastern United States
Summary

Process Description

Calculation Method for Sequestering SOC - *Linear Plateau*   No-till time period   100   years
Average SOC Sequestered   300   kg C/ha/yr   Release Rate after No-till   0.1   tonne CE/ha/yr
Time until Steady State   15   years

Economic

		Cost $/ha/yr	LC Avoided CE tonne/ha/yr	$/tonne LC avoided CE
Average Annual Costs *(years 1 - 1)*		31.00	0.265	117.02
(years 2 - 15)		26.00	0.265	98.15
(years 16 - 20)		26.00	-0.035	-740.76
(years 21 - 100)		1.00	-0.035	-28.49
		($/ha)	*(tonne/ha)*	*'$/tonne LC avoided CE)*
CO_2 Sink Enhancement, NPV Basis *(years 1 - 100)*		305.75	2.322	131.69
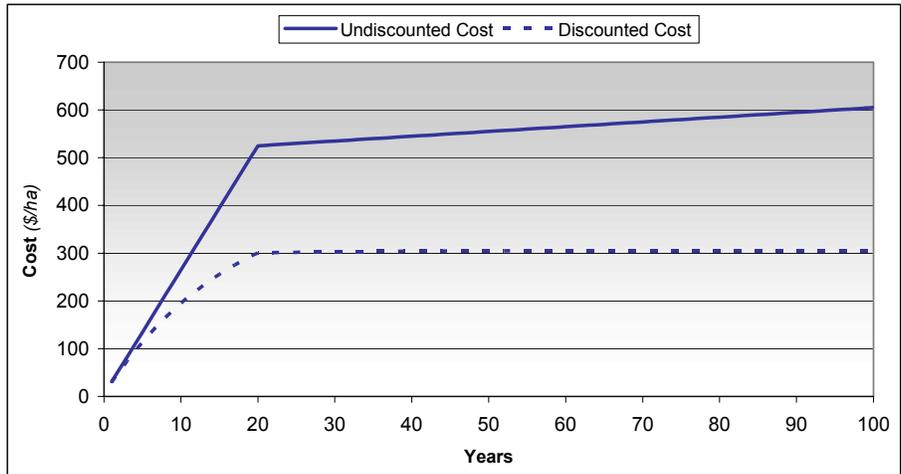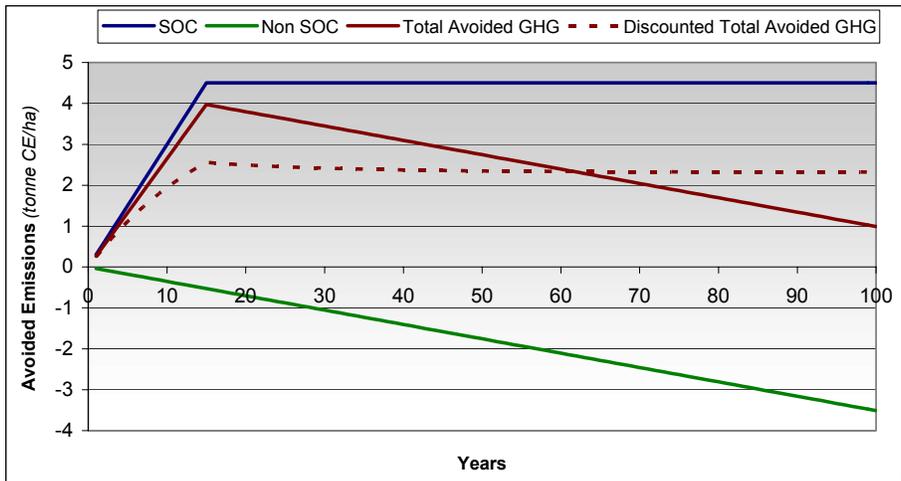
22.2.5 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 22-8. This sensitivity output presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till cotton is switched back to intensive-till, SOC levels decrease at a rate of 70 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 22-8
Cotton rotation sensitivity summary

Cropland: Cotton
Southeastern United States
Sensitivity Summary

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Linear Plateau*
SOC Sequestered until Steady State (kg C/ha/yr)	300
Time Until Steady State (years)	15
SOC Release Rate after no-till time period (tonne C/ha/yr)	0.1
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$25.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed	**5 years** **10 years** **15 years** **20 years**

Push the adjacent button to update the sensitivity summary costs below.

CO_2 Sink Enhancement Costs *(years 1-100)*

No-till Time Period *(years)*	Farmer Adoption Incentive Time Period *(years)*	**NPV Basis** LC avoided GHG basis *($/tonne C equivalent)*
5	5	234.84
10	10	172.19
15	15	135.16
20	20	149.97
100	5	54.33
100	10	87.99
100	15	113.05
100	20	131.69

22.3 Cotton (Sensitivity Cases with No Tillage Effect on N_2O Emissions)

These cases are the same as the cotton base cases in Section 22.2 except that no change in N_2O emissions is assumed as a result of reducing tillage. These cases correspond to columns 3 and 4 of Table 22-1. Assuming no increase in N_2O emissions due to switching from intensive-till to no-till results in significantly lower costs of CO_2 abatement (\$132 vs. \$91/tonne CE LC avoided in the 300 kg SOC/ha/year case and \$350 vs. \$160/tonne CE LC avoided in the 150 kg SOC/ha/year case). The bases for the results in columns 3 and 4 in Table 22-1 are discussed in the following sections using output from the cotton spreadsheet model developed for this project.

22.3.1 Summary of Avoided GHG Emissions

Example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till cotton with no change in N_2O emissions is presented in Table 22-9. These results correspond to the third column in Table 22-1.

Table 22-9
Cotton example spreadsheet output summarizing changes in GHG emissions due to switching from intensive-till to no-till with no change in N_2O emissions

Cropland: Cotton
Southeastern United States
Life Cycle (LC) Avoided GHG Emissions
(Due to Switching from Intensive-Till to No-Till)

Changes in GHG Emissions

				kg CE/ha/yr
Average Soil Organic Carbon (SOC) sequestered *(years	1	- 15	)*	-300
CO_2 Emissions from Tillage-System Inputs: *(years	1	- 100	)*	
Fuel				-23.8
Machinery MTR				-4.3
N fertilizer				0.0
Herbicides				0.0
Total				-28.1
N_2O Emissions from Soil *(years	1	- 100	)*	0.0

Avoided GHG Emissions

				Annual Average	
				kg CE/ha/yr	tonne CE/ha/yr
*(years	1	- 15	)*	328.1	**0.328**
*(years	16	- 100	)*	28.1	**0.028**

22.3.2 Summary

Example spreadsheet output summarizing costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis is presented in Table 22-10. This output corresponds to the third column in Table 22-1.

22.3.3 Sensitivity Summary

Example spreadsheet sensitivity summary output is presented in Table 22-11. This sensitivity output corresponds to the third column in Table 22-1 and presents costs assuming adoption incentive payments for 5, 10, 15, and 20 years. These costs are presented assuming that no-till is maintained for the full 100-year planning horizon or for only as long as adoption incentives are paid to the farmer, after which the land is converted back to intensive-till. This analysis assumes that when no-till is switched back to intensive-till, SOC levels decrease at a rate of 70 kg/ha/yr. A base case of incentive payments for 10 years was selected for comparing costs with other CO_2 sink enhancement or storage options.

Table 22-10
Cotton costs and life-cycle (LC) avoided GHG on a carbon equivalent (CE) basis when changing from intensive-till to no-till with no change in N$_2$O emissions

Cropland: Cotton
Southeastern United States
Summary

Process Description

Calculation Method for Sequestering SOC -	*Linear Plateau*		No-till time period	100	years
Average SOC Sequestered	300	kg C/ha/yr	Release Rate after No-till	0.1	tonne CE/ha/yr
Time until Steady State	15	years			

Economic

	Cost	LC Avoided CE	
	$/ha/yr	tonne/ha/yr	$/tonne LC avoided CE
Average Annual Costs *(years 1 - 1)*	31.00	0.328	94.48
(years 2 - 15)	26.00	0.328	79.24
(years 16 - 20)	26.00	0.028	925.23
(years 21 - 100)	1.00	0.028	35.59
	($/ha)	(tonne/ha)	'$/tonne LC avoided CE)
CO$_2$ Sink Enhancement, NPV Basis *(years 1 - 100)*	305.75	3.357	91.08
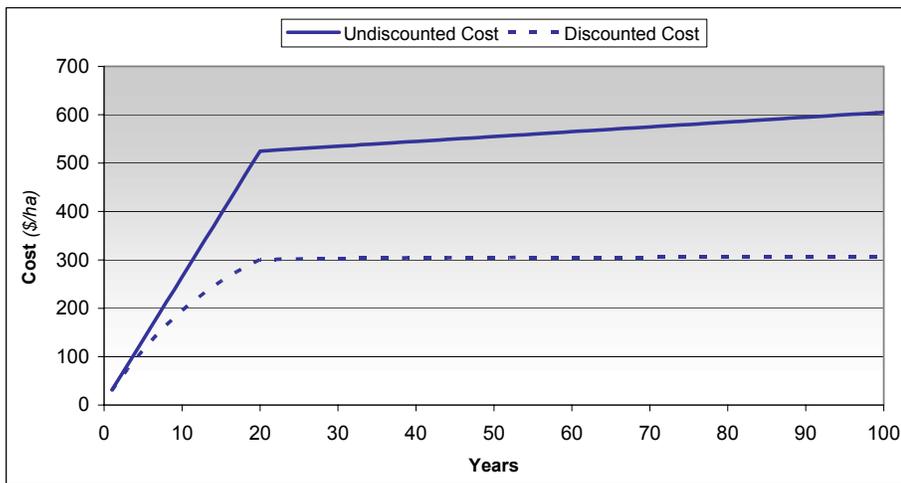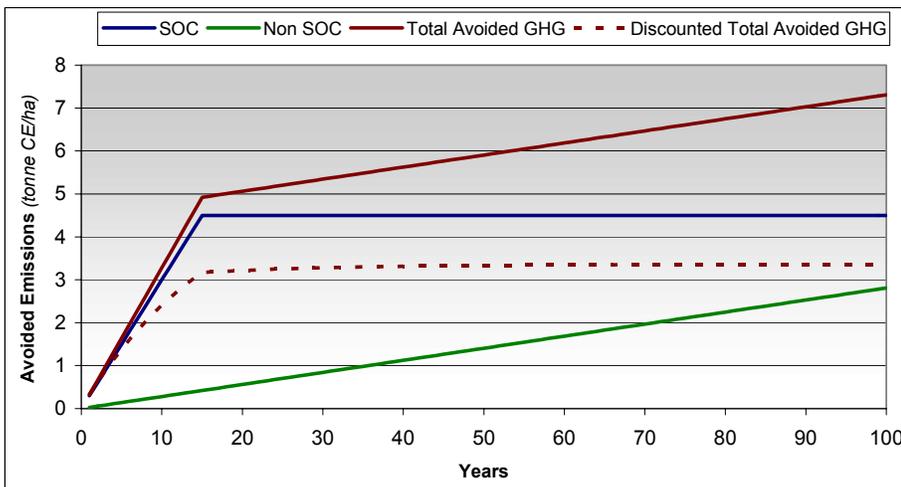
Table 22-11
Cotton example spreadsheet sensitivity summary output when changing from intensive-till to no-till with no change in N$_2$O emissions

<div align="center">

Cropland: Cotton
Southeastern United States
Sensitivity Summary

</div>

Current Input Variable Values

Calculation Method for Sequestering CO_2	*Linear Plateau*
SOC Sequestered until Steady State (kg C/ha/yr)	300
Time Until Steady State (years)	15
SOC Release Rate after no-till time period (tonne C/ha/yr)	0.1
Farmer Adoption Incentive to Reduce Tillage ($/ha/yr)	$25.00
Transaction Costs	$5.00
Transaction Time Period (years)	1
Monitoring Costs	$1.00
Monitoring Time Period (years)	100
After-Tax Discount Rate	6.09%

Sensitivity Input

Farmer Adoption Incentive Time Period Viewed

> **5 years**
> **10 years**
> **15 years**
> **20 years**

Push the adjacent button to update the sensitivity summary costs below.

CO$_2$ Sink Enhancement Costs *(years 1-100)*

No-till Time Period *(years)*	Farmer Adoption Incentive Time Period *(years)*	**NPV Basis** LC avoided GHG basis *($/tonne C equivalent)*
5	5	157.14
10	10	123.84
15	15	102.84
20	20	110.85
100	5	37.58
100	10	60.86
100	15	78.19
100	20	91.08

22.4 References

1   West, Tristram O. and Wlfred M. Post. 2002. Soil organic carbon sequestration rates for crops with reduced tillage and enhanced rotation. Submitted to Soil Science Society of America Journal.

2   Eve, M.D., M. Sperow, K. Howerton, K. Paustian, and R.F. Follett. 2002. Predicted impact of management changes on soil carbon storage for each cropland region of the conterminous United States. J. Soil and Water Conservation. 57 (4) 196-204.

3   Langemeier, L.N. and R.K. Taylor. 1998. A look at machinery cost. Kansas Farm Management Guide, MF-842. Kansas State University, Department of Agricultural Economics.

4   West, Tristram O. and Gregg Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems, and Environment (in press)

5   Mummey, Daniel L., Jeffrey L. Smith, and George Blum. 1998. Assessment of alternative soil management practices on N2O emissions from U.S. agriculture. Agriculture, Ecosystems, and Environment 70:79-87.

23
SUMMARY COMPARISONS AND CONCLUSIONS

Presented in this chapter are comparisons among options evaluated in this project and between CO_2 capture, transport and storage and indirect capture by forests and cropland via reducing tillage using the costs of capture from another EPRI study[1].

23.1 Transport and Storage

Shown in Table 23-1 is a comparison of the transport and storage costs of captured CO_2 developed in this study on a \$/tonne of CO_2 and \$/tonne of C on a levelized annual equivalent life cycle greenhouse gas avoided basis rounded off to the nearest dollar. Bear in mind that the transport costs include a small portion of the compression costs normally included in the capture costs in many studies. This was necessitated by the use of the capture costs from the previous EPRI study which only compressed the CO_2 to 83 bar (1200 psia) rather than the 153 bar (2200 psia) required at the pipeline inlet. This difference represents a small fraction of the costs of CO_2 transport and storage (\$0.75/tonne of CO_2 or \$2.7/tonne of C). Included are the base case and a range for each cost. These cases are intended to represent realistic ranges of the important variables and the details of the cases can be found in the appropriate chapter for each storage method. Plotted in Figure 23-1 are the values on a CO_2 basis to visually represent the comparisons.

Table 23-1
CO_2 transport and storage cost comparison on a levelized annual CO_2 equivalent life cycle greenhouse gas avoided basis

Case	Base Case	High Cost Case	Low Cost Case	Base Case	High Cost Case	Low Cost Case
	\$/tonne CO_2	\$/tonne CO_2	\$/tonne CO_2	\$/tonne C	\$/tonne C	\$/tonne C
EOR	(12)	74	(91)	(45)	271	(334)
ECBMR	(6)	19	(26)	(20)	69	(94)
Depleted Gas Res.	5	19	1	18	71	4
Depleted Oil Res.	4	11	1	14	41	4
Aquifer	3	12	1	11	43	4
Ocean Pipeline	6	14	3	20	52	11
Ocean Tanker	18	23	16	65	84	58
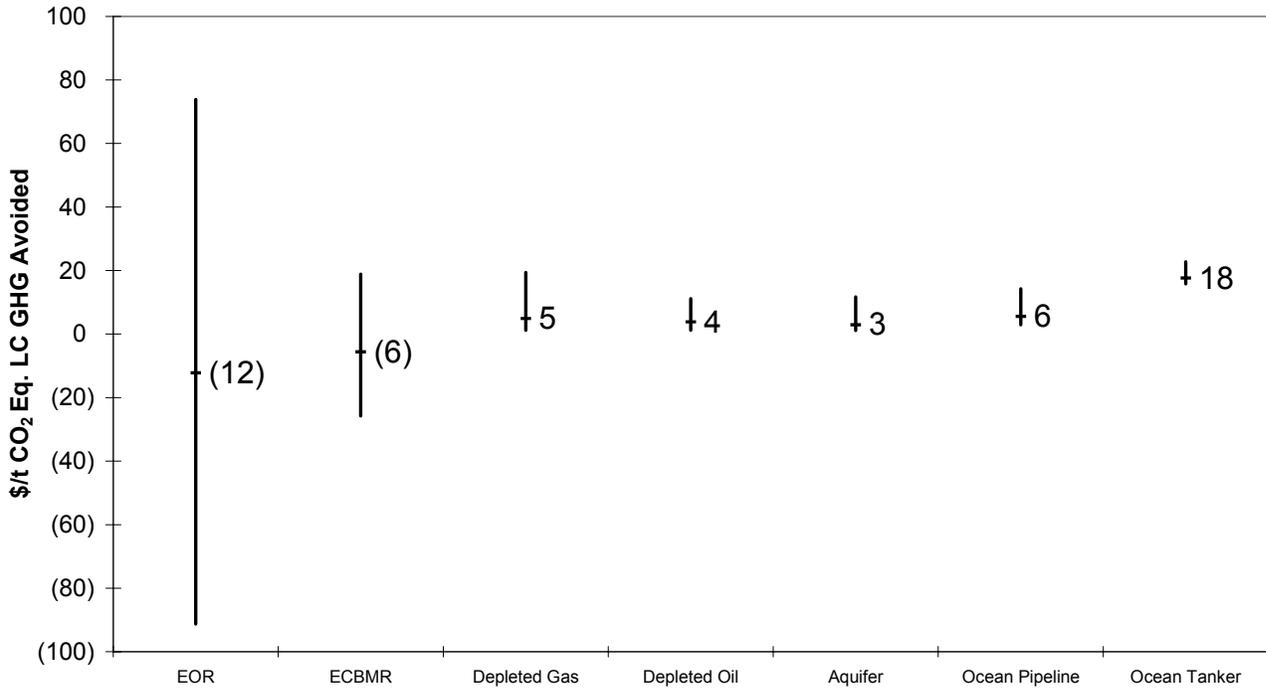
Figure 23-1
CO_2 transport and storage cost comparison on a levelized annual $/t of CO_2 equivalent life cycle greenhouse gas avoided basis

In looking at the comparisons, the base case for EOR and ECBMR show a negative value base case and larger ranges than the other cases. This illustrates that, at the oil price used and no separate charge for CO_2, these base cases operate at a profit. The large ranges show that the costs are very sensitive to changes in the variables. This illustrates how site specific these cases may be. The depleted gas, oil, aquifer and ocean pipeline are similar in value. Their ranges are more compressed although they still change by several factors. The tanker case evaluates as the most expensive and has the smallest range. This case is driven by the capital costs of the tanker, port, and platforms and the variables chosen in the high and low case only impact a small portion of the costs.

23.2 Capture, Transport and Storage

As discussed in Chapter 2, in order to compare capture, transport and storage with the indirect sequestration options, all of the cases have been put on a net present value (NPV) basis. This occurs because of the wide range of emissions and costs as a function of time over the 100-year span of the evaluation. Shown in Table 23.2 are the cases developed in this study on a $/tonne of CO_2 and $/tonne of C on a NPV equivalent life cycle greenhouse gas avoided basis rounded off to the nearest dollar. A plot of the $/t CO_2 information is shown in Figure 23.2.

Table 23-2
CO₂ capture, transport and storage cost comparison on a NPV equivalent life cycle greenhouse gas avoided basis

Case	Base Case	Base Case
	$/tonne CO_2	$/tonne C
EOR	4	15
ECBMR	11	41
Depleted Gas Res.	23	86
Depleted Oil Res.	22	81
Aquifer	21	77
Ocean Pipeline	24	89
Ocean Tanker	39	143
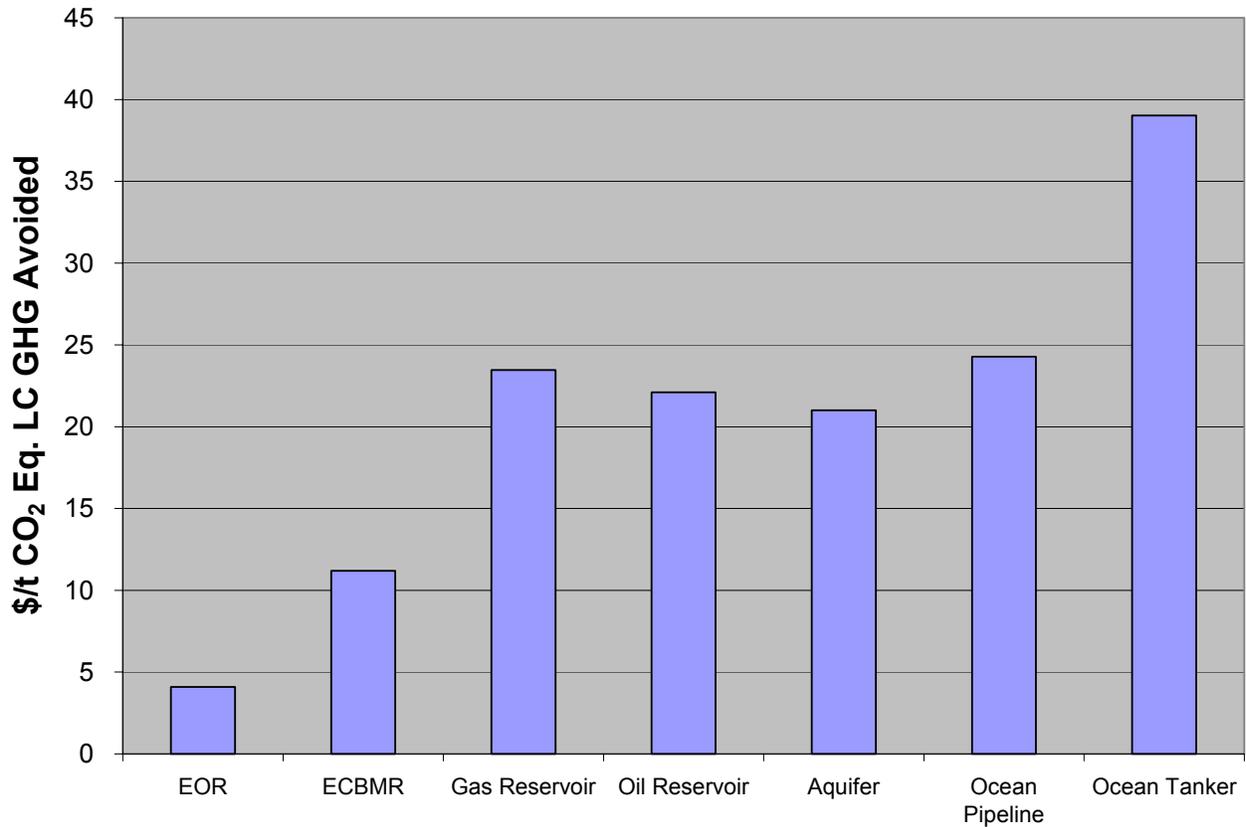
Figure 23-2
CO₂ capture, transport and storage cost comparison on a NPV $/t of CO₂ equivalent life cycle greenhouse gas avoided basis

23.3 Forest management

Shown in Table 23-3 is a comparison of the forestry cases developed in this study on a $/tonne of CO_2 and $/tonne of C on a NPV life cycle greenhouse gas avoided basis. Sensitivity to productivity are indicated where data was available to calculate the case. The information in this table is for forestry cases that include above and below ground carbon and timber products & revenues.

Table 23-3
Forestry cases NPV cost comparison (LC equivalent greenhouse gas avoided, including above and below ground carbon and timber products & revenues).

Case	Base Case-Medium Productivity	Low Cost Case-High Productivity	High Cost Case-Low Productivity	Base Case-Medium Productivity	Low Cost Case-High Productivity	High Cost Case-Low Productivity
	$/tonne CO_2	$/tonne CO_2	$/tonne CO_2	$/tonne C	$/tonne C	$/tonne C
US Pine	15	11		54	40	
US Fir	2	1		7	3	
Cedar	(15)	(14)	(11)	(56)	(51)	(39)
Pine-Oak	1	(1)	2	2	(3)	6
Miombo	(24)			(87)		
Mango	(43)			(158)		
Deforest	3			10		

Where data was available, productivity (carbon stored/area), could affect costs significantly. Shown in Figure 23-3 is a bar chart of the $/tonne CO_2 costs from Table 26.2 to visually represent the comparisons.
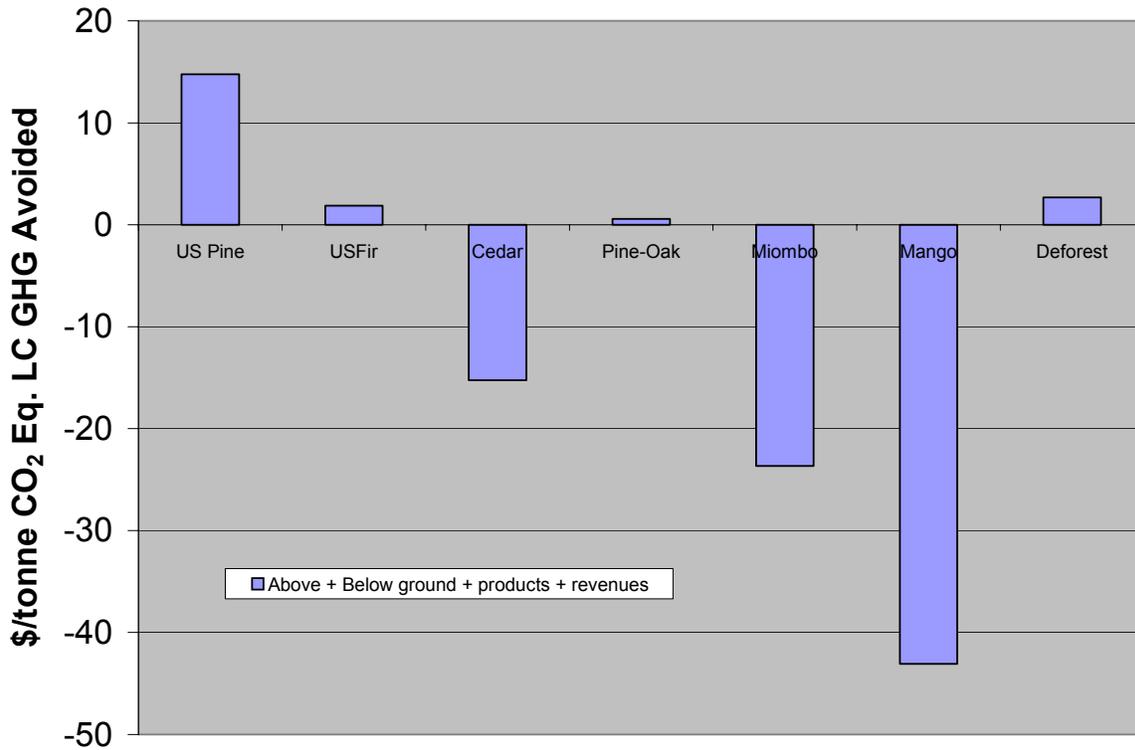
Figure 23-3
Forestry cost comparison on a NPV $/t of CO$_2$ equivalent life cycle greenhouse gas avoided basis

The only case with a significant cost is the US pine case and this is because the land costs are high and the timber revenues are not enough to offset them. US fir and Pine-Oak are generally revenue neutral and the Cedar, Miombo and Mango are negative costs due to the high value of their products. Prevention of deforestation is also a low-cost option.

23.4 Cropland via Reducing Tillage

Shown in Table 23-4 are the cases developed in this study for the cropland cases on a $/tonne of CO$_2$ and $/tonne of C on a NPV equivalent life cycle greenhouse gas avoided basis rounded off to the nearest dollar. A plot of the $/t CO$_2$ information is shown in Figure 23-4.

Summary Comparisons and Conclusions

Table 23-4
Cropland cases NPV equivalent life cycle greenhouse gas avoided basis

Case	Base Case-10 y Incentive	High Cost Case- 20 y Incentive	Low Cost Case-5 y Incentive	Base Case-10 y incentive	High Cost Case- 20 y Incentive	Low Cost Case-5 y Incentive
	$/tonne CO_2	$/tonne CO_2	$/tonne CO_2	$/tonne C	$/tonne C	$/tonne C
Corn/soybean	13	20	8	48	72	30
Continuous corn	14	21	8	51	77	30
Wheat/fallow	13	19	9	49	71	32
Continuous cotton	24	36	15	88	132	54
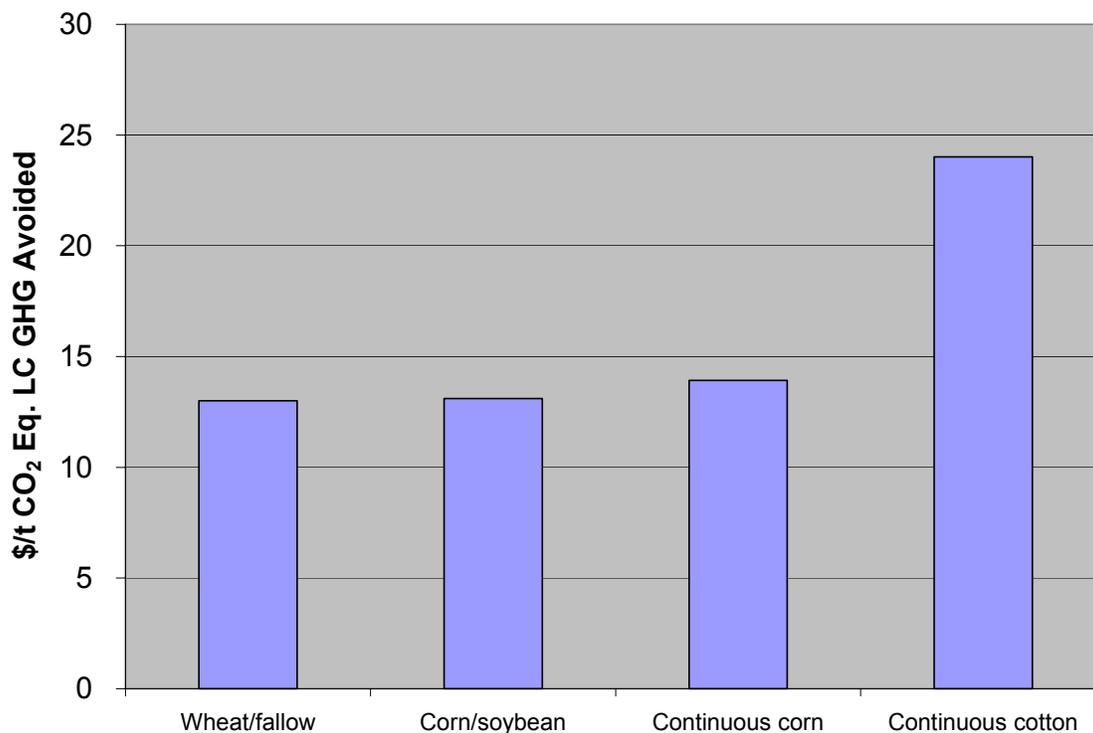
Figure 23-4
Cropland cases NPV $/t CO_2 equivalent life cycle greenhouse gas avoided basis

All of these options are fairly expensive compared to the other options in the study. However, the length of time that the incentive has to be paid has a significant impact on the cost.

23.5 Direct Verses Indirect Sequestration

Shown in Figure 23-5 is a comparison of all of the base case values in $/tonne of CO_2 equivalent LC GHG avoided on a net present value plotted from lowest to highest cost.
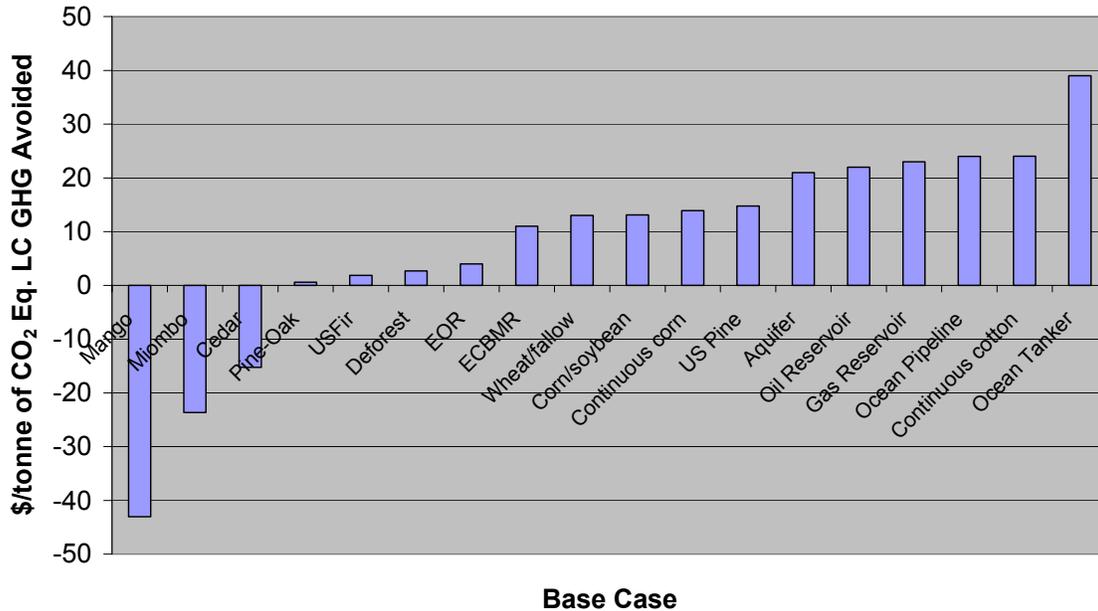
Figure 23-5
Comparison of direct and indirect sequestration cases.

As shown in Figure 23-5, all of the forestry options are the least expensive except for the US Pine case. Next are the EOR and ECBMR options followed by most of the cropland options. Figure 26-7 includes the available high and low cases. The main impact of these cases is on the cropland cases where the low cases would make them competitive with ECBMR and the high cases would make them about the same as the other geologic storage cases.
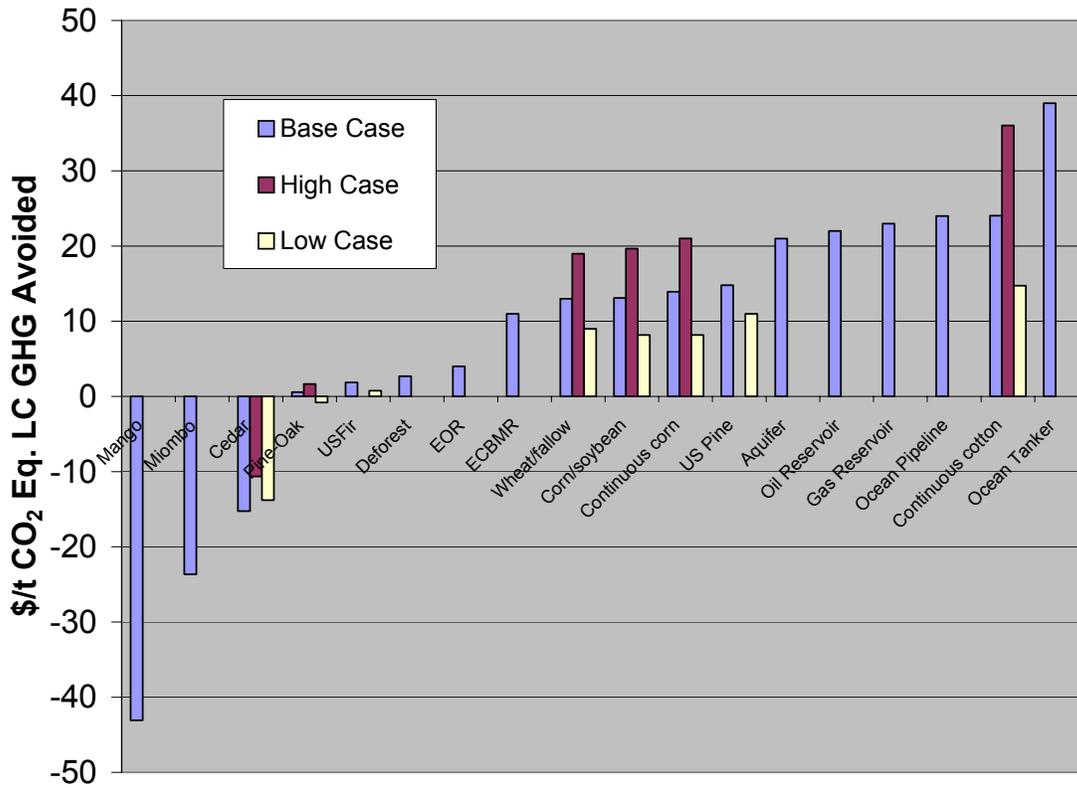
Figure 23-6
Comparison of direct and indirect sequestration cases including high and low cases.

Base-case forest and cropland areas required to offset LC GHG emissions avoided by base-case CO_2 capture and storage options are presented in Table 23-5. These land area equivalents are for a 100-year planning horizon. The carbon equivalent (CE) LC GHG emissions avoided by the capture and storage options assume CO_2 capture and injection into storage reservoirs during the 20-year book life of the capture and storage plants and storage of injected CO_2 for another 80 years. For the ocean storage options, the CE LC GHG avoided is reduced for leakage of CO_2 throughout the 100-year storage period. Zero CO_2 leakage is assumed for the other CO_2 storage options. The CE LC GHG emissions avoided by the forest and cropland options assume that the improved forestry or cropland practices are maintained for 100 years. Generally, ten times or more cropland than forest land is required to offset the CO_2 storage options.

Table 23-5
Base-case forest and cropland areas required to offset LC GHG emissions avoided by base-case CO$_2$ capture and storage options.

Equivalent Forestry / Cropland Area Required to
Offset Geologic & Ocean Options
LC Avoided GHG Basis (100 year summation)

Forestry System - Medium Productivity *(Above/below ground C, non-CO2 GHGs, & timber products/revenues)*		Aquifer Storage	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Enhanced Oil Recovery	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Depleted Oil Reservoirs	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Depleted Gas Reservoirs	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Coal Bed Methane Recovery	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Ocean Pipeline Storage	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage	Ocean Tanker Storage	Forestry / Cropland Area to Equal CO$_2$ Capture & Storage
	(tonne CE/ha)	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*	*(Mtonne CE)*	*(Mha)*
Plantation, USA, Loblolly Pine	183.14	9.81	0.05	9.09	0.05	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.15	28.00	0.15
Plantation, USA, Douglas Fir	452.65	9.81	0.02	9.09	0.02	9.81	0.02	9.81	0.02	9.54	0.02	28.28	0.06	28.00	0.06
Plantation (Taungya), Mexico, Spanish cedar	277.40	9.81	0.04	9.09	0.03	9.81	0.04	9.81	0.04	9.54	0.03	28.28	0.10	28.00	0.10
Restoration, Mexico, Pine-oak	183.39	9.81	0.05	9.09	0.05	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.15	28.00	0.15
Restoration, Southern Africa, Miombo	59.26	9.81	0.17	9.09	0.15	9.81	0.17	9.81	0.17	9.54	0.16	28.28	0.48	28.00	0.47
Agro- forestry, Southern India, Mango- tamarind	71.53	9.81	0.14	9.09	0.13	9.81	0.14	9.81	0.14	9.54	0.13	28.28	0.40	28.00	0.39
Avoidance of deforestation, Mexico,Various	207.66	9.81	0.05	9.09	0.04	9.81	0.05	9.81	0.05	9.54	0.05	28.28	0.14	28.00	0.13
Cropland System Two Year Corn/Soybean Rotation *(Intensive-till to No-till)*	6.51	9.81	1.51	9.09	1.39	9.81	1.51	9.81	1.51	9.54	1.46	28.28	4.34	28.00	4.30
Continuous Corn *(Intensive-till to No-till)*	12.33	9.81	0.80	9.09	0.74	9.81	0.80	9.81	0.80	9.54	0.77	28.28	2.29	28.00	2.27
Continuous Cotton *(Intensive-till to No-till)*	0.99	9.81	9.90	9.09	9.18	9.81	9.90	9.81	9.90	9.54	9.64	28.28	28.56	28.00	28.28
Two Year Wheat / Fallow Rotation *(Intensive-till to No-till)*	6.58	9.81	1.49	9.09	1.38	9.81	1.49	9.81	1.49	9.54	1.45	28.28	4.30	28.00	4.26

23.6 Conclusions

Making these comparisons was a challenge due to the differences between direct and indirect cases. The resulting numbers should only be used as a relative indication of cost. Site-specific characteristics could significantly change the outcome of the comparisons. In this study, the forestry options are very attractive along with capture using EOR for storage. Other factors, such as land availability and storage option location and capacity will also play a significant part in which options make the most sense at a given site.

The current work should only be considered a starting point. Better cost information and improvements to processes are likely to be developed and need to be incorporated into updates of this information. In addition, there are plans to update and add to portions of the current work to answer questions that arose but were beyond the scope of the current effort. For example, what happens to the costs if the power plant operates for longer than the plant book life? Also, how do the economics look for other power generation options? These and other questions will be evaluated in updates to this work.

23.7 REFERENCES

1   DOE/EPRI. 2000. Evaluation of innovative fossil fuel power plants with CO2 removal. EPRI, Palo Alto, California; U.S. Department of Energy–Office of Fossil Energy, Germantown, Maryland, and U.S. Department of Energy/NETL, Pittsburgh, Pennsylvania: 1000316.

A
DETAILED LIFE-CYCLE GHG EMISSIONS AVOIDED VIA CAPTURING AND STORING CO$_2$

Detailed life-cycle (LC) GHG emissions avoided via capturing and storing CO$_2$ in the base cases considered in this project are presented in Tables A-1 to A-7. Methodology for calculating these emissions is described in Chapters 2 and 3.

Detailed Life-Cycle GHG Emissions Avoided via Capturing and Storing CO2

Table A-1
EOR base case detailed analysis of LC GHG emissions avoided

Enhanced Oil Recovery: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	**100**	51,599	**28**	**$50,000**	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

GHG (CO2 Equivalents) Emmited During CO2 Capture & Storage

With CO$_2$ Capture (Case 3a)

IGCC Plant

		GHG Emissions tonnes/year		
		CO$_2$	N$_2$0	CH$_4$
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		243,338	3,433	66,762
Total (mg CO$_2$ Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**110,876**		

Compression of Captured CO$_2$ to Pipeline Spec

CO$_2$ Compression

		CO$_2$	N$_2$0	CH$_4$
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		1,605	23	438
CO$_2$ Compression Total (*CO$_2$ Equivalent*)		**2,066**		

Transportation & Sequestration of Captured CO$_2$

CO$_2$ Transportation

		CO$_2$	N$_2$0	CH$_4$
Pipeline Construction		913	0.0	0.0
Pipeline Decommissioning		91	0.0	0.0
Total		1,005	0	0
CO$_2$ Sequestration-EOR				
Power	25,142 kW	128,378	1	155
Plant Construction				
Aboveground Equipment		279	0.0	0.0
Subsurface Equipment		64	0.0	0.0
Plant Decommissioning		34	0.0	0.0
Total		128,755	1	155
CO2 Transportation & Sequestration Total		129,759	1	155
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		129,759	210	3,569
Transportation & Sequestration Total (*CO$_2$ Equivalent*)		**133,538**		

Without CO$_2$ Capture (Case 3b)

IGCC Plant

		GHG Emissions tonnes/year		
		CO$_2$	N$_2$0	CH$_4$
Coal Mine		30,417	0.5	1.4
Mine Methane Vented		577	minor	2,619
Coal Train		1,821	minor	minor
Power Plant Emissions		2,133,828	11.4	minor
Power Plant Construction		1,006	0.0	0.0
Power Plant Decommissioning		101	0.0	0.0
Total Power Plant		2,167,749	12	2,620
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		2,167,749	3,530	60,262
Total (mg CO$_2$ Equivalent / kWh)		728,612	1,186	20,255
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**750,053**		

Amount of Emitted & Avoided GHG *(CO$_2$ Equivalents)*

Capture

	With CO2 Capture	Without CO2 Capture	Difference
kg CO$_2$ equivalent emitted/kWh	0.111	0.750	0.639
CO$_2$ equivalent avoided, tonne/yr			1,807,446

Total System

CO$_2$ equivalent avoided by capture, tonne/yr	1,807,446
CO$_2$ equivalent emitted from storage, tonne/yr	135,604
CO$_2$ equivalent LC avoided, tonne/yr	1,671,842
CO$_2$ equivalent LC avoided, % of CO$_2$ captured	77.5%
CO$_2$ equivalent LC avoided, % of CO$_2$ equivalent avoided during capture	92.5%

Storage (CO2 Compression, Transportation, and Sequestration)

Compression CO$_2$ equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO$_2$ equivalent emitted, tonne/yr	133,538
Total CO$_2$ equivalent emitted, tonne/yr	135,604

Table A-2
ECBMR base case detailed analysis of LC GHG emissions avoided

Enhanced Coal Bed Methane: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

GHG (CO_2 Equivalents) Emmited During CO_2 Capture & Storage

With CO_2 Capture (Case 3a)

IGCC Plant — *GHG Emissions tonnes/year*

		CO_2	N_2O	CH_4
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		243,338	3,433	66,762
Total (mg CO_2 Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO_2 Equivalent / kWh*)		**110,876**		

Compression of Captured CO_2 to Pipeline Spec

CO_2 Compression

		CO_2	N_2O	CH_4
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO_2 Equivalent		1,605	23	438
CO_2 Compression Total (*CO_2 Equivalent*)		**2,066**		

Transportation & Sequestration of Captured CO_2

CO_2 Transportation

		CO_2	N_2O	CH_4
Pipeline Construction		913	0.0	0.0
Pipeline Decommissioning		91	0.0	0.0
Total		1,005	0	0
CO_2 Sequestration-ECBM				
Power	9,259 kW	47,276	0.3	57
Plant Construction				
Aboveground Equipment		42	0.0	0.0
Subsurface Equipment		73	0.0	0.0
Plant Decommissioning		12	0	0
Total		47,402	0	57
CO2 Transportation & Sequestration Total		48,407	0	57
100 Year Multiplier		1	296	23
CO_2 Equivalent		48,407	77	1,314
Transportation & Sequestration Total (*CO_2 Equivalent*)		**49,798**		

Without CO_2 Capture (Case 3b)

IGCC Plant — *GHG Emissions tonnes/year*

		CO_2	N_2O	CH_4
Coal Mine		30,417	0.5	1.4
Mine Methane Vented		577	minor	2,619
Coal Train		1,821	minor	minor
Power Plant Emissions		2,133,828	11.4	minor
Power Plant Construction		1,006	0.0	0.0
Power Plant Decommissioning		101	0.0	0.0
Total Power Plant		2,167,749	12	2,620
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		2,167,749	3,530	60,262
Total (mg CO_2 Equivalent / kWh)		728,612	1,186	20,255
Power Plant Total (*mg CO_2 Equivalent / kWh*)		**750,053**		

Amount of Emitted & Avoided GHG (*CO_2 Equivalents*)

Capture	With CO_2 Capture	Without CO_2 Capture	Difference
kg CO_2 equivalent emitted/kWh	0.111	0.750	0.639
CO_2 equivalent avoided, tonne/yr			1,807,446

Total System

CO_2 equivalent avoided by capture, tonne/yr	1,807,446
CO_2 equivalent emitted from storage, tonne/yr	51,864
CO_2 equivalent LC avoided, tonne/yr	1,755,582
CO_2 equivalent LC avoided, % of CO_2 captured	81.4%
CO_2 equivalent LC avoided, % of CO_2 equivalent avoided during capture	97.1%

Storage (CO2 Compression, Transportation, and Sequestration)

Compression CO_2 equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO_2 equivalent emitted, tonne/yr	49,798
Total CO_2 equivalent emitted, tonne/yr	51,864

A-3

Detailed Life-Cycle GHG Emissions Avoided via Capturing and Storing CO2

Table A-3
Aquifer storage base case detailed analysis of LC GHG emissions avoided

Aquifer Storage: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

With CO₂ Capture (Case 3a)

IGCC Plant — GHG Emissions tonnes/year

		CO_2	N_2O	CH_4
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO_2 Equivalent		243,338	3,433	66,762
Total (mg CO_2 Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO_2 Equivalent / kWh*)		**110,876**		

Compression of Captured CO_2 to Pipeline Spec
CO_2 Compression

		CO_2	N_2O	CH_4
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO_2 Equivalent		1,605	23	438
CO_2 Compression Total (*CO_2 Equivalent*)		**2,066**		

Transportation & Sequestration of Captured CO_2
CO_2 Transportation

	CO_2	N_2O	CH_4
Pipeline Construction	913	0.0	0.0
Pipeline Decommissioning	91	0.0	0.0
Total	1,005	0	0

CO_2 Sequestration-Aquifer Storage

	CO_2	N_2O	CH_4
Power	minor	minor	minor
Plant Construction			
Aboveground Equipment	3	0	0
Subsurface Equipment	0	0	0
Plant Decommissioning	0	0	0
Total	4	0	0
CO2 Transportation & Sequestration Total	1,008	0	0
100 Year Multiplier	1	296	23
CO_2 Equivalent	1,008	0	0
Transportation & Sequestration Total (*CO_2 Equivalent*)	**1,008**		

Without CO₂ Capture (Case 3b)

IGCC Plant — GHG Emissions tonnes/year

	CO_2	N_2O	CH_4
Coal Mine	30,417	0.5	1.4
Mine Methane Vented	577	minor	2,619
Coal Train	1,821	minor	minor
Power Plant Emissions	2,133,828	11.4	minor
Power Plant Construction	1,006	0.0	0.0
Power Plant Decommissioning	101	0.0	0.0
Total Power Plant	2,167,749	12	2,620
100 Year Multiplier	1	296	23
Total Power Plant CO_2 Equivalent	2,167,749	3,530	60,262
Total (mg CO_2 Equivalent / kWh)	728,612	1,186	20,255
Power Plant Total (*mg CO_2 Equivalent / kWh*)	**750,053**		

Amount of Emitted & Avoided CO₂

Capture	With CO2 Capture	Without CO2 Capture	Difference
kg CO_2 equivalent emitted/kWh	0.111	0.750	0.639
CO_2 equivalent avoided, tonne/yr			1,807,446

Storage (CO2 Compression, Transportation, and Sequestration)	
Compression CO_2 equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO_2 equivalent emitted, tonne/yr	1,008
Total CO_2 equivalent emitted, tonne/yr	3,074

Total System

CO_2 equivalent avoided by capture, tonne/yr	1,807,446
CO_2 equivalent emitted from storage, tonne/yr	3,074
CO_2 equivalent LC avoided, tonne/yr	1,804,372
CO_2 equivalent LC avoided, % of CO_2 captured	83.6%
CO_2 equivalent LC avoided, % of CO_2 equivalent avoided during capture	99.8%

Table A-4
Depleted oil reservoir base case detailed analysis of LC GHG emissions avoided

Depleted Oil Reservoir: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

With CO$_2$ Capture (Case 3a)

IGCC Plant

		GHG Emissions tonnes/year		
		CO$_2$	N$_2$0	CH$_4$
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		243,338	3,433	66,762
Total (mg CO$_2$ Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**110,876**		

Compression of Captured CO$_2$ to Pipeline Spec
CO$_2$ Compression

		CO$_2$	N$_2$0	CH$_4$
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		1,605	23	438
CO$_2$ Compression Total (*CO$_2$ Equivalent*)		**2,066**		

Transportation & Sequestration of Captured CO$_2$
CO$_2$ Transportation

	CO$_2$	N$_2$0	CH$_4$
Pipeline Construction	913	0.0	0.0
Pipeline Decommissioning	91	0.0	0.0
Total	1,005	0	0

CO$_2$ Sequestration-Depleted Oil Reservoir

	CO$_2$	N$_2$0	CH$_4$
Power	minor	minor	minor
Plant Construction			
Aboveground Equipment	5	0.0	0.0
Subsurface Equipment	12	0.0	0.0
Plant Decommissioning	2	0.0	0.0
Total	19	0	0

	CO$_2$	N$_2$0	CH$_4$
CO2 Transportation & Sequestration Total	1,023	0	0
100 Year Multiplier	1	296	23
CO$_2$ Equivalent	1,023	0	0
Transportation & Sequestration Total (*CO$_2$ Equivalent*)	**1,024**		

Without CO$_2$ Capture (Case 3b)

IGCC Plant

		GHG Emissions tonnes/year		
		CO$_2$	N$_2$0	CH$_4$
Coal Mine		30,417	0.5	1.4
Mine Methane Vented		577	minor	2,619
Coal Train		1,821	minor	minor
Power Plant Emissions		2,133,828	11.4	minor
Power Plant Construction		1,006	0.0	0.0
Power Plant Decommissioning		101	0.0	0.0
Total Power Plant		2,167,749	12	2,620
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		2,167,749	3,530	60,262
Total (mg CO$_2$ Equivalent / kWh)		728,612	1,186	20,255
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**750,053**		

Amount of Emitted & Avoided CO$_2$

Capture	With CO2 Capture	Without CO2 Capture	Difference
kg CO$_2$ equivalent emitted/kWh	0.111	0.750	0.639
CO$_2$ equivalent avoided, tonne/yr			1,807,446

Total System	
CO$_2$ equivalent avoided by capture, tonne/yr	1,807,446
CO$_2$ equivalent emitted from storage, tonne/yr	3,089
CO$_2$ equivalent LC avoided, tonne/yr	1,804,356
CO$_2$ equivalent LC avoided, % of CO$_2$ captured	83.6%
CO$_2$ equivalent LC avoided, % of CO$_2$ equivalent avoided during capture	99.8%

Storage (CO2 Compression, Transportation, and Sequestration)	
Compression CO$_2$ equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO$_2$ equivalent emitted, tonne/yr	1,024
Total CO$_2$ equivalent emitted, tonne/yr	3,089

Detailed Life-Cycle GHG Emissions Avoided via Capturing and Storing CO2

Table A-5
Depleted gas reservoir base case detailed analysis of LC GHG emissions avoided

Depleted Gas Reservoir: Greenhouse Gas Life-Cycle (LC) Analysis

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

With CO$_2$ Capture (Case 3a)

IGCC Plant

GHG Emissions tonnes/year

		CO$_2$	N$_2$O	CH$_4$
Coal Mine		33,698	0.5	1.6
Mine Methane Vented		639	minor	2,901
Coal Train		1,821	minor	minor
Power Plant Emissions		205,812	11.0	minor
Power Plant Construction		1,243	0.0	0.0
Power Plant Decommissioning		124	0.0	0.0
Total Power Plant		243,338	12	2,903
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		243,338	3,433	66,762
Total (mg CO$_2$ Equivalent / kWh)		86,053	1,214	23,609
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**110,876**		

Compression of Captured CO$_2$ to Pipeline Spec

CO$_2$ Compression

		CO$_2$	N$_2$O	CH$_4$
Compression Power	2,650 kW	1,598	0.1	19
Construction		6.1	0.0	0.0
Decommissioning		0.6	0.0	0.0
Total		1,605	0.1	19
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		1,605	23	438
CO$_2$ Compression Total (*CO$_2$ Equivalent*)		**2,066**		

Transportation & Sequestration of Captured CO$_2$

CO$_2$ Transportation

	CO$_2$	N$_2$O	CH$_4$
Pipeline Construction	913	0.0	0.0
Pipeline Decommissioning	91	0.0	0.0
Total	1,005	0	0

CO$_2$ Sequestration-Depleted Gas Reservoir

	CO$_2$	N$_2$O	CH$_4$
Power	minor	minor	minor
Plant Construction			
Aboveground Equipment	6	0.0	0.0
Subsurface Equipment	27	0.0	0.0
Plant Decommissioning	3	0.0	0.0
Total	36	0	0

	CO$_2$	N$_2$O	CH$_4$
CO2 Transportation & Sequestration Total	1,041	0	0
100 Year Multiplier	1	296	23
CO$_2$ Equivalent	1,041	0	0
Transportation & Sequestration Total (*CO$_2$ Equivalent*)	**1,041**		

Without CO$_2$ Capture (Case 3b)

IGCC Plant

GHG Emissions tonnes/year

		CO$_2$	N$_2$O	CH$_4$
Coal Mine		30,417	0.5	1.4
Mine Methane Vented		577	minor	2,619
Coal Train		1,821	minor	minor
Power Plant Emissions		2,133,828	11.4	minor
Power Plant Construction		1,006	0.0	0.0
Power Plant Decommissioning		101	0.0	0.0
Total Power Plant		2,167,749	12	2,620
100 Year Multiplier		1	296	23
Total Power Plant CO$_2$ Equivalent		2,167,749	3,530	60,262
Total (mg CO$_2$ Equivalent / kWh)		728,612	1,186	20,255
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)		**750,053**		

Amount of Emitted & Avoided CO$_2$

	With CO2 Capture	Without CO2 Capture	Difference
Capture			
kg CO$_2$ equivalent emitted/kWh	0.111	0.750	0.639
CO$_2$ equivalent avoided, tonne/yr			1,807,446

Total System

CO$_2$ equivalent avoided by capture, tonne/yr	1,807,446
CO$_2$ equivalent emitted from storage, tonne/yr	3,107
CO$_2$ equivalent LC avoided, tonne/yr	1,804,339
CO$_2$ equivalent LC avoided, % of CO$_2$ captured	83.6%
CO$_2$ equivalent LC avoided, % of CO$_2$ equivalent avoided during capture	99.8%

Storage (CO2 Compression, Transportation, and Sequestration)

Compression CO$_2$ equivalent emitted, tonne/yr	2,066
Transportation and sequestration CO$_2$ equivalent emitted, tonne/yr	1,041
Total CO$_2$ equivalent emitted, tonne/yr	3,107

Table A-6
Ocean pipeline storage base case detailed analysis of LC GHG emissions avoided

Ocean Pipeline Storage: Greenhouse Gas Life-Cycle (LC) Analysis *(without leakage)*

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

GHG (CO$_2$ Equivalents) Emmited During CO$_2$ Capture & Storage

With CO$_2$ Capture (Case 3a)

IGCC Plant

	GHG Emissions tonnes/year		
	CO$_2$	*N$_2$0*	*CH$_4$*
Coal Mine	33,698	0.5	1.6
Mine Methane Vented	639	minor	2,901
Coal Train	1,821	minor	minor
Power Plant Emissions	205,812	11.0	minor
Power Plant Construction	1,243	0.0	0.0
Power Plant Decommissioning	124	0.0	0.0
Total Power Plant	243,338	12	2,903
100 Year Multiplier	1	296	23
Total Power Plant CO$_2$ Equivalent	243,338	3,433	66,762
Total (mg CO$_2$ Equivalent / kWh)	86,053	1,214	23,609
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)	**110,876**		

Compression of Captured CO$_2$ to Pipeline Spec

CO2 Compression

		CO$_2$	*N$_2$0*	*CH$_4$*
Compression Power	7,950 kW	4,794	0.2	57
Construction		18.3	0.0	0.0
Decommissioning		1.8	0.0	0.0
Total		4,814	0.2	57
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		4,814	68	1,315
CO$_2$ Compression Total (*CO$_2$ Equivalent*)		**6,197**		

Transportation & Sequestration of Captured CO$_2$

CO2 Transportation

		CO$_2$	*N$_2$0*	*CH$_4$*
Pipeline Construction		913	0.0	0.0
Pipeline Decommissioning		91	0.0	0.0
Total		1,005	0	0
CO$_2$ Sequestration-Ocean				
Compression Power	5,650 kW	3,407	0.2	41
Construction		17.6	0.0	0.3
Decommissioning		2	0.0	0.0
Ocean Pipeline Construction		1155	0.0	0.0
Ocean Pipeline Decommissioning		116	0.0	0.0
Total		4,698	0.2	41
CO2 Transportation & Sequestration Total		5,702	0.2	41
100 Year Multiplier		1	296	23
CO$_2$ Equivalent		5,702	48	941
Transportation & Sequestration Total (*CO$_2$ Equivalent*)		**6,692**		

Without CO$_2$ Capture (Case 3b)

IGCC Plant

	GHG Emissions tonnes/year		
	CO$_2$	*N$_2$0*	*CH$_4$*
Coal Mine	30,417	0.5	1.4
Mine Methane Vented	577	minor	2,619
Coal Train	1,821	minor	minor
Power Plant Emissions	2,133,828	11.4	minor
Power Plant Construction	1,006	0.0	0.0
Power Plant Decommissioning	101	0.0	0.0
Total Power Plant	2,167,749	12	2,620
100 Year Multiplier	1	296	23
Total Power Plant CO$_2$ Equivalent	2,167,749	3,530	60,262
Total (mg CO$_2$ Equivalent / kWh)	728,612	1,186	20,255
Power Plant Total (*mg CO$_2$ Equivalent / kWh*)	**750,053**		

Amount of Emitted & Avoided GHG (*CO$_2$ Equivalents*)

Capture	With CO2 Capture	Without CO2 Capture	Difference
kg CO$_2$ equivalent emitted/kWh	0.111	0.750	0.639
CO$_2$ equivalent avoided for a single IGCC plant, tonne/yr			1,807,446
Number of IGCC plants transporting CO$_2$ to ocean site			3
Total CO$_2$ equivalent avoided, tonne/yr			5,422,337

Storage (CO2 Compression, Transportation, and Sequestration)	
Compression CO$_2$ equivalent emitted, tonne/yr	6,197
Transportation and sequestration CO$_2$ equivalent emitted, tonne/yr	6,692
Total CO$_2$ equivalent emitted, tonne/yr	12,889

Total System

CO$_2$ equivalent avoided by capture, tonne/yr	5,422,337
CO$_2$ equivalent emitted from storage, tonne/yr	12,889
CO$_2$ equivalent LC avoided w/o leakage, tonne/yr	5,409,447
CO$_2$ equivalent LC avoided w/o leakage, % of CO$_2$ captured	83.6%
CO$_2$ equivalent LC avoided w/o leakage, % of CO$_2$ equivalent avoided during capture	99.8%

Detailed Life-Cycle GHG Emissions Avoided via Capturing and Storing CO2

Table A-7
Ocean tanker storage base case detailed analysis of LC GHG emissions avoided

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Ocean Tanker Storage: Greenhouse Gas Life-Cycle (LC) Analysis *(without leakage)*

	Coal Flow tonne/day	Carbon wt. %	Carbon Emission, %	Rail Transport Km	Flue Gas tonne/day	Construction Energy GJ/tonne	$ of Total Plant Cost per Tonne of Steel	TPC Power Plant M$
Case 3a	3,474	63.75%	8.68%	100	51,599	28	$50,000	$662,484
Case 3b	3,136	63.75%	99.70%	100	53,383	28	$50,000	$535,983

GHG (CO₂ Equivalents) Emmited During CO₂ Capture & Storage

With CO₂ Capture (Case 3a)

IGCC Plant

	GHG Emissions tonnes/year		
	CO_2	N_2O	CH_4
Coal Mine	33,698	0.5	1.6
Mine Methane Vented	639	minor	2,901
Coal Train	1,821	minor	minor
Power Plant Emissions	205,812	11.0	minor
Power Plant Construction	1,243	0.0	0.0
Power Plant Decommissioning	124	0.0	0.0
Total Power Plant	243,338	12	2,903
100 Year Multiplier	1	296	23
Total Power Plant CO₂ Equivalent	243,338	3,433	66,762
Total (mg CO₂ Equivalent / kWh)	86,053	1,214	23,609
Power Plant Total (*mg CO₂ Equivalent / kWh*)	**110,876**		

Compression of Captured CO2 to Pipeline Spec

CO₂ Compression

Compression Power	7,950 kW	4,794	0.2	57
Construction		18.3	0.0	0.0
Decommissioning		1.8	0.0	0.0
Total		4,814	0.2	57
100 Year Multiplier		1	296	23
CO₂ Equivalent		4,814	68	1,315
CO₂ Compression Total (*CO₂ Equivalent*)		**6,197**		

Transportation & Sequestration of Captured CO₂

CO₂ Transportation

	CO_2	N_2O	CH_4
Pipeline Construction	913	0.0	0.0
Pipeline Decommissioning	91	0.0	0.0
Total	1,005	0	0

CO₂ Sequestration-Ocean

Tanker Emissions from Fuel	2,395	0	0
Tanker Boil Off	53,362	0	0
Construction	1034	0.0	15.3
Decommissioning	103	0.0	1.5
	56,895	0	17

CO2 Transportation & Sequestration Total	57,899	0	17
100 Year Multiplier	1	296	23
CO₂ Equivalent	57,899	2	386
Transportation & Sequestration Total (*CO₂ Equivalent*)	**58,287**		

Without CO₂ Capture (Case 3b)

IGCC Plant

	GHG Emissions tonnes/year		
	CO_2	N_2O	CH_4
Coal Mine	30,417	0.5	1.4
Mine Methane Vented	577	minor	2,619
Coal Train	1,821	minor	minor
Power Plant Emissions	2,133,828	11.4	minor
Power Plant Construction	1,006	0.0	0.0
Power Plant Decommissioning	101	0.0	0.0
Total Power Plant	2,167,749	12	2,620
100 Year Multiplier	1	296	23
Total Power Plant CO₂ Equivalent	2,167,749	3,530	60,262
Total (mg CO₂ Equivalent / kWh)	728,612	1,186	20,255
Power Plant Total (*mg CO₂ Equivalent / kWh*)	**750,053**		

Amount of Emitted & Avoided GHG *(CO₂ Equivalents)*

Capture

	With CO2 Capture	Without CO2 Capture	Difference
kg CO₂ equivalent emitted/kWh	0.111	0.750	0.639
CO₂ equivalent avoided, tonne/yr			1,807,446
Number of IGCC plants transporting CO₂ to ocean site			3
Total CO₂ equivalent avoided, tonne/yr			5,422,337

Storage *(CO2 Compression, Transportation, and Sequestration)*

Compression CO₂ equivalent emitted, tonne/yr	6,197
Transportation and sequestration CO₂ equivalent emitted, tonne/yr	58,287
Total CO₂ equivalent emitted, tonne/yr	64,484

Total System

CO₂ equivalent avoided by capture, tonne/yr	5,422,337
CO₂ equivalent emitted from storage, tonne/yr	64,484
CO₂ equivalent LC avoided, tonne/yr	5,357,852
CO₂ equivalent LC avoided, % of CO₂ captured	82.8%
CO₂ equivalent LC avoided, % of CO₂ equivalent avoided during capture	98.8%

B
EXPLANATION OF PROCESS INPUT AND SUMMARY SPREADSHEETS

Process Input sheet

The **Process Input** sheet includes key physical and economic parameters for estimating CO_2 storage costs. As for the entire spreadsheet, parameters in blue and contained in rectangular boxes can be varied by the user.

Design Basis Section

Definitions of these parameters can be found in the 'Methodology Used' section of the relevant chapter. Base-case estimates of these parameters are entered in the orientation version of the spreadsheet. The design basis assumes that one IGCC (Case 3a) CO_2 capture plant provides the CO_2 for the EOR, ECBMR and geologic storage options. In the case of the ocean pipeline and ocean tanker storage options, however, it is assumed that the quantity of CO_2 handled is equal to that supplied by three IGCC plants.

Economic Section

For the EOR and ECBMR options, the revenue generated from the enhanced production can offset or partially offset CO_2 storage costs. In the case of the other storage options, however, there is no value-added product.

EOR and ECBMR Storage Options Only

The economic section of the process input sheet is structured the same for the EOR and ECBMR options. Therefore, the description that is given below, which directly relates to the EOR case, also applies to the ECBMR scenario.

For EOR, Wellhead Oil Price is the key economic parameter. The Wellhead Oil Price and the Oil Production rate (Design Basis section) determine the enhanced oil revenue from the EOR operation. The CO_2 storage cost minus enhanced oil revenue gives the net cost of storing CO_2. When oil revenue is greater than the CO_2 storage cost, the net cost of storing CO_2 is negative (i.e., a revenue). From the perspective of an EOR operation, a positive net storage cost equals the breakeven CO_2 tipping fee. A negative net storage cost equals the breakeven CO_2 purchase price. Note that a Breakeven Oil Price is provided in the Process Input sheet. This is the

Wellhead Oil Price required for oil revenues to offset the cost of CO_2 Storage. Finally, the Oil Royalty is the percent of the Wellhead Oil price received by the owner of the oil rights and the Wellhead Oil Price minus the Oil Royalty gives the Oil Credit.

All Storage Options

The After-Tax Discount Rate (see Table 2-1 in Section 2.1.1) is used to calculate the net present value (NPV) of CO_2 revenues (i.e., CO_2 price times tonnes CO_2 abated) and CO_2 abatement costs to reflect the time-value of money. For regulated economics, the return on debt and equity is set by regulators and the discount rate equals the overall annual return to debt and equity. With assumptions in Table 2-1 of Section 2.1.1, the after-tax discount rate is 6.09 percent. Note that the carrying charge varies with discount rate because, in a regulated environment, the discount rate is the overall annual return to debt and equity, a parameter that is built into the carrying charge. A 6.09 percent After-tax Discount Rate gives a 15.0 percent Levelized Carrying Charge Factor.

Summary Sheet

The four sections in this sheet summarize the cost of capturing and storing CO_2. The bottom-line costs in Summary sheet sections 1-3 are in units of $/tonne CO_2 captured or avoided. Costs in Summary sheet section 4 are in units of $/MWh and indicate incremental effects of CO_2 capture, CO_2 storage, and Year 21-100 storage costs on cost of electricity (COE).

Summary Sheet Section 1 - Levelized Annual CO_2 Storage Costs (years 1-20)

Summary sheet section 1 provides results for a levelized annual storage cost analysis for years 1-20, the book life of the storage operation.

Costs in Summary sheet section 1 are presented on a CO_2 Captured Basis (column 1) and a Life-Cycle (LC) Avoided GHG Basis for storage only (column 3). General approaches for calculating costs on these bases are described on in Sections 2.2 and 2.3.

Summary Sheet Section 2 - Levelized Annual CO_2 Capture and Net Storage Costs (years 1-20)

This section is similar to Summary sheet section 1, but presents costs for capture and storage combined. Costs in this section are presented on a CO_2 Captured Basis (column 1), CO_2 Avoided Basis for capture and storage combined (column 2) and a Life-Cycle (LC) Avoided GHG Basis for capture and storage combined (column 3). General procedures for calculating costs on these bases are described in Sections 2.2 and 2.3 of this report.

Summary Sheet Section 3 - CO$_2$ Capture and Storage Costs, NPV Basis (years 1-100)

The structure of this section is the same as for Summary sheet section 2 except that the first four lines contain net present values (NPVs) for years 1-100 instead of annual levelized values for years 1-20. The last line in Summary sheet section 3 contains costs in units of $/tonne CO$_2$; these bottom-line costs are calculated as the breakeven CO$_2$ price required to offset CO$_2$ capture and storage costs. Note that this breakeven CO$_2$ price is constant over time. This is the price at which the NPV of CO$_2$ revenues (i.e., CO$_2$ price times CO$_2$ stored or avoided) equals the NPV of costs for CO$_2$ capture and storage combined. The theory for calculating the breakeven CO$_2$ price is presented in Section 2.4. The same theory and procedures are used for the forestry and cropland CO$_2$ sink enhancement options in this project. Using these procedures, the bottom-line costs ($/tonne CO$_2$ equivalent of GHG avoided on a life-cycle basis) in Column 3 of Summary sheet section 3 can be compared with life-cycle costs for forestry and cropland sink enhancement options that differ greatly from CO$_2$ capture/storage options in the timing of when costs occur and when CO$_2$ is stored and/or leaks back to the atmosphere.

Equation (8) in Section 2.4 reduces to a ratio of total CO$_2$ abatement costs to total CO$_2$ abatement for cases in which annual CO$_2$ storage costs and annual CO$_2$ abatement change proportionally over time. For the CO$_2$ capture and storage options in this project, CO$_2$ abatement costs and CO$_2$ abatement are levelized over time for years 1-20. This means that the bottom-line costs in Summary sheet section 3 ($/tonne of CO$_2$) are the same as in Summary sheet section 2 unless monitoring and/or transaction costs occur in years 21-100 without corresponding levels of CO$_2$ abatement. The difference in bottom-line costs for Summary sheet sections 2 and 3 is also increased if CO$_2$ leaks occur in years 21-100.

Summary Sheet Section 4 - Cost of Electricity, $/MWh

Costs in Summary sheet section 4 are in units of $/MWh and indicate incremental effects of CO$_2$ capture (years 1-20), CO$_2$ storage (years 1-20), and CO2 storage (years 21-100, e.g., monitoring and/or transaction costs) on COE. Procedures for calculating these incremental effects on COE are in Section 2.1.4.

C
STATUS AND COSTS OF EXISTING FORESTRY SEQUESTRATION PROJECTS

The first forestry-based greenhouse gas offset projects took place in the early 1990s, as shown in Table C-1[1]. These were voluntary projects since there were no legal requirements to abate greenhouse gases. The voluntary aspect was somewhat reflected in the price paid for carbon sequestration, which averaged about $0.2/t C based upon the costs to the investor. The signing of the UN Framework Convention on Climate Change in Rio de Janeiro in 1992 launched the concept of Joint Implementation to reduce greenhouse gas emissions. This led to an increase in investment in forestry sequestration. Between 1992 and the First Conference of the Parties (COP-1) in 1995 the average price paid for carbon sequestration is estimated to be about $2/t C, 10 times higher than before. At COP-1 developing countries' concerns about the concept of Joint Implementation resulted in a compromise that consisted of a pilot phase during which projects were called Activities Implemented Jointly (AIJ). These projects were conducted with the objective of establishing protocols and creating experiences but without allowing carbon crediting between developed countries. In this new environment where companies were faced with great uncertainty about the potential value of projects, there was a large reduction in investment in new sequestration projects and the willingness to pay for sequestration fell to $0.6/t C. In the year preceding COP-3 in Kyoto in December 1997 there was great anticipation that binding commitments would be agreed, which would entail hard costs for industrialized countries. This led to an increase in the level of investment in forestry sequestration projects and the average price paid increased to $12/tC. Following COP-3 there was even more interest in forestry sequestration and the price paid for carbon credits in some cases rose as high as $20-25/t C. The supply of carbon offsets became more organized and more sophisticated. This is the case for the Costa Rican national program, which is the first producer-led carbon-offset initiative in the world and the first to utilize independent certification and insurance.

Table C-1
Forestry sequestration projects initiated until mid-1998

Project name	Date proposed / initiated	Carbon offset (1000 t C)	Area (ha)	Host country	Investor country	Project description
AES—Care	1990	10,500	186,000	Guatemala	USA	Agroforestry
Face Malaysia	1992	4,250	25,000	Malaysia	Netherlands	Enrichment planting
Face—Kroknose	1992	3,080	16,000	Czech R.	Netherlands	Park rehabilitation
Face Netherlands	1992	885	5,000	Netherlands	Netherlands	Urban forestry
ICSB—NEP 1	1992	56	1,400	Malaysia	USA	Reduced impact logging
AES—Oxfam—Coica	1992	15,000	1,500,000	South America	USA	Forest protection
ASS—Nature Conservancy	1992	15,380	58,000	Paraguay	USA	Forest protection
Face—Profafor	1993	9,660	75,000	Ecuador	Netherlands	Small farmers plantation forestry
RUSAFOR—SAP	1993	79	450	Russia	USA	Plantation forestry
Face Uganda	1994	6,750	27,000	Uganda	Netherlands	Forest rehabilitation
Rio Bravo	1994	1,300	87,000	Belize	USA	Forest protection and management
Carfix	1994	2,000	91,000	Costa Rica	USA	Forest protection, and management
Ecoland/Tenaska	1995	350	2,500	Costa Rica	USA	Forest conservation
ICSB—NEP 2	1996	39	980	Malaysia	USA	Reduced Impact Logging
Noel Kempif M.	1996	14,000	1,000,000	Bolivia	UK/USA	Forest conservation and management
Klinki forestry	1997	1,600	87,000	Costa Rica	USA	Reforestation with klinki
Burkina Faso	1997	67	300,000	Burkina Faso	Denmark	Fire wood community forestry
Scolel Te	1997	15	13,000	Mexico	UK/France	Community forestry

Table C-1 (continued)
Forestry sequestration projects initiated until mid-1998

Project name	Date proposed / initiated	Carbon offset (1000 t C)	Area (ha)	Host country	Investor country	Project description
PAP OCIC	1997	18,000	570,000	Costa Rica	Norway, USA	Forest conservation
Norway—Costa Rica	1997	230	4,000	Costa Rica	Norway	Forest rehabilitation and conservation
Tesco 'green petrol'	1998	n.a.	n.a.	Undefined	UK	Forestry
Green fleet initiative	1997	n.a.	n.a.	Australia	Australia	Reforestation
AES—Ilha Bananal	1998	n.a.	260,800	Brazil	USA	Forest rehabilitation and conservation
NSWSF + utilities	1998	1,300	10,000	Australia	Australia	Reforestation
World Bank Prototype Carbon Fund	1998	n.a.	n.a.	International	International	Renewable energy and forestry
ProNatura—Peugeot	1999	n.a.	n.a.	Brazil	France	Forest rehabilitation and management
TNC Guaraquecaba	1999	n a	N a.	Brazil	USA	Forest conservation, rehabilitation and management
Totals/average		**104,541**	**4,239,930**			

Status and Costs of Existing Forestry Sequestration Projects

References

1   Moura Costa P., Forestry-based greenhouse gas mitigation: a short history of market evolution, Global Greenhouse Emissions Trader Issue 8, Sept.2000, p2-3.

D
PUBLISHED COSTS OF FORESTRY CARBON SEQUESTRATION

The following table is intended to give an indication of the range of published costs of forestry carbon sequestration and marginal values of land. In some of the references, best estimates or median costs are given along with ranges, which are shown here in brackets.

Table D-1
Published costs of forestry carbon sequestration

Ref.	Description	Country	Establishment $/ha	Maintenance $/ha y	Land
1	Tree planting	USA			$/ha/y
	Pacific – pasture		531		31
	- cropland		445		143
	- forest		610		11
	South.East – pasture		166		66
	- cropland		147		126
	- forest		299		23
	Other regions – pasture		155-484		31-69
	- cropland		141-373		111-200
	- forest		287-378		11-30
2	Afforestation	Argentina	988		
		USA	255 (39-373)		
	Reforestation	Argentina	1684 (662-1684)		
		Australia	347 (306-740)		
		Brazil	637 (293-1207)		
		Canada	417 (335-513)		
		China	393 (329-410)		
		Germany	1391 (442-3662)		
		India	477 (220-1845)		
		Malaysia	303 (285-309)		
		Mexico	402 (354-526)		
		S. Africa	952 (910-993)		
		USSR	83 (69-171)		
		USA	256 (53-346)		

Published Costs of Forestry Carbon Sequestration

Table D-2 (continued)
Published costs of forestry carbon sequestration

Ref.	Description	Country	Establishment $/ha	Maintenance $/ha y	Land
3	Reforestation	Boreal	324 (127-455)		
		Temperate	357 (257-911)		
		Tropical	450 (303-1183)		
	Afforestation	Temperate	259 (41-444)		
	Agroforestry	Tropical	454 (255-699)		
4	Reforestation, public land	USA	680 (230-996)		0
	Reforestation, private land	USA	680 (230-996)		84 $/ha/y
	Reforestation	Tropical	395 (153-680)		0
5	Plantations (softwood)	Australia	428 establishment, 232 replanting after harvest	17 management +19 fire insurance	250-1500 $/ha
6	Plantations – lowland	UK	1762	42-49	2980 $/ha (950-4750)
	- upland		3124	39-77	
7	Plantations	Industrialised countries	680	20	
		Developing countries	400	20	
8	Pasture land value	USA			
	Cropland value				
9	Pasture land value				
	Cropland value				

Note: Exchange rate assumed to be 2 Aus$/US$

References

1   Moulton R.J. and Richards K.R., Costs of sequestering carbon through tree planting and forest management in the United States, USDA Forest Service General Technical Report WO-58, Dec. 1990.

2   Winjum J.K, Dixon R.K. and Schroeder P.E., Forest management and carbon storage: an analysis of 12 key forest nations, Water, Air and Soil Pollution 70: 239-257, 1993.

3   Sedjo R.A. et. Al., The economics of managing carbon via forestry: assessment of existing studies, Environmental and Resource Economics 6: 139-165, 1995.

4   Sanghi A.K. and Michael K.S., Carbon sequestering through reforestation: cost and potential for New York, Air & waste management Association 84th Annual Meeting &Exhibition, Vancouver, B.C., June 16-21, 1991.

5   Bureau of Transport and Communication Economics, Costs of Carbon Sequestration through afforestation: greenhouse gas emissions Australian transport, Working Paper 23 , Commonwealth of Australia, 1996, ISBN 0 642 24591 6.

6   ETSU, Full fuel cycle study on power generation schemes incorporating the capture and disposal of carbon dioxide, volume 5: pulverised coal super-critical steam cycle with offset forestry CO2 mitigation, report produced for the IEA Greenhouse Gas R&D Programme, Oct. 1994.

7   Huotari, J. Helynen S and Flyktman M, Indirect biofixation of CO2, VTT Finland, report CRE/CON 1424 produced for IEA Greenhouse Gas R&D Programme, Sept. 1993.

8   USDA Agricultural land values, March 2000, www.usda.gov/nass/

9   USDA Agricultural cash rents, July 2000, www.usda.gov/nass/

E
ESTIMATING ECONOMIC INCENTIVES REQUIRED TO ACHIEVE ADOPTION OF CONSERVATION-TILLAGE SYSTEMS IN SELECTED REGIONS OF THE UNITED STATES

Background

The purpose of this appendix is to provide first-approximation regional estimates of economic incentives ($/hectare) necessary to induce farmers to adopt reduced-tillage practices in regionally important cropping systems.

This appendix indicates the likely range of incentives required to achieve adoption of conservation-tillage systems and estimates incentives for the four regional case studies listed below. The four case studies were selected to (1) represent regions and cropping systems with the greatest amount of avoided GHG emissions that could be achieved by reducing tillage and (2) illustrate the range of amounts per hectare and costs of avoided GHG emissions that could be achieved by reducing tillage.

1. Corn/soybean rotations in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N_2O emissions (Chapter 19)

2. Continuous corn cropping systems in the Corn Belt being converted from intensive-till to either no-till or moderate-till. This case includes best-case and worst-case scenarios concerning effects of reducing tillage on N fertilizer requirements and on N_2O emissions (Chapter 20)

3. Wheat/fallow rotations in the western Great Plains being converted from intensive-till to no-till. This case includes variations in the amount of SOC sequestered and amount of N_2O emissions due to reducing tillage (Chapter 21)

4. Intensive-till cotton to no-till cotton in the southeastern U.S. This case includes variations in the amount of SOC sequestered and amount of N_2O emissions due to reducing tillage (Chapter 22)

Tillage-system budgets and yield distributions over time were used to estimate the incentive levels required to foster the adoption of conservation-tillage systems.

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Budgeting Case Study Tillage Systems

Regional budgets were developed for tillage and cropping systems within each case study. Consistent budgeting methodology was used across tillage and cropping systems and regions as follows. The chemical and fertilizer application rates, seed, drying, insurance and miscellaneous costs were based on state Agricultural Extension Service budgets whenever possible. In instances where published costs were not found (for example, for no-tillage corn/soybean chemical use in Indiana), regional specialists were contacted for the application/cost information.

The various state Agricultural Extension Service budgets employ varying methods for estimating machine variable costs; therefore, in this study pre-harvest machinery operating costs were estimated using the standardized methodology of the American Society of Agricultural Engineers (ASAE) reported by the AAEA Task Force on Commodity Costs and Returns[1]. ASAE methodology uses estimated engineering equations along with typical machinery hours, age, size and type to estimate all costs associated with repair, maintenance, fuel and lubrication. Machinery hours, repair costs, and fuel costs for each piece of machinery were included in the budget. Total variable costs include both repair and fuel costs. Labor hours were based on the sum of all machinery time. It has become common practice to custom hire the harvesting field operation; therefore, this study used the lower bound custom hire estimates from published state Agricultural Extension Service publications. Cotton budgets were the one exception where the range of custom hire costs is so wide that there is a high rate of error in using the custom rate. Therefore, cotton harvest cost was based on ASAE agricultural engineering estimates. Interest on pre-harvest costs was calculated using a 7.5% interest rate and labor costs were calculated at $8/hour for all regions. The sources of the individual budgets are listed in Attachment E-1 of Appendix E.

Estimating the Incentives to Adopt Reduced-Tillage Practices

Published research has shown that in many cases the mean net returns on reduced-tillage practices are equal to or greater than the returns from conventional tillage due to decreases in input costs, yet only 35% of agricultural lands have adopted conservation tillage practices[2]. One factor inhibiting the adoption of reduced tillage is the additional risk perceived by farmers and the perceived effects of these risks on net returns[3,4,5,6]. These risks include: the potential for reduced yields during initial years of adoption, the increased yield variability that reduced tillage practices may introduce, input use variability, and the human and/or physical capital investment that producers may incur. For this study, the impacts of these factors are represented in a probability distribution of net returns that farmers may perceive to be riskier than that associated with conventional practices. This study assumed that yield variation and production inputs are the primary factors of risk in cropland systems. The reduced tillage incentive must overcome the cost of net-returns variability before a risk adverse farmer will adopt reduced-tillage practices. Therefore, before finding the incentive level which will compel a switch to reduced tillage, farmer risk aversion behavior must be considered.

A methodological framework, referred to as the expected utility model[7], provides a useful means for evaluating risk-return tradeoffs in agricultural production settings. In the expected utility model, the certainty equivalent (CE) for a risky decision is the return on a risk-free investment

that makes the decision maker indifferent between the payoff from the risky decision and the payoff from the risk-free investment. The CE from one decision (*x*) is greater than for another decision (*y*) if, and only if, decision *x* yields greater utility than decision *y*, hence making decision *x* preferable over decision *y* by a risk averse individual. This relationship allows inferences to be made about the risk rankings of alternative agricultural practices. Finally, the CE is calculated in monetary units and thus can be used as an indicator of the economic differences between conventional and alternative practices. For example, in terms of reduced tillage, the CE of profit per unit of land area can be approximated using Equation 1[8].

$$CE(NR_x) = E(NR_x) - \lambda/2 Var(NR_x) \qquad\qquad \text{Eq. 1}$$

Where $E(NR_x)$ is the expected net return for tillage practice x,   is the value of the Pratt-Arrow absolute risk aversion coefficient, and $Var(NR_x)$ is the variance of net returns for tillage practice x.

Freund[9] has shown that the linear mean-variance objective function is consistent with the negative exponential utility function (assumes constant absolute risk aversion) and normally distributed profits. Thus, if $CE(NR_x) > CE(NR_y)$, then practice x is a risk efficient strategy for a risk averse farmer because it provides a higher expected utility and would be adopted by the farmer. The difference in the CE profit, $CEI = CE(NR_x) - CE(NR_y)$, provides an estimated monetary value, or incentive, that a risk averse farmer would need to be compensated for in order to adopt alternative tillage practice x.

Incentive levels for reduced-tillage practices were calculated using estimated certainty equivalents. The incentive level is defined as the monetary value that would make the producer indifferent between a certain choice (current practice) and a risky proposition (alternative tillage system).

Analytical Procedure

Incentive level estimation requires the estimation of the net returns of both the conventional tillage practices and the alternative reduced-tillage practices for each rotation and in each region. Total variable cost is given by the regional budgets for important combinations cropping and tillage systems. To estimate the gross revenue side of the equations, it is necessary to estimate the yield levels of the various regional cropping and tillage systems. Through an extensive literature and data search, fourteen tillage experiments which studied the side-by-side yield effects of alternative tillage practices were identified which match the cases in this study. The most rigorous eight of these fourteen studies were selected to represent the cases of interest. The reasons for the selection of these eight are reported in Attachment E-2 of Appendix E. This analysis uses the selected regional tillage experiments to estimate the tillage-system effects on yield and therefore gross revenue. The mean yield, standard deviation and coefficients of variation and variable costs for each cropping system, tillage system, and region are presented in Table E-1.

In some cases, budgets were altered to appropriately fit the tillage practices in individual experiments. For example, in the Central Corn Belt region, one study used chisel plow for the

conventional tillage practice while another experiment used disking for the conventional tillage practice. The regional rotation budget was altered to accurately represent the conventional tillage practice of each experiment.

All budget and yield sources are indicated in Attachment E-2. To make comparisons across differing rotation periods, the total variable costs and total net returns of all rotations were converted to annual average costs and revenues. Hence, final incentive levels were also computed on an annul basis.

Risk is a significant factor to include in analysis of an incentive level which would prompt farmers to switch to an alternative practice. To include risk, an empirical distribution of yields from each experiment was computed for each experiment. Attachment 3 includes histograms of the distributions of the tillage systems compared. Using randomly selected yield levels from the empirical distributions of each experiment and using them in conjunction with their specific production cost budgets, the net returns were simulated 300 times. This procedure provided a probability distribution of net returns for each cropping and tillage system and region.

Table E-1
Yield mean, standard deviation, and coefficient of variation and variable costs at selected sites.

Region	Rotation	Site & Crop	Tillage	Mean (Mg/ha)	St.Dev. (Mg/ha)	Coef. Var.	Variable Cost ($/ha)
Corn Belt	Corn/ Soybean	IAAP-corn	Intensive	9.15	2.57	0.28	434.92
			No-Till	8.76	2.19	0.25	436.67
		IAAP-soybean	Intensive	2.92	0.31	0.11	285.51
			No-Till	2.81	0.30	0.11	286.84
		NERDF-corn	Intensive	9.93	1.57	0.16	434.92
			Reduced	9.64	1.67	0.17	470.61
			No-Till	9.71	1.85	0.19	436.67
		NERDF-soybean	Intensive	3.03	0.60	0.20	285.51
			Reduced	2.92	0.62	0.21	320.80
			No-Till	2.96	0.62	0.21	286.84
		ARC-corn	Intensive	11.96	1.73	0.14	445.98
			Reduced	12.06	1.71	0.14	447.49
			No-Till	11.61	1.74	0.15	413.53
		ARC-soybean	Intensive	3.54	0.44	0.12	303.29
			Reduced	3.39	0.46	0.14	311.47
			No-Till	3.38	0.58	0.17	277.50
	Cont. Corn	NERDF-corn	Intensive	8.88	2.04	0.23	488.17
			Reduced	8.42	2.25	0.27	525.86
			No-Till	8.18	2.11	0.26	491.93
		ARC-corn	Intensive	11.21	1.86	0.17	484.69
			Reduced	11.09	1.68	0.15	485.68
			No-Till	9.68	1.88	0.19	453.22
Central Great Plains	Cont. Sorghum	RMF-sorghum	Intensive	5.37	1.45	0.27	290.60
			No-Till	5.24	1.32	0.25	320.95
	Sorghum/ Soybean	RMF-soybean	Intensive	2.64	0.58	0.22	254.68
			No-Till	2.78	0.65	0.23	265.48
		RMF-sorghum	Intensive	7.83	1.31	0.17	273.06
			No-Till	8.26	1.45	0.18	302.75
Western Great Plains	Wheat/ Fallow	SWK1-wheat	Intensive	2.56	0.76	0.30	203.31
			No-Till	2.74	0.75	0.27	249.94
	Wheat/ Sorghum /Fallow	SWK1-wheat	Intensive	2.19	0.96	0.43	203.31
			No-Till	2.23	0.77	0.35	249.94
		SWK1-sorghum	Intensive	3.59	1.24	0.34	273.06
			No-Till	4.31	1.18	0.27	304.40
Mississippi River Corridor	Corn/ Soybean	ALB-corn	Intensive	8.15	1.52	0.19	377.22
			No-Till	8.67	1.27	0.14	437.04
		ALB-soybean	Intensive	2.40	0.53	0.22	253.84
			No-Till	2.33	0.39	0.16	268.37
	Cotton	MES-cotton	Intensive	8.94	3.03	0.34	694.34
			No-Till	9.07	2.65	0.29	706.32

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The distributions of net returns were analyzed using the SIMETAR© software to estimate confidence premium levels under risk aversion[10]. A risk aversion coefficient of .02 was selected for the analysis after reviewing the literature of risk aversion in agriculture at the per hectare level[11, 5, 12]. The confidence premium represents the payment that is necessary to equal the perceived net returns under risk aversion of the alternative practice; in other words, the risk premium is the incentive level necessary for producers to adopt the alternative practice. The estimated incentive levels by each case study region and rotation are presented in Table E-2.

Table E-2
Incentive levels under base yields and prices

Proposed Switch	Region	Site abbv.* & Drainage	Conventional Rotation	Alternative Rotation	Incentive level under Base Yields and Prices ($/ha)
Intensive Till To No- Till	Corn Belt	IAAP Poor	Corn/Soybean	Corn/Soybean	25.18
		NERDF Well	Corn/Soybean	Corn/Soybean	20.51
		NERDF Well	Cont. Corn	Cont. Corn	66.05
		ARC Poor	Cont. Corn	Cont. Corn	99.98
	Central Great Plains	RMF	Cont. Soybean	Cont. Soybean	6.84
		RMF	Sorghum/Soybean	Sorghum/Soybean	0.74
		NAF	Cont. Sorghum	Cont. Sorghum	36.1
	Western Great Plains	SWK1	Wheat/Fallow	Wheat/Fallow	14.63
		SWK1	Wheat /Fallow	Wheat/Sorghum/ Fallow	15.17
	Mississippi River Corridor	ALB	Corn/Soybean	Corn/Soybean	19.67
		MES	Cont. Cotton	Cont. Cotton	23.2
Intensive Till To Reduced Till (Ridge Till)	Corn Belt	ARC Poor	Corn/Soybean	Corn/Soybean	15.22
		NERDF Well	Corn/Soybean	Corn/Soybean	56.17
		ARC Poor	Cont. Corn	Cont. Corn	3.51
		NERDF Well	Cont. Corn	Cont. Corn	101.26

* Note: Definition of site abbreviations can be found in Attachment E-2.

Discussion of Incentive Level Results

One would expect that the incentive level for switching from intensive-till to no-till would be higher for poorly drained soils than for well drained soils, and this is the result in the Corn Belt rotations of corn/soybean and continuous corn. The corn/soybean incentive is $25/ha for poorly drained soil and $20/ha for well drained soil. The continuous corn incentive for poorly drained soils is $100/ha and $66/ha for well drained soils. In the continuous corn rotation, no-till yields decline considerably, thereby making no-till continuous corn very uncompetitive and resulting in very high incentive levels. Risks of lower and more variable yields associated with no-till continuous corn have been lowered somewhat in recent years via improvements in technology and experience.

When looking at the switch from intensive to reduced tillage, we see that the incentive levels are much higher in the well drained soil type than the poorly drained. The poor soil drainage studies saw little yield drop in the reduced tillage system and in some cases even increased yield (corn in corn/soybean rotation, ARC site). The reduced tillage systems in well drained soils lost yield in all sites. One hypothesis for this result is that the poorer soils are simultaneously reaping the advantages of both less tillage and better drainage. The reduced tillage system studied in these experiments is the ridge till system, where a field cultivator is used to build high rows in which the crops are planted. This would give the needed drainage at a minimum of tillage intrusion.

In the central great plains, the profitability of intensive- and no-tillage sorghum/soybean rotations are about the same, with only a $0.74/ha incentive level estimated to bring no-till into production. Continuous Sorghum has a very high incentive level of $36/ha. The mean yields are fairly close, but the increased cost of no-till sorghum causes the high incentive level in this case.

In the wheat/fallow and wheat/sorghum/fallow rotations of the western Great Plains, the yields with no-till were actually higher than with intensive-till and yield variations with no-till were less. The incentive level of around $15/ha is a result of the higher cost of no-till in these systems.

In the Mississippi River Corridor region, the experimental results show that the switch from corn/soybean to corn/soybean-wheat would take an incentive level of $74/ha. The wheat yield of the analysis is from a separate continuous wheat rotation in the region and this results in a mean yield of 4 tonne/ha, which is very low. The poor returns from wheat combined with the extra cost of the added crop, lead to this very high incentive level. It is assumed that this is a very extreme estimate of the incentive level. By leaving wheat out of the rotation, the analysis shows an incentive level of $20/ha for switching to no-till corn/soybean.

The experimental yield results of continuous cotton in the Mississippi River Corridor region show no-till slightly higher and with less variation. The $23/ha incentive level is therefore the result of the higher cost ($12/ha) and risk of no-till.

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Sensitivity of Incentives to Changes in Revenue

The incentive levels described above (Table E-2) are based on current prices and therefore revenue. As prices (and revenue) change, the incentive levels will also change. Revenue at four other levels (10% and 20% more and less than current prices) was estimated using the same methodology as above. This enables revenue sensitivity equations to be estimated, which represent the change in incentive as the level of revenue changes. All resulting equations are listed in Table E-5. As prices change, the percentage change in revenue from the baseline level of revenue can be computed as represented in Equation 2. The baseline yields and revenues are listed in Table E-3, and the baseline prices are reported in Table E-4. The new incentive level can then be estimated using the computed equations which follow the form of Equation 3 and are listed in Table E-5.

Equation 2: $\%\Delta \mathrm{Re}\,venue = ((\sum_{i=1}^{n}(P_i * Y_i) / J) - Base\,\mathrm{Re}\,venue) / Base\,\mathrm{Re}\,venue$,

where **n** is the number of crops and **J** is the number of years in rotation.

Equation 3: Incentive level $= \beta_0 + \beta_1(\%\Delta \mathrm{Re}\,venue)$

Response of the various rotation incentive levels to changes in revenue varies considerably. Most follow the general trend that as revenues increase, incentive levels increase. But in seven rotations, incentive levels decrease as total revenue increases. This is due to two separate causes. In some cases, the variance in yields of conventional tillage is more than the variance of no-tillage yields. This causes the relative amount of revenues under conventional tillage to become more "risky" as revenues increase. Therefore, to a risk adverse producer, conventional tillage becomes less attractive. The other cause occurs in the comparisons to the conventional wheat/fallow rotation of the western Great Plains. The cost of the conventional wheat/fallow rotation is low compared to the alternative no-tillage practices. At low prices (revenue) the extra cost of the alternative practices is not offset by extra revenue, but as crop prices increase, the increase in mean expected total revenue offsets the higher cost of the rotation practice. This makes the alternative practices relatively more attractive at higher revenues; therefore, the incentive decreases.

The estimated incentive levels reported in Table E-2 are to be considered as the average incentives required by producers to adopt the alternative tillage system at baseline levels of commodity prices. However, more than likely the incentive would vary across farm sizes, types of operators, and other factors, all variables which are beyond the scope of this study.

Table E-3
Base yields and revenues by experimental site and rotation.

Proposed Switch	Region	Site abbv.*	Rotation & Drainage	Base Yields (Mg/ha)		Base Revenue ($/ha/yr)
Intensive Till To No- Till	Corn Belt	IAAP	Corn/ Soybeans: poor	Corn	9.15	646.41
				Soybeans	2.96	
		NERDF	Corn/ Soybeans: well	Corn	9.95	684.22
				Soybeans	3.03	
		NERDF	Cont. Corn: well	Corn	8.94	690.15
		ARC	Cont. Corn: poor	Corn	11.23	866.58
	Central Great Plains	RMF	Cont. Soybeans	Soybeans	2.69	533.74
		RMF	Sorghum/ Soybeans	Sorghum	8	560.92
				Soybeans	2.69	
		NAF	Cont. Sorghum	Sorghum	5.38	395.36
	Western Great Plains	SWK1	Wheat/ Fallow	Wheat	1.95	102.13
		SWK1	Wheat/Sorghum/ Fallow	Wheat	1.95	102.13
	Mississippi River Corridor	ALB	Corn/ Soybeans	Corn	8.2	556.72
				Soybeans	2.42	
		MES	Cont. Cotton	Cotton	0.97	1,107.18
Intensive Till To Reduced Till	Corn Belt	ARC	Corn/ Soybeans: poor	Corn	12.04	818.02
				Soybeans	3.56	
		NERDF	Corn/ Soybeans: well	Corn	9.95	684.22
				Soybeans	3.03	
		ARC	Cont. Corn: poor	Corn	11.23	886.58
		NERDF	Cont. Corn: well	Corn	8.94	690.15

* Note: Definition of site abbreviations can be found in Attachment 2.

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Table E-4
Base prices

Crop	Price($/Mg)
Corn	77.16
Soybeans	198.41
Wheat	104.72
Sorghum	73.49
Cotton	1,144.62

Table E-5
Revenue sensitivity equations

Proposed Switch	Region	Site* & Drainage	Conventional Rotation	No-Till Rotation	Incentive level Equation
Intensive Till to No-Till	Corn Belt	IAAP Poor	Corn/Soybean	Corn/Soybean	$25.18^t+0.067^t$ (%ΔRev) r^2=.99
		NERDF well	Corn/Soybean	Corn/Soybean	$20.51^t+0.533^t$ (%ΔRev) r^2=.99
		NERDF well	Cont. Corn	Cont. Corn	$66.05^t+0.681^t$ (%ΔRev) r^2=.99
		ARC poor	Cont. Corn	Cont. Corn	$99.98^t+1.525^t$ (%ΔRev) r^2=.99
	Central Great Plains	RMF	Cont. Soybeans	Cont. Soybean	$6.84^t+0.00^t$ (%ΔRev) r^2=.99
		RMF	Sorghum/ Soybean	Sorghum/ Soybean	$0.74^t-0.163^t$ (%ΔRev) r^2=.99
		NAF	Cont. Sorghum	Cont. Sorghum	$36.10^t+0.052^t$ (%ΔRev) r^2=.99
	Western Great Plains	SWK1	Wheat/ Fallow	Wheat/ Fallow	$14.63^t-0.075^t$ (%ΔRev) r^2=.99
		SWK1	Wheat/ Fallow	Wheat/Sorghum/ Fallow	$15.17^t-0.684^t$ (%ΔRev) r^2=.99
	Mississippi River Corridor	ALB	Corn/ Soybean	Corn/ Soybean	$19.67^t-0.216^t$ (%ΔRev) r^2=.99
		MES	Cont. Cotton	Cont. Cotton	$23.2^t+0.708^t$ (%ΔRev) r^2=.99
Intensive Till to Reduced Till	Corn Belt	ARC Poor	Corn/Soybean	Corn/Soybean	$15.22^t+0.109^t$ (%ΔRev) r^2=.99
		NERDF Well	Corn/Soybean	Corn/Soybean	$56.17^t+0.200^t$ (%ΔRev) r^2=.99
		ARC Poor	Cont. Corn	Cont. Corn	$3.51^t-0.068^t$ (%ΔRev) r^2=.99
		NERDF Well	Cont. Corn	Cont. Corn	$101.26^t+0.897^t$ (%ΔRev) r^2=.99

* Note: Definition of site abbreviations can be found in Attachment E-2.
t=all coefficients significant at the 0.00 level of significance.

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Attachment E-1 of Appendix E: Budget and Yield Sources

Case#1: **Convent. corn/soybeans to no till**

Case#2: **Convent. continuous corn to no-till**

Budgets:

Iowa: Ag Decision Maker, Mike Duffy, January 2002.   Seed, Fert, insurance, misc, and Dry
APAC Budgets   Pre Harvest Machinery, chemicals

Indiana: Dobbins, C.L., et al. "2002 Purdue Crop Guide   For conventional fertilizer app rates,drying insurance, mis
Craig Dobbins, Purdue Ag Econ Dept.   Herbicide
Ohio State Crop Budgets   Herbicide
APAC Budgets   Pre-harvest Machinery
Indiana Custom Rates, D.H.Doster   Harvest cost

Iowa

NERDF, Nashua, IA

Data: Research Farm Manager, Ken Pecinovsky [kennethp@willowtree.com]
Site: North-East Research and Demonstration Farm, located near Nashua, Iowa in the northeast corner of the state
Soil: Kenyon Loam, Tile Drained=Well Drained
Years: 1978-2001

IAAP, Burlington, IA

Data: Brown, H.J. "Tillage System Effects on Crop Growth and Production Costs for a Corn-Sobean Rotation",
   J.Prod.Agic. Vol 2 no 3 1989
Site: Iowa Army Ammunition Plant near Burlington, IA, Southeastern part
Soil: Poorly drained Taintor/somewhat poorly drained Mahaska…silty clay loams
Years: 1980-1990

SERDF, Crawfordsville, IA

Data: Southeast Research and Demonstration Farm--2000 Annual Progress Reports, Farm Manager, Kevin VanDee 641
Site: Southeast Research and Demonstration Farm, Crawfordsville, IA,
Soil: Poory Drained Kalona Soil, 2) Well Drained Nira Soils
Years: 1980-2001

Indiana

ARC, West Lafayette, IN

Data: Cropping Systems Research Report 2001, T.D. West, T.J. Vyn, Department of Agronomy, Purdue Univesity
Site: Purdue Agronomy Research Center(ARC), West Lafayette, West-Central Indiana
Soil: Chalmers Silty clay loam soil (4%OM),"Poorly Drained"
Years: 1975-2001

PPAC, Wanatah, IN

Data: Cropping Systems Research Report 2001, T.D. West, T.J. Vyn, Department of Agronomy, Purdue University
Site: Pinney-Purdue agricultural center(PPAC), Wanatah, IN, Northern Indiana
Soil: Sebewa Loam, "Very Poorly Drained"
Years: 1997-2001

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Case#3:   *Convent. sorghum, soybeans and sorghum/soybeans to no-till.*

Budgets:

Kansas:	Kansas State Farm Management Guides	seed, fert, chemicals,misc
	APAC Budgets	Pre-harvest machinery
	Kansas State Custom Rates	Harvest cost

NAF, Manhattan, KS

Data:	LONG-TERM NITROGEN MANAGEMENT AND TILLAGE EFFECTS ON GRAIN SORGHUM,
	R.E. Lamond, G.M. Pierzynski and D.A. Whitney
Site:	North Agronomy Farm, Manhattan, KS
Soil:	Smolan silty clay loam, 2.3% organic matter, 6.1 pH, Bray-1 P of 26 ppm and exchangeable K of 305 ppm.
Years:	1982-2001

USE THIS DATA FOR A)SORGHUM CONTINUOUS CONVENT TO SORGHUM CONT. NOTILL

RMF, Lincoln, NE

Data:	Dickey,Elbert C., Paul Jasa,Robert Grisso,
	Long Term Tillage Effects on Grain Yield and Soil Properties in a Soybean/Grain Sorghum RotationJ.Prod.Ag.Vol7,no4,1994
Site:	Rogers Memorila Farm, near Lincoln, Nebraska
Soil:	Sharpsburg silty clay loam (fine, montmorillonitic, mesic Typic Argiudolls)
Years:	1981-1990
	USE THIS DATA FOR A)SOYBEAN/SORGHUM CONVENT TO SOYBEAN/SORGHUM NOTILL,
	B) SOYBEAN CONTINUOUS CONVENT TO SOYBEAN CONT. NOTILL

Case#4:   *Convent. wheat/fallow to no-till in Western Great Plains*

Case#5:   *Convent. wheat/fallow to wheat/sorghum/fallow and wheat/corn/fallow in Wester Great Plains*

Budgets:

Kansas:	Kansas State Farm Management Guides	seed, fert, chemicals,misc
	APAC Budgets	Pre-harvest machinery
	Kansas State Custom Rates	Harvest cost

RHBES, Fort Hays Exp. Station, KS

Fort Hays Branch Experiment Station

Data:	Jeff Williams sent data from a grad thesis.
Site:	Fort Hays, KS Exp Station
Soil:	
Years:	1976-1986
	USE THIS DATA FOR WH/FALLOW CONVENTIONAL TO A)WH/FALLOW/SORGHUM NO TILL AND B)WH/FALLOW NO TILL

SWK1, Garden City, KS

Data:	"Cropping System and Tillage Effects on Available Soil Water and Yield of Grain sorghum and Winter Wheat",
	Norwood,C.A. et al., J.Prod.Agric.,Vol.3,no.3.1990.87-91:
	Norwood,"An Economic Comparisn of the wheat fallow and wheat sorghum fallow cropping systems"
	J.Pro.Ag.Vol6,No2,april-june 1993.
Site:	Southwest Kansas Res.-Extension Ctr.,Garden City, KS
Soil:	Satanta loam(fine-loamy,mixed,mesic Aridic Agriustoll)ph of 7.0, organ matter of 1.3%
Years:	1979-1987
	USE THIS DATA FOR A)WH/FALLOW CONVENT TO WH/FALLOW/SORGHUM NO TILL,
	B)WH/FALLOW CONVENT TO WH/FALLOW NOTILL

SWK2, Garden City, KS--not using now

Data:	POST-HARVEST WEED CONTROL IN A WHEAT-FALLOW ROTATION,Alan Schlegel and Troy Dumler
Site:	Southwest Kansas Res.-Extension Ctr.,Garden City, KS
Soil:	Satanta loam(fine-loamy,mixed,mesic Aridic Agriustoll)ph of 7.0, organ matter of 1.3%
Years:	1996-2001
	USE THIS DATA FOR A)WH/FALLOW CONVENT TO WH/FALLOW NOTILL

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Case#6: *Convent Corn/Soybean to Corn/wheat-soybeans in Mid South*

Budgets:

Tennessee: TN Field Crop Budgets, Ag. Ext. Service   all but custom
                   TN Custom Rates,Ag. Ext. Service   Harvest Costs

ALB--soybean/corn

Data: Edwards, J.H., D.L. Thurlow, and J.T. Eason. 1988. Influence of Tillage and Crop Rotation on Yields of Corn, Soybean, and Wheat. Agronomy Journal 80:76-80.
Site: Sand Mt Substation, Crossville, AL
Soil: fine sandy loam, well drained
Years: 1980-1984

ALB--soybean/corn

Data: Tillage and wheat Production, Touchton, Joseph t., etal. Department of Agronomy, Auburn University.
Site: Monroeville, AL
Soil: Sumpter soil
Years: 1984-1992

Case#7: *Convent Cotton to No-Till in Mid South.*

Budgets:

Tennessee: TN Field Crop Budgets, Ag. Ext. Service   all
                   Not using custom rates for cotton.   The custom price spread is too large and would lead to either severe over or under estimation.

MES, Milan, TN

Data: Bradley,J.F. "Success with No-Till Cotton" in Arkansas Agricultural Experiment Station Special Publication 160, pp.46-48;revised 01-25-95
Site: Milan, Tennessee
Soil: Grenada Silt Loam
Years: 1981-1994

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Attachment E-2 of Appendix E: Site Selection

Corn Belt

Corn/Soybean Rotation
Well Drained Soil
There are two experimental data sets from "well drained soils", the NERDF and SERDF sites. Both NERDF and SERDF experiments are carried out in small test plots in Iowa. The "well drained" soil in the SERDF experiment was on a 2-9% slope. The lesser slopes in this region are poorly drained. The NERDF experiment "well drained" soils are on a 1-2% slope and may be more representative of "well drained" soils for the region as a whole. NERDF has 24 years of data compared to SERDF's 11 years. For these reasons the *NERDF site is preferred at the representative for well drained soils*.

Corn/Soybean Rotation
Poorly drained Soil
There are four experimental data sets from "poorly drained soils", SERDF, IAAP, PPAC, and ARC. The PPAC site is excluded because it only has 5 years of data. The SERDF, ARC and IAAP sites have 11, 24, and 10 years of data respectively. Both the SERDF and ARC experiments were conducted on small test plots. The IAAP site is unique in that it was conducted on a 432 acre site, therefore standard field equipment could be used. Although the ARC site has more years of data, *the uniqueness of the scale of the IAAP site makes it preferable in the switch to no-tillage.* The IAAP site has no reduced tillage data, therefore we use the ARC site for the switch to reduced tillage.

Continuous Corn
Well Drained Soil
As mentioned above, the "well drained" soil in the SERDF experiment was on a 2-9% slope. The lesser slopes in this region are poorly drained. The NERDF experiment "well drained" soils are on a 1-2% slope and may be more representative of "well drained" soils for the region as a whole. NERDF has 24 years of data compared to SERDF's 11 years. For these reasons the *NERDF site is preferred at the representative for well drained soils*.

Continuous Corn
Poorly Drained Soil
There are three continuous corn data sets from poorly drained soils, SERDF, PPAC and ARC sites. As stated above an Eastern experiment would be more preferred, as it may represent the more common poorly drained soils of the eastern part of the corn belt. The ARC site has 24 years of data compared to PPAC's 5 years of data. Also the PPAC site is very far north and may not be representative of the region. *For these reasons the ARC site is preferred*.

Western Great Plains
Wheat/fallow and wheat/sorghum/fallow
FHBES experiment data was sent from a graduate research paper. Much of the information concerning the experiment is missing, such as soil type, experiment plot size and chemical use. The SWK1 site has more specific information. Additionally the SWK1 site is further west, in Garden City, as opposed to Hays, Kansas. For these reasons, *SWK1 site is preferred.*

Attachment E-3 of Appendix E: Yield Comparisons

Corn Belt: Corn/Soybean Rotation
Iowa Army Ammunition Plant (IAAP)
Burlington, IA
Corn Yield, poorly drained
Intensive mean=136.7
No-Till mean=131.0

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Corn Belt: Continuous Corn
Northeast Research and Demo Farm (NERDF)
Nashua, IA
Corn Yield, well drained
Intensive mean=132.7
No-Till mean=122.2

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Corn Belt: Corn/Soybean Rotation
Purdue Agronomy Research Center(ARC)
W. Lafayette, IN
Corn Yield, poorly drained
Intensive mean=178.8
Reduced mean=180.4

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Corn Belt: Corn/Soybean Rotation
Purdue Agronomy Research Center (ARC)
W. Lafayette, IN
Soybean Yield, poorly drained

Intensive mean=52.9
Reduced mean=50.7

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions
of the United States

Corn Belt: Corn/Soybean Rotation
Northeast Research and Demo Farm (NERDF)
Nashua, IA
Corn Yield, well drained
Intensive mean=148.4
Reduced mean=144.1

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions
of the United States

Estimating Economic Incentives Required to Achieve Adoption of Conservation-Tillage Systems in Selected Regions of the United States

Corn Belt: Continuous Corn
Northeast Research and Demo Farm(NERDF)
Nashua, IA
Corn Yield, well drained
Intensive=132.7
Reduced mean=125.9

F
ESTIMATING STATE-LEVEL SOC RESPONSES

The purpose of this appendix is to describe how state-level SOC response curves were developed for Indiana and Iowa. The state curves were developed from carbon storage projects recently completed by Smith et al.[1] in Indiana and Brenner et al.[2] in Iowa. These projects provided state-level estimates of increased SOC as a result of switching corn/soybean rotations from intensive-till to moderate-till or no-till. These were point estimates for 10 years after switching tillage-systems. These projects provided county-level point estimates for 10 and 20 years after switching tillage systems. At least two data points in addition to the zero-zero point are needed to characterize the nonlinear increase in SOC that results from reducing tillage. Therefore, county-level SOC response data (10- and 20-year data points) were selected from counties that represent the state-wide range of SOC responses and also provide a mean response that passes through the state-wide mean for 10 years after switching tillage. In Indiana, Allen and Gibson Counties represented the range of SOC responses and the mean of curves for Tippecanoe and Gibson Counties were used to represent the state mean (Table F-1). This interpolation process was performed for corn/soybean rotations switched from intensive-till to both moderate-till and no-till and resulted in state curves that passed through or very nearly through the state mean 10-year data points for corn/soybean rotations. Curves for the same counties were used to develop state curves for continuous corn switched from intensive-till to both moderate-till and no-till.

More specifically, a quadric regression was performed for each county-level set of data points (i.e., for 0, 10, and 20 years). The quadratic responses were transformed as described by Bock et al.[3] to provide SOC as a function of the maximum increase in SOC (ΔSOCs) and a slope or efficiency factor (E). An example of this process for the first SOC response in Table F-1 is illustrated in Figure F-1.

For both Indiana (Figure F-2) and Iowa (Figure F-3), there was a linear relationship between E and ΔSOCs for the range of curves generated. Therefore, the mean of two or more curves was calculated using the mean of E values for the curves being averaged and the mean of ΔSOCs values for the curves being averaged.

Finally, state curves were calculated for corn/soybean rotations switched from intensive-till to moderate-till or no-till using weighted averages for the E and ΔSOCs parameters for hydric and non-hydric soils. In Indiana, 79 percent of the soils are non-hydric and 21 percent of the soils are hydric (personal communication, John Brenner, NRCS). The same process was conducted for continuous corn. Results of these weighted averages are at the end of Table F-1.

The same overall process was performed for Iowa (Table F-2). Buchanan and Greene Counties were used to represent the range of responses in Iowa and the mean of curves from Buchanan, Pottawattamoe, and Greene Counties were used to represent the state mean. In Iowa, 77 percent

of the soils are non-hydric and 23 percent of the soils are hydric (personal communication, John Brenner, NRCS).

State	County	Rotation	Tillage	Hydric	Texture
IN	Allen	C/SB	No	N	L

Year	ΔSOC	
0	0	
10	5100	from IN carbon storage project (Table 1)
20	8100	from IN carbon storage project (Table 1)
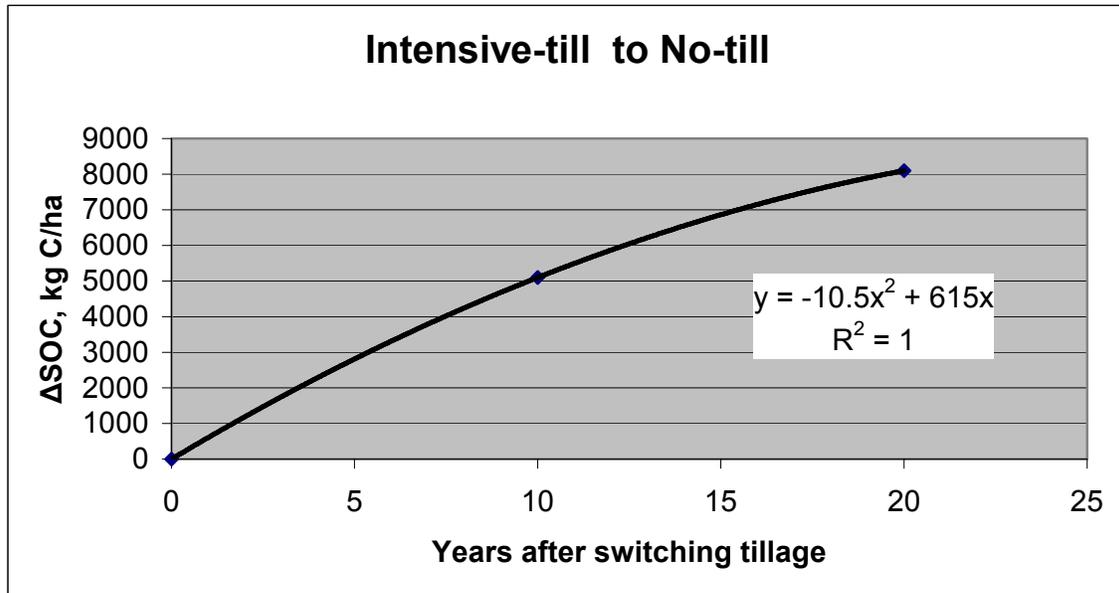
ΔSOC=B1*Years+B2*Years*Years=(10*E)*Years-(25*E*E/ΔSOCs)*Years*Years

B1=	615	from graph
B2=	-10.5	from graph
E=	61.5	=slope factor for best-fit quadratic response=B1/10
ΔSOCs=	9005	=increase in SOC to reach the new steady-state SOC=(-25*E*E)/B2
Ys=	29.3	=years to reach the new steady-state SOC=ΔSOCs/(5*E)

Figure F-1
Quadratic regression and transformation procedure
for SOC response to reducing tillage
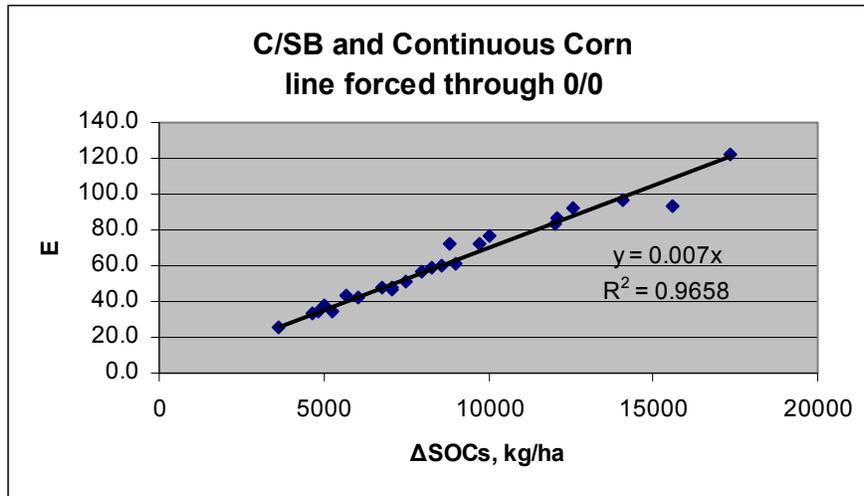
Figure F-2
Linear relationship between E and ΔSOCs for the Indiana data from Table F-1
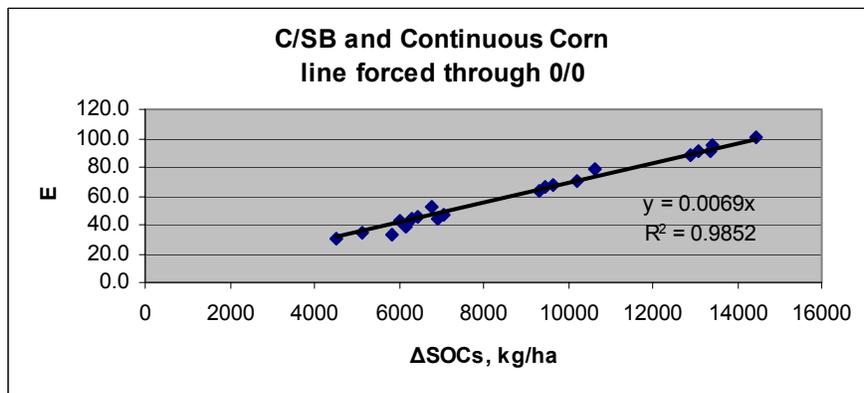
Figure F-3
Linear relationship between E and ΔSOCs for the Iowa data from Table F-2

Estimating State-Level SOC Responses

Table F-1
Increases in SOC due to switching from intensive-till to no-till or moderate till in Indiana

Table 1. Increases in SOC due to switching from intensive-till to no-till or moderate-till in counties selected to represent the range and mean of county-level responses in Indiana, Smith et al. (2002).

| | | | | | | ΔSOC | | Quadratic SOC Response | | |
| | | | | | | 10 years | 20 years | ΔSOCs | E (slope factor) | Years to ΔSOCs (Ys) |
State	County	Rotation	Tillage	Hydric	Texture					
						kg C/ha				
IN	Allen	C/SB	No	N	L	5100	8100	9005	61.5	29.3
IN	Allen	C/SB	No	N	CL	5000	8000	9000	60.0	30.0
							Mean	9003	60.8	29.7
IN	Allen	C/SB	No	Y	L	4300	6800	7511	52.0	28.9
IN	Allen	C/SB	No	Y	CL	4200	6700	7501	50.5	29.7
							Mean	7506	51.3	29.3
IN	Allen	C/SB	Moderate	N	L	3500	5400	5778	43.0	26.9
IN	Allen	C/SB	Moderate	N	CL	3500	5600	6300	42.0	30.0
							Mean	6039	42.5	28.5
IN	Allen	C/SB	Moderate	Y	L	2800	4300	4578	34.5	26.5
IN	Allen	C/SB	Moderate	Y	CL	2900	4600	5104	35.0	29.2
							Mean	4841	34.8	27.9
IN	Allen	C	No	N	L	10200	15900	17223	124.5	27.7
IN	Allen	C	No	N	CL	9900	15700	17415	119.5	29.1
							Mean	17319	122.0	28.4
IN	Allen	C	No	Y	L	7500	11700	12685	91.5	27.7
IN	Allen	C	No	Y	CL	7500	11600	12447	92.0	27.1
							Mean	12566	91.8	27.4
IN	Allen	C	Moderate	N	L	6900	10700	11517	84.5	27.3
IN	Allen	C	Moderate	N	CL	7300	11500	12633	88.5	28.5
							Mean	12075	86.5	27.9
IN	Allen	C	Moderate	Y	L	4700	7400	8123	57.0	28.5
IN	Allen	C	Moderate	Y	CL	5200	8200	9020	63.0	28.6
							Mean	8572	60.0	28.6
IN	Tippecanoe	C/SB	No	N	L	4900	7700	8429	59.5	28.3
IN	Tippecanoe	C/SB	No	N	CL	4800	7500	8148	58.5	27.9
							Mean	8289	59.0	28.1
IN	Tippecanoe	C/SB	No	Y	L	4000	6400	7200	48.0	30.0
IN	Tippecanoe	C/SB	No	Y	CL	4000	6300	6918	48.5	28.5
							Mean	7059	48.3	29.3
IN	Tippecanoe	C/SB	Moderate	N	L	3500	5300	5565	43.5	25.6
IN	Tippecanoe	C/SB	Moderate	N	CL	3500	5400	5778	43.0	26.9
							Mean	5672	43.3	26.3
IN	Tippecanoe	C/SB	Moderate	Y	L	2700	4200	4538	33.0	27.5
IN	Tippecanoe	C/SB	Moderate	Y	CL	2800	4400	4817	34.0	28.3
							Mean	4678	33.5	27.9
IN	Tippecanoe	C	No	N	L	8200	13500	16056	96.5	33.3
IN	Tippecanoe	C	No	N	CL	7700	12700	15167	90.5	33.5
							Mean	15612	93.5	33.4
IN	Tippecanoe	C	No	Y	L	6400	9900	10625	78.5	27.1
IN	Tippecanoe	C	No	Y	CL	6000	9000	9375	75.0	25.0
							Mean	10000	76.8	26.1
IN	Tippecanoe	C	Moderate	N	L	6600	10400	11429	80.0	28.6
IN	Tippecanoe	C	Moderate	N	CL	7200	11400	12615	87.0	29.0
							Mean	12022	83.5	28.8
IN	Tippecanoe	C	Moderate	Y	L	4400	6900	7532	53.5	28.2
IN	Tippecanoe	C	Moderate	Y	CL	4900	7700	8429	59.5	28.3
							Mean	7981	56.5	28.3

State	County	Rotation	Tillage	Hydric	Texture	10 years	20 years	ΔSOCs	E (slope factor)	Years to ΔSOCs (Ys)
IN	Gibson	C/SB	No	N	L	4300	6700	7253	52.5	27.6
IN	Gibson	C/SB	No	N	SICL	3600	5700	6308	43.5	29.0
					Mean			6781	48.0	28.3
IN	Gibson	C/SB	No	Y	L	3500	5400	5778	43.0	26.9
IN	Gibson	C/SB	No	Y	SICL	2600	4000	4267	32.0	26.7
					Mean			5023	37.5	26.8
IN	Gibson	C/SB	Moderate	N	L	2900	4600	5104	35.0	29.2
IN	Gibson	C/SB	Moderate	N	SICL	2900	4700	5410	34.5	31.4
					Mean			5257	34.8	30.3
IN	Gibson	C/SB	Moderate	Y	L	2300	3500	3692	28.5	25.9
IN	Gibson	C/SB	Moderate	Y	SICL	1900	3100	3616	22.5	32.1
					Mean			3654	25.5	29.0
IN	Gibson	C	No	N	L	8700	13400	14311	107.0	26.8
IN	Gibson	C	No	N	SICL	7300	11900	13856	86.5	32.0
					Mean			14084	96.8	29.4
IN	Gibson	C	No	Y	L	6400	9900	10625	78.5	27.1
IN	Gibson	C	No	Y	SICL	5000	7000	7042	65.0	21.7
					Mean			8834	71.8	24.4
IN	Gibson	C	Moderate	N	L	5900	9100	9734	72.5	26.9
IN	Gibson	C	Moderate	N	SICL	6100	10700?			
			Mean					9734	72.5	26.9
IN	Gibson	C	Moderate	Y	L	3800	6000	6613	46.0	28.8
IN	Gibson	C	Moderate	Y	SICL	4000	6500	7521	47.5	31.7
					Mean			7067	46.8	30.3

Interpolated state curves--means of Tippaconoe and Gibson County curves

						ΔSOC		Quadratic SOC Response		
State	County	Rotation	Tillage	Hydric	Texture	10 years	20 years	ΔSOCs	E (slope factor)	Years to ΔSOCs (Ys)
						kg C/ha				
IN	Tippeconoe	C/SB	No	N	Mean			8289	59.0	28.1
IN	Gibson	C/SB	No	N	Mean			6781	48.0	28.3
				Interpolated state curve		4400	6901	7535	53.5	28.2
				State mean--Smith et al. (2002)		4225	not avail.			
IN	Tippeconoe	C/SB	No	Y	Mean			7059	48.3	29.3
IN	Gibson	C/SB	No	Y	Mean			5023	37.5	26.8
				Interpolated state curve		3527	5532	6041	42.9	28.0
				State mean--Smith et al. (2002)		3500	not avail.			
IN	Tippeconoe	C/SB	Moderate	N	Mean			5672	43.3	28.8
IN	Gibson	C/SB	Moderate	N	Mean			5257	34.8	30.3
				Interpolated state curve		3204	5016	5464	39.0	29.6
				State mean--Smith et al. (2002)		3200	not avail.			
IN	Tippeconoe	C/SB	Moderate	Y	Mean			4678	33.5	27.9
IN	Gibson	C/SB	Moderate	Y	Mean			3654	25.5	29.0
				Interpolated state curve		2428	3811	4166	29.5	28.5
				State mean--Smith et al. (2002)		2400	not avail.			
IN	Tippeconoe	C	No	N	Mean			15612	93.5	33.4
IN	Gibson	C	No	N	Mean			14084	96.8	29.4
				Interpolated state curve		7989	12931	14848	95.1	31.4
IN	Tippeconoe	C	No	Y	Mean			10000	76.8	26.1
IN	Gibson	C	No	Y	Mean			8834	71.8	24.4
				Interpolated state curve		5961	8995	9417	74.3	25.2
IN	Tippeconoe	C	Moderate	N	Mean			12022	83.5	28.8
IN	Gibson	C	Moderate	N	Mean			9734	72.5	26.9
				Interpolated state curve		6402	10007	10878	78.0	27.9
IN	Tippeconoe	C	Moderate	Y	Mean			7981	56.5	28.3
IN	Gibson	C	Moderate	Y	Mean			7067	46.8	30.3
				Interpolated state curve		4277	6783	7524	51.6	29.3

Estimating State-Level SOC Responses

						Weighted state means assuming 79% non-hydric soils and 21% hydric soils				
IN	State	C/SB	No	Mean	Mean	4217	6614	7220.8	51.3	28.2
IN	State	C/SB	Moderate	Mean	Mean	3041	4763	5191.6	37.0	28.1
IN	State	C	No	Mean	Mean	7587	11942	13103.5	92.0	28.5
IN	State	C	Moderate	Mean	Mean	5956	9331	10173.6	72.5	28.1

Table F-2
Increases in SOC due to switching from intensive-till to no-till or moderate-till in Iowa

Table 2. Increases in SOC due to switching from intensive-till to no-till or moderate-till in counties selected to represent the range and mean of county-level responses in Iowa, Brenner et al. (2001).

State	County	Rotation	Tillage	Hydric	Texture	ΔSOC 10 years	ΔSOC 20 years	Quadratic SOC Response ΔSOCs	E (slope factor)	Years to ΔSOCs (Ys)
						kg C/ha				
IA	Buchanan	C/SB	No	N	L	5800	9200	10208	70.0	29.2
IA	Buchanan	C/SB	No	N	CL	5800	9200	10208	70.0	29.2
							Mean	10208	70.0	29.2
IA	Buchanan	C/SB	No	Y	L					
IA	Buchanan	C/SB	No	Y	CL	6400	9900	10625	78.5	27.1
							Mean	10625	78.5	27.1
IA	Buchanan	C/SB	Moderate	N	L	3800	6100	6901	45.5	30.3
IA	Buchanan	C/SB	Moderate	N	CL	4000	6400	7200	48.0	30.0
							Mean	7051	46.8	30.2
IA	Buchanan	C/SB	Moderate	Y	L					
IA	Buchanan	C/SB	Moderate	Y	CL	4200	6400	6760	52.0	26.0
							Mean	6760	52.0	26.0
IA	Buchanan	C	No	N	L	7600	12100	13504	91.5	29.5
IA	Buchanan	C	No	N	CL	7500	11900	13210	90.5	29.2
							Mean	13357	91.0	29.4
IA	Buchanan	C	No	Y	L					
IA	Buchanan	C	No	Y	CL	8300	13100	14429	100.5	28.7
							Mean	14429	100.5	28.7
IA	Buchanan	C	Moderate	N	L	3100	5000	5704	37.0	30.8
IA	Buchanan	C	Moderate	N	CL	3500	5700	6624	41.5	31.9
							Mean	6164	39.3	31.4
IA	Buchanan	C	Moderate	Y	L					
IA	Buchanan	C	Moderate	Y	CL	3700	6000	6914	44.0	31.4
							Mean	6914	44.0	31.4
IA	Greene	C/SB	No	N	L	5200	8200	9020	63.0	28.6
IA	Greene	C/SB	No	N	CL	5300	8500	9601	63.5	30.2
							Mean	9311	63.3	29.4
IA	Greene	C/SB	No	Y	L	5400	8500	9327	65.5	28.5
IA	Greene	C/SB	No	Y	CL	5500	8700	9614	66.5	28.9
							Mean	9471	66.0	28.7
IA	Greene	C/SB	Moderate	N	L	3400	5300	5741	41.5	27.7
IA	Greene	C/SB	Moderate	N	CL	3600	5700	6308	43.5	29.0
							Mean	6025	42.5	28.4
IA	Greene	C/SB	Moderate	Y	L	3500	5500	6021	42.5	28.3
IA	Greene	C/SB	Moderate	Y	CL	3700	5900	6601	44.5	29.7
							Mean	6311	43.5	29.0
IA	Greene	C	No	N	L	7300	11500	12633	88.5	28.5
IA	Greene	C	No	N	CL	7300	11700	13200	87.5	30.2
							Mean	12917	88.0	29.4
IA	Greene	C	No	Y	L	7600	11900	12964	92.5	28.0
IA	Greene	C	No	Y	CL	7500	11900	13210	90.5	29.2
							Mean	13087	91.5	28.6
IA	Greene	C	Moderate	N	L	2500	4000	4500	30.0	28.6
IA	Greene	C	Moderate	N	CL	2500	4000	4500	30.0	28.6
							Mean	4500	30.0	28.6
IA	Greene	C	Moderate	Y	L	2800	4400	4817	34.0	28.3
IA	Greene	C	Moderate	Y	CL	2900	4700	5410	34.5	34.1
							Mean	5114	34.3	31.2

Estimating State-Level SOC Responses

State	County	Rotation	Tillage	Hydric	Texture					
IA	Pottawattamoe	C/SB	No	N	L	5700	9000	9919	69.0	28.8
IA	Pottawattamoe	C/SB	No	N	CL	5500	8600	9352	67.0	27.9
							Mean	9636	68.0	28.4
IA	Pottawattamoe	C/SB	No	Y	L					
IA	Pottawattamoe	C/SB	No	Y	CL					
							Mean			
IA	Pottawattamoe	C/SB	Moderate	N	L	3700	5800	6328	45.0	28.1
IA	Pottawattamoe	C/SB	Moderate	N	CL	3800	6000	6613	46.0	28.8
							Mean	6471	45.5	28.5
IA	Pottawattamoe	C/SB	Moderate	Y	L					
IA	Pottawattamoe	C/SB	Moderate	Y	CL					
							Mean			
IA	Pottawattamoe	C	No	N	L	7900	12600	14102	95.0	29.7
IA	Pottawattamoe	C	No	N	CL	7700	11900	12758	94.5	27.0
							Mean	13430	94.8	28.4
IA	Pottawattamoe	C	No	Y	L					
IA	Pottawattamoe	C	No	Y	CL					
							Mean			
IA	Pottawattamoe	C	Moderate	N	L	2900	4900	6235	33.5	37.2
IA	Pottawattamoe	C	Moderate	N	CL	2800	4600	5445	33.0	33.0
							Mean	5840	33.3	35.1
IA	Pottawattamoe	C	Moderate	Y	L					
IA	Pottawattamoe	C	Moderate	Y	CL					
							Mean			

Interpolated state curves--means of Buchanan, Tippaconoe, and Pottawattamoe County curves

State	County	Rotation	Tillage	Hydric	Texture	ΔSOC 10 years	ΔSOC 20 years	ΔSOCs	Quadratic SOC Response E (slope factor)	Years to ΔSOCs (Ys)
						kg C/ha				
IA	Buchanan	C/SB	No	N	Mean			10208	70.0	29.2
IA	Greene	C/SB	No	N	Mean			9311	63.3	29.4
IA	Pottawattamoe	C/SB	No	N	Mean			9636	68.0	28.4
				Interpolated state curve		5551	8786	9718	67.1	29.0
				State mean--Brenner et al. (2001)		5600	not avail.			
IA	Buchanan	C/SB	No	Y	Mean			10625	78.5	27.1
IA	Greene	C/SB	No	Y	Mean			9471	66.0	28.7
IA	Pottawattamoe	C/SB	No	Y	Mean					
				Interpolated state curve		5926	9255	10048	72.3	27.9
				State mean--Brenner et al. (2001)		5800	not avail.			
IA	Buchanan	C/SB	Moderate	N	Mean			7051	46.8	30.2
IA	Greene	C/SB	Moderate	N	Mean			6025	42.5	28.6
IA	Pottawattamoe	C/SB	Moderate	N	Mean			6471	45.5	28.5
				Interpolated state curve		3718	5887	6515	44.9	29.1
				State mean--Brenner et al. (2001)		3700	not avail.			
IA	Buchanan	C/SB	Moderate	Y	Mean			6760	52.0	26.0
IA	Greene	C/SB	Moderate	Y	Mean			6311	43.5	29.0
IA	Pottawattamoe	C/SB	Moderate	Y	Mean					
				Interpolated state curve		3903	6061	6536	47.8	27.5
				State mean--Brenner et al. (2001)		3850	not avail.			
IA	Buchanan	C	No	N	Mean			13357	91.0	29.4
IA	Greene	C	No	N	Mean			12917	88.0	29.4
IA	Pottawattamoe	C	No	N	Mean			13430	94.8	28.4
				Interpolated state curve		7552	11958	13235	91.3	29.0
IA	Buchanan	C	No	Y	Mean			14429	100.5	28.7
IA	Greene	C	No	Y	Mean			13087	91.5	28.6
IA	Pottawattamoe	C	No	Y	Mean					
				Interpolated state curve		7925	12501	13758	96.0	28.7
IA	Buchanan	C	Moderate	N	Mean			6164	39.3	31.4
IA	Greene	C	Moderate	N	Mean			4500	30.0	28.6
IA	Pottawattamoe	C	Moderate	N	Mean			5840	33.3	35.1
				Interpolated state curve		2886	4711	5501	34.2	31.7
IA	Buchanan	C	Moderate	Y	Mean			6914	44.0	31.4
IA	Greene	C	Moderate	Y	Mean			5114	34.3	31.2
IA	Pottawattamoe	C	Moderate	Y	Mean					

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						Weighted state means assuming 77% non-hydric soils and 23% hydric soils				
IA	State	C/SB	No	Mean	Mean	5637	8895	9793.8	68.3	28.7
IA	State	C/SB	Moderate	Mean	Mean	3761	5929	6519.8	45.6	28.6
IA	State	C	No	Mean	Mean	7638	12083	13354.9	92.3	28.9
IA	State	C	Moderate	Mean	Mean	2976	4843	5619.2	35.3	31.8

Estimating State-Level SOC Responses

References

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2   Brenner, J., K. Paustian, G. Bluhm, J. Cipra, M. Easter, E.T. Elliott, T. Kautza, K. Killian, J. Schuler and S. Williams. 2001. Quantifying the change in greenhouse gas emissions due to natural resource conservation practice application in Iowa. Final report to the Iowa Conservation Partnership. Colorado State University Natural Resource Ecology Laboratory and USDA Natural Resources Conservation Service, Fort Collins, CO, USA.

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