Agricultural Mitigation of Greenhouse Gases: Science and Policy Options

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Introduction

With the adoption of the U.S. Framework Convention on Climate Change, calling for actions to decrease the buildup of greenhouse gases (GHGs) in the atmosphere, interest has grown about agriculture's role in mitigating GHG increases. Three of the major GHGs — carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) — are emitted to and/or removed from the atmosphere in significant amounts through agricultural activity. Thus, the potential for agriculture to mitigate GHG emissions has been the subject of intensive scientific investigation the past several years.

The focus of a forthcoming Council on Agricultural Science and Technology (CAST) report is to summarize and synthesize the most recent research on the potential to mitigate GHG emissions through improvements in agricultural and land management practices. The report is designed to inform policy and decision makers in government and industry, agricultural producers, environmental and other nongovernmental organizations, and the general public. A major objective of the report has been to bring together biophysical and ecological information with economics and policy analysis, to provide a clearer picture of the potential role of agriculture in GHG mitigation strategies. In addition, a major aim has been to address all three major greenhouse gases and to consider the potential tradeoffs and/or synergisms between practices aimed at carbon sequestration and mitigation of N_2O and CH_4 emissions, in order to understand the net effect of all three gases (CO_2, N_2O and CH_4), which can be expressed as an aggregate 'global warming potential' (GWP) value. It is hoped that this synthesis will inform the debate on GHG mitigation in ongoing national and international efforts to deal with global climate change. This paper presents a brief synopsis of some of the findings of the CAST report.

Mitigation of Carbon Dioxide Fluxes through Carbon Sequestration in North American Agriculture

Carbon dioxide is exchanged continuously between soils and the atmosphere, primarily through the processes of photosynthesis and incorporation of plant-derived organic matter into soils (CO_2 influx), and the decomposition of that organic matter by soil organisms (CO_2 outflux). The amount of carbon (C) stored in soils depends primarily on the balance between C inputs from plant (and animal) residues and C emissions from decomposition. Thus, increasing soil C stocks requires increasing C inputs and/or decreasing the decomposition. Both inputs and decomposition rates are affected by natural factors such as climate (temperature and rainfall) and soil physical factors (soil texture, clay mineralogy, profile development), as well as agricultural management practices; thus rates will vary, geographically, across the US and between different management systems. In general, C sequestration will be favored under management systems that (1) minimize soil disturbance and erosion, (2) maximize the amount of crop-residue return, and (3) maximize water- and nutrient-use efficiency of crop production. Although it may be impossible to optimize all these system attributes simultaneously, practices that effectively sequester C share one or more of these traits.

Decreasing tillage intensity, especially by using no-tillage practices, has been found to promote C sequestration. In long-term field experiments comparing no-till to conventionally, i.e., intensively, tilled annual crop systems, adoption of no-till typically results in increases in soil C of 0.1 to 0.7 metric tonnes ha^{-1} yr^{-1} (Dick et al. 1998, Janzen et al. 1998, Paustian et al. 1997) over periods of 10 to 30 yr. Rates tend to be higher in mesic climates with high levels of crop residue inputs, and lower in semi-arid regions supporting lower levels of primary production. In semi-arid regions, no-till adoption provides increased water storage, enabling more continuous crop rotations with elimination or decreased frequency of bare fallowing (Black and Tanaka 1997, Peterson et al. 1998). The effects of no-till systems under these conditions are synergistic in that adoption of no-till enables higher crop inputs through more intensified rotations, lower decomposition rates accompanying (bare) summer-fallowing, greater water-use efficiency, and less soil disturbance (Peterson et al. 1998). No-till by itself, without decreasing or eliminating summer fallow, will have much less of a positive impact on soil C sequestration (Jones et al. 1997, Peterson and Westfall 1997).

Increasing the amount of residue returned to soil can be managed through a variety of practices, including high-residue yielding crops, hay crops in rotation, application of manure and biosolids, and improved management of fertilizer, water, and pests. Most cropland soils show a clear response to increasing amounts of C return such that soil organic carbon levels, over time, are often directly proportional to the amount of C added to soil under different management treatments (Huggins et al. 1998, Paustian et al. 1998, Rasmussen et al. 1980). Eventually, for any given level of input, soil C levels tend toward equilibrium, limiting the amount and duration of additional C storage. Cropland production and residue inputs in the United States have increased dramatically since the 1950s, in part as a result of increased use of fertilizers, pesticides, and irrigation (Allmaras et al. 2000, Reilly and Fuglie 1998). Where production is water- or nutrient-limited, provision of these water and nutrient inputs can contribute to C sequestration. However, energy costs associated with manufacture and distribution of fertilizer, energy for irrigation pumping, as well as potential increased emissions of N_2O and CH_4 must be considered, for these costs may offset part or all the gains in C storage. However, use of these inputs usually will be determined primarily as a means of achieving the objective of food production and not as a means of mitigating GHG emissions. Practices promoting optimally efficient water and nutrient use, however, will likely have the greatest benefits in terms of decreased GHGs.

Various management practices on grazing lands (pasture and rangeland) can increase soil C. On poorly managed grazing lands depleted of soil carbon, practices that increase production and C inputs can build up soil C. Such practices include improving grazing management, using improved species, sowing legumes, fertilizing, and irrigating. In an analysis of more than 100 published studies, Conant et al. (2001) reported that C increase rates for different management improvements averaged between 0.1 - 1 metric tonnes C ha $yr^{\cdot\ -1}$, the highest rates occurring with conversion of cultivated land to perennial grasses, e.g., to pasture or CRP. Average rates of C increase were about 0.3 tonnes C ha $yr^{\cdot\ -1}$ for fertilization, about 0.2 tonnes C ha $yr^{\cdot\ -1}$ for improved grazing or irrigation, and about 0.1 tonnes C ha $yr^{\cdot\ 1}$ for introduction of legumes. Restoring degraded soils and ecosystems (Lal and Bruce 1999) reforesting and afforesting (Brown et al. 1996), retiring marginal lands through set-asides such as the Conservation Reserve Program (CRP) and controlling desertification (Lal and Bruce 1999) are important options for improving biomass productivity and sequestering C in the soil and in the ecosystem. As for annual crop systems, management of grazing lands and degraded lands for greenhouse gas mitigation needs to consider the net effects of practices on GWP. For example, high nitrogen (N) fertilization rates in intensively managed pastures may cause large N_2O emissions that wipe out benefits from carbon sequestration, whereas phosphorus (P) fertilization and/or moderate N in highly P or N-limited systems can yield large gains in productivity and carbon sequestration with little increase in N_2O emissions. Improvements in pasture productivity and forage quality through improved management can sequester carbon and also reduce methane emissions from grazing livestock (Johnson et al. 2000).

Preliminary estimates of the biophysical potential for soil carbon sequestration from cropland and grazing lands in the US have been made, considering the use of existing management and land use practices such as adoption of no-till, elimination of summer fallow in semi-arid croplands, use of winter cover crops, improved residue management, improved pasture management and set-aside of marginal and environmentally sensitive cropland to perennial grass and tree cover (Fig. 1). The various estimates suggest a potential of around 80-150 million metric tonnes C (MMTC) or more per year over a 2-3 decade period for cropland soils and somewhat less for grazing lands. This can be compared to estimates of current carbon sequestration of about 15 MMTC per year for cropland and 6 MMTC for grazing land (Eve et al. 2001, UNFCCC 2000).

To date, most estimates of potentials have been based on highly aggregated data and thus have considerable uncertainty, which has not been formally assessed. Moreover, these biophysical potentials do not consider the economic factors that will limit the adoption of carbon sequestering practices (as discussed below). On the other hand, the development of new technology to specifically enhance carbon sequestration rates and thus increase biophysical potentials is just beginning to be explored (DOE 1999a). Finally, current national estimates of carbon sequestration potential do not include effects of management changes on CO_2 emissions from agricultural inputs, including fuel use, fertilizers, and pesticides, currently accounting

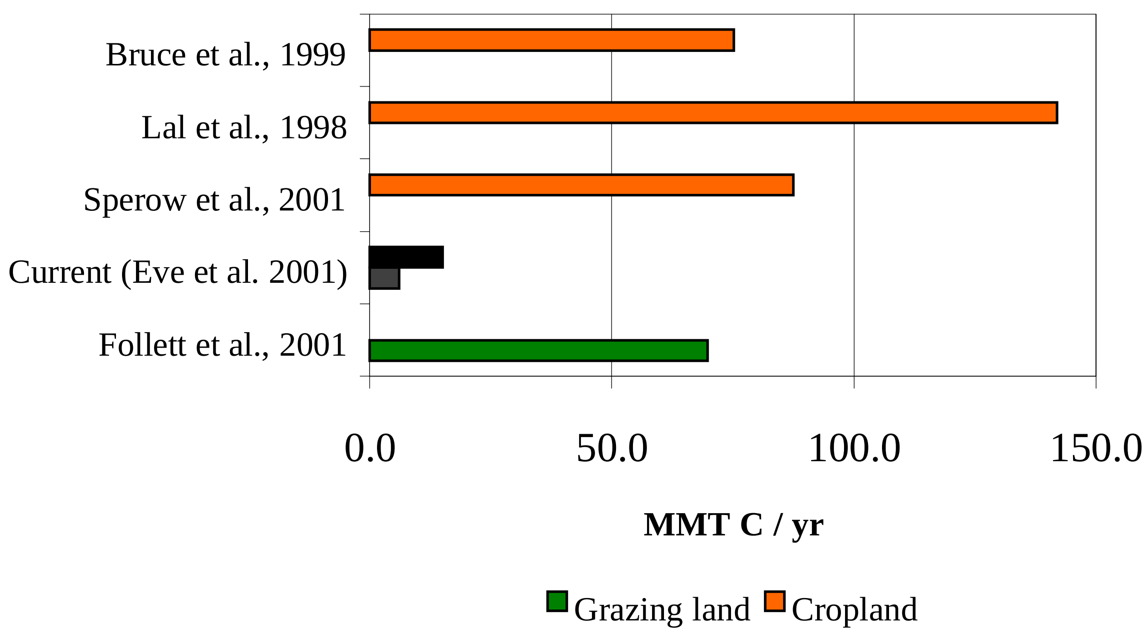

Fig. 1. Recent estimates of potential carbon sequestration on US agricultural and grazing lands. All estimates are based on widespread adoption of existing management practices to sequester carbon but do not include economic factors that will limit adoption rates. Stipled bars show estimates of current net soil C accumulation based on the Intergovernmental Panel on Climate Change national inventory methodology.

for about 28 MMTC emission per year. Some carbon sequestering practices such as no-till will decrease fossil C use (i.e. less fuel use for traction) while other practices, for example, adding cover crops to rotations may increase fossil C use (i.e. due to more field operations).

In addition to C sequestration, increasing soil organic matter levels generally carries with it substantial benefits to soil biological, chemical and physical attributes, which translate into improved fertility and soil sustainability. These improvements include enhanced water storage capacity, increased water infiltration, reduced runoff (and erosion), increased soil buffering capacity, and increased storage of essential plant nutrients.

Mitigation of Nitrous Oxide Fluxes in North American Agriculture

Agriculture is a major contributor of nitrous oxide (N_2O) emissions to the atmosphere (Table 1), one of the more powerful greenhouse gases. The major sources include emissions from soils due to microbial metabolism of nitrogen, through the processes of nitrification and denitrification. The same processes act on animal wastes, resulting in emissions both in storage and when applied to the field. Emissions occur both directly on agricultural lands and from nitrogen transported to non-agricultural lands, through gaseous and leaching/runoff losses from agricultural soils.

Table 1. U.S. and global emissions of N_2O from agricultural sources for 1990. (Gg = gigagrams = 10^9g = kilotonnes). Based on EPA (2000) and Mosier et al. (1998a). Uncertainty is on the order of 50%.

Emission source	U.S.	Global
	Gg N_2O	
Agricultural soil management	620	3900
Manure management	40	300
Indirect emissions from agriculturally-derived N on non-cropped ecosystems	270	2100
Total	930	6300

A portion of the N that is added to and cycles through soil is subject to microbial transformations, including oxidative pathways (nitrification) and reductive pathways (denitrification) involving mineral N compounds, both of which can form N_2O as a byproduct. While rates of emissions from soil vary considerably due to a number of factors, many studies show a rough proportionality between the total N entering the soil from anthropogenic inputs (i.e. fertilizer, manure, planted legumes) and the amount lost as N_2O (Bouwman 1996). Because most cropped soils emit N_2O at a rate about 1.5% of their N inputs, decreasing N inputs in cropping systems could decrease N_2O emissions directly, by about 1.5% of N inputs saved. The type of input is less important than the amount, i.e., synthetic fertilizers, manure, and biological N_2 fixation have equivalent effects on N_2O flux in most intensive cropping systems. Nitrogen is used inefficiently in most cropping systems: typically, only half of N inputs are captured in crop biomass and the remainder is lost from the system through leaching and or through gaseous losses of N_2, N_2O, NO_x, or NH_3. Because for crops in the United States there is a direct relation been soil N-availability and crop yield, the agronomic challenge is to decrease N inputs without decreasing yield.

Kroeze and Mosier (2000) estimated that improved crop N-use efficiency could decrease soil derived N_2O emissions from agriculture by as much as 35% globally, with even greater savings in the input-intensive systems of North America, Europe, and the former Soviet Union. Such savings could be achieved by the application of existing technology, largely by better matching crop N-needs with soil N-availability (Table 2). Any practice that tightens the coupling between soil N-release and crop growth will lead to enhanced nutrient-use efficiency and to diminished need for external N, thereby decreasing N_2O flux. And any practice capturing N within the system before its potential loss can help conserve available N for later use by the crop.

Table 2. Agricultural options for reducing N_2O fluxes. Based on Cole et al. (1996) and Kroeze and Mosier (2000).

Mitigation target	Practice	Comment
Soil emissions associated with N fertilization and soil N cycling	Soil N-tests	Can reduce overfertilization of crops. Only about one-half of US corn acreage in the mid-1990's was tested for soil N before planting.
	Fertilizer timing	Fertilizing in synchrony with active crop growth. On only 30% of corn acreage was N applied after planting and 30% of corn acreage received fall-applied N in 1995, leading to high risk for overwinter losses and N_2O emissions.
	Fertilizer placement	Fertilizer banding can increase N use efficiency, reducing volatilization by as much as 35% and increase yield by as much as 15%. On only 40% of U.S. corn acreage in the mid-1990s were nutrients banded.
	Nitrification and urease inhibitors	Nitrogen applied as ammonium or mineralized from soil must be nitrified to nitrate before it is available for denitrification. Inhibitors delay the transformation of ammonium to nitrate and urea to ammonium to help match the timing of N supply with crop demand. Nitrification inhibitors were used on less than 10% of U.S. corn acreage in 1995.
	Cover crops	Winter or fallow cover crops can prevent the build-up of residual soil N, catching N that otherwise would be emitted as N_2O or leached, improving N use efficiency. Yet cover crops were used on only 4% of major field crop acres in the United States in 1995.
Emissions from animal waste	Waste storage	Storing animal waste anaerobically can minimize N_2O losses.
	Waste disposal	Mitigating post-storage emissions by same practices as for N fertilization (see above), to increase N uptake by crops and reduce loses to competing sinks such as N_2O production and leaching.
Indirect soil emissions from N added to non-cropland areas	Maximizing crop N-use	Practices outlined above will minimize N loss for crop fields.
	Managing riparian zones	Planting filter strips and trees near riparian zones will help keep leached N from becoming N_2O at streamside or farther downstream.
	Managing ammonia	Ammonia gas (NH_3) volatilized from confined-animal facilities or from anhydrous ammonia fertilizers becomes rainwater NH_4^+. Animal waste can be handled to minimize NH_3 emissions by the storage of waste in lagoons or other anaerobic systems. Proper injection of anhydrous ammonia fertilizers can reduce losses.
	Treating wastewater	Much of the N in sewage wastewater derives from human food consumption. Removal of N before it is released as effluent will prevent it from becoming N_2O in downstream environments

Nitrous oxide emissions from animal wastes can be significant (Table 1). Confined animals excrete as dung and urine 80 to 95% of the N in their diet, and some proportion of this N is emitted as N_2O during collection, storage, and treatment. In general, N_2O emissions increase with the N content of waste, the extent to which waste is allowed to become aerobic (allowing the initiation of nitrification-denitrification reactions) and the length of storage (Mosier et al. 1998). For waste of a given N content, anaerobic lagoons will result in the least N_2O emissions whereas solid storage and dry-lot handling will promote emissions (Table 2).

Nitrogen lost from agricultural fields, for example through ammonia volatilization and nitrate leaching, can be transported offsite and become available again for emission as N_2O. Nitrogen in food crops is either consumed directly by humans or to produce meat or milk that is subsequently consumed. Most of this N then enters sewage treatment plants, where it is available for conversion to N_2O or to nitrate that enters riverine systems and subsequently may be denitrified. And N volatilized as NH_3 from fields, pastures, or animal facilities or emitted from soil as NO_x will reenter, as inadvertent nitrate and ammonium fertilizer, downwind. Both reducing the amount of off-site N loss and managing the non-cropland areas offer options for N_2O mitigation (Table 2).

All these mitigation strategies have other environmental benefits. First, increasing on-farm N-use efficiency will lessen groundwater nitrate loading and eutrophication of surface and coastal waters. Tighter farm N cycles will help decrease NH_3 and NO_x emissions to the atmosphere, subsequently decreasing deposition-N inputs to nonagricultural ecosystems. Making crop N-use more efficient also will decrease the need for synthetic N-fertilizer, which produces CO_2 in its manufacture, so substituting excess manure for synthetic N will provide measurable CO_2 mitigation. Some N_2O mitigation practices also will mitigate CO_2 more directly. Riparian forests that can mitigate against indirect N_2O fluxes will store C in growing vegetation for a number of decades, and both riparian forests and cropping systems with cover crops accumulate C in soil.

Mitigation of Methane Fluxes in North American Agriculture

The most important North American agricultural sources of CH_4 are ruminant livestock and livestock-waste management. Rice production and burning of agricultural crop residue are important globally but are minor sources in North America. Aerobic soils constitute an important sink for CH_4, through microbial oxidation of methane. However, intensive agriculture has been found to significantly reduce this sink compared to native forest and grassland ecosystems, which contributes indirectly to increasing methane concentrations in the atmosphere.

In the United States, CH_4 production from enteric fermentation in livestock totals approximately 5.7 Tg CH_4 (Table 3). Fermentation by microflora in the anaerobic environment of the rumen leads to CH_4 emissions ranging from 2 to 12% of gross feed-energy intake (Johnson et al. 1993).

Considerable CH_4 is emitted from the microbial, anaerobic decomposition of livestock waste. The relative amount of CH_4 produced is determined by the waste-management system. When manure (some combination of urine and feces) is stored or treated in systems promoting anaerobic conditions, e.g., as a liquid in lagoons, ponds, tanks, or pits, organic matter decomposition generates CH_4. When manure is handled as a solid or deposited on grazing lands, it tends to decompose aerobically and to produce little CH_4 (Safley et al. 1992).

Table 3. U.S. and global emissions of CH_4 from agricultural sources. (Tg = teragrams = 10^{12}g = millon tonnes). U.S. numbers are from EPA (2000) and global numbers are based on Cole et al. (1996). Uncertainties associated with methane fluxes are on the order of 20-40%.

Emission source	U.S.	Global
	Tg CH_4	
Livestock – Enteric fermentation	5.7	80
Livestock – Manure management	2.9	15
Rice Production	0.4	30
Agricultural residue burning	<0.05	5
Total	8	130

Methanotrophic microbes found in most aerobic soils actively oxidize atmospheric CH_4. Conversion from native grasslands and forests to managed pastures and cultivated crops generally decreases the normal aerobic soil CH_4 sink. Mosier et al. (1999) found that fertilization of native grassland decreased CH_4 uptake rates by about 35% and cultivation decreased consumption an additional 15%. In irrigated maize and wheat, N fertilization did not decrease CH_4 consumption further, but rates were 85 to 90% lower than in native grasslands. Recovery of CH_4 oxidation after plowing in shortgrass steppe grassland systems likely requires several decades (Mosier et al. 1997). Robertson et al. (2000) found CH_4 oxidation rates in corn-soybean-wheat cropping systems in Michigan to be 80% lower than in adjacent native forests. Rates were equally low in perennial crops (alfalfa and poplar trees) and recovered very slowly after abandonment from agriculture.

Successful development and implementation of mitigation strategies for agricultural sources of CH_4 require comprehensive understanding of the effects of land-use change and agricultural practice on fluxes of these gases and on mechanisms of control. To ensure that interactions and feedback are accounted for, proposed mitigation technologies should be evaluated within the context of farm-production systems.

Opportunities for decreasing CH_4 emissions from intensively managed cattle are somewhat limited because these operations currently are quite efficient. However, the U.S. Department of Energy (DOE 1999b) recently reviewed U.S. GHG emissions and suggested that, as a result of expected improvements in milk production/cow, CH_4 emissions/unit milk produced will decline, with a decrease of 30% envisioned for the dairy industry. The main options for decreasing CH_4 emissions from the beef industry are refinements to the marketing system and improvements in cow calf sector performance. Achievable decreases of CH_4 emissions from beef cattle in the United States are projected to be in the range of 20%. Specific practices to decrease CH_4 emissions from ruminants are outlined in Table 4.

Most CH_4 produced in anaerobic digestion constitutes a wasted energy source that can be recovered by adapting manure-management and treatment practices to collect CH_4. The by-products of anaerobic manure digestion can be utilized as animal feeds, aquaculture supplements, or crop fertilizers. Methods of decreasing CH_4 are outlined in Table 4.

Because certain practices decreasing CH_4 emissions may enhance N_2O emissions, their adoption must be considered in the context of a whole-system GWP analysis (Robertson et al. 2000). Specifically, spreading manure on crop fields will mitigate N_2O, but only if done in a manner optimizing rate and timing of application for maximum crop uptake. Substituting synthetic fertilizers for compost in flooded rice systems adds to the CO_2 cost associated with fertilizer manufacture. And whereas draining flooded rice-fields during the growing season may decrease CH_4 emissions, it also may decrease soil C storage and enhance N_2O emissions.

Many of the management practices capable of mitigating CH_4 emissions in agricultural systems also can improve crop and animal productivity. Using feed additives to inhibit rumen CH_4 production increases the amount of fixed C available for livestock weight gain. Using covered lagoons to capture CH_4 from livestock waste, and large-scale digesters to produce energy from the captured CH_4 will make farms less dependent on purchased energy and will decrease the CO_2 associated with energy production. Properly spreading digested manure on crop fields will provide limited nutrients to crops, thereby decreasing reliance on synthetic fertilizer sources and saving the economic and CO_2 expense of fertilizer. Managing water and nutrients differently in flooded rice may provide both water and fertilizer savings.

Table 4. Agricultural options for reducing CH_4 fluxes based on Cole et al. (1996).

Emissions from enteric fermentation	Feed ratios to decrease digestion time	Because most CH_4 is produced in the rumen by fermentation, the longer the feed remains in the rumen, the more C is converted to CH_4. Practices to speed the passage of feed through the rumen include use of more digestible feed, chopping feed to increase surface area, using concentrated supplements.
	Feed additives	Edible oils and ionophores as additives can inhibit rumen methanogens.
	Specialized rumen bacteria	Researchers developing genetically modified rumen bacteria producing less CH_4.
	Livestock production efficiency	Improving the efficiency of livestock production will decrease CH_4 emissions because fewer animals will be needed to produce the same amount of product.
Emissions from livestock waste	Using covered lagoons	Suitable for large-scale, intensive-farming operations.
	Using large-scale digesters	Technically advanced CH_4 digesters can be integrated with large livestock-operations. Estimates of profitable emissions reduction from dairy and swine operations are 25 and 19% of 1990 emissions, respectively.
	Alternate waste-storage practices	Solid rather than liquid manure handling (this practice may promote N_2O formation); applying manure to land as soon as possible; aerating manure during composting (this practice may promote N_2O formation).

Biofuels

Biofuels offer a means of decreasing dependence on fossil fuels for energy and chemicals. Biofuels can include dedicated energy crops, agricultural wastes and residues, and methane from agricultural wastes. The energy supplied by such systems can be used for power, fuel, or chemical feedstocks, which can supplant current fossil sources of these commodities and hence decrease the flow of associated GHGs to the atmosphere. With respect to agriculture, the major opportunities for increased use of biofuels lie in crops and residues grown and/or collected on U.S. farms. These include corn produced for conversion to fuel ethanol, cellulosic crops such as trees and grasses, and crop residues such as corn stover and bagasse. The contributions that biofuels can make to GHG mitigation depend on three factors: (1) whether they can be produced on American farms at prices competitive with traditional agricultural products, (2) whether the energy derived from these crops will be cost competitive with fossil-energy sources; and (3) whether the ecological and economic benefits of biofuels will be factored into the pricing/evaluation equation. Overlying these issues is the efficiency with which biofuels decrease GHGs, a function of energy expended in production, processing, and utilization of biofuel energy.

To illustrate the interplay of these factors in GHG mitigation, the factors influencing potential for a dedicated energy crop, switchgrass (*Panicum virgatum*), to achieve wide-scale adoption in biofuels production (McLaughlin et al. 2001) are examined.

Economic analysis of the conversion of different land uses including cropland, CRP, pasture, and other idle land suggest that significant gains in biofuel production potential occur within a price range between $30-40 per metric tonne (Walsh et al. 1999). The sensitivity of production levels to feedstock price forms an important framework for calculating soil C sequestration/unit land area, and fuel based displacement of atmospheric emissions of GHGs by switchgrass production.

Combining estimates of GHG decreases from fuel replacement with estimates of soil C sequestration (0.78 metric tonnes C per hectare per year) provides a combined estimate of GHG mitigation that might be effected by the most efficient dedicated energy crop system (switchgrass managed as a dedicated energy crop, with whole-plant conversion to energy). For an area of 16.9 Mha (available at a feedstock price of $44/metric tonne), the estimated mitigation potential is 35-125 MMTC per year, mainly from fossil fuel offsets but also including soil carbon sequestration. This number expresses the range of gains from total use of the feedstock to produce ethanol (low end of range) to the most efficient power cycle (15% cofire with coal) at the upper end. Other biofuel-production systems that use part of the plant (corn grain), harvest a portion of the residue (stover or rice straw), or do not include perennial harvest-management strategies will very likely result in decreased mitigation/unit land area.

Policy Options and Design for Agricultural emissions of Greenhouse Gases

Numerous papers on the economics of controlling GHG emissions have been published (e.g., Falk and Mendelsohn 1993, Nordhaus 1991), but few have focused specifically on the analysis of sequestration and GHG mitigation in agricultural soils (Feng et al. 2000, McCarl and Schneider 2000). Thus many questions remain regarding the design and implementation of policies to encourage soil C sequestration and soil GHG emissions reductions.

There are at least three scenarios under which programs to decrease GHG emission could be established. First, international agreements could allow terrestrial sinks, both forest and agricultural, to count toward a country's commitment to decrease GHGs. Such a scenario has the potential to create a major role for agricultural C sequestration, including income generation associated with altered farming and land-use practices. Second, even in the absence of credit for agricultural sinks in the international community, the United States could adopt policies encouraging soil C sequestration, for soil C is an indicator of long-term soil productivity and likely is correlated with many beneficial environmental attributes. Depending on how this policy is implemented, it may have significant income-generating potential for agricultural sources. And, third, voluntary arrangements whereby emitters buy offsetting credits from farmers or their representatives may arise if consumers are willing to pay extra for climate change-neutral products. Unless international or national policies generate official credit for C sinks, however, C sequestration probably will not be a major determinant of farming practice or income.

Alternative government policies depend critically on which, if any, of these scenarios comes to pass. For example, there is little role, beyond standard market oversight, for a government program if the third scenario is adopted. Likewise, if international credit for agricultural sinks is not approved, a GHG marketable credits program is less likely to be worth implementing inasmuch as trading from energy and other sectors is likely to play a key role in such a market. Nonetheless, many issues must be addressed before any government policy concerning GHG control from agricultural sources can be implemented effectively.

Acceptance of agricultural sinks by the international community will require that a program address four key concerns. First, because damages depend on total GHG-stock, the policy will need to account fully for all changes in C uses in a country, as well as all GHGs, e.g., N_2O and CH_4, i.e. full greenhouse land and gas accounting. Second, it will be necessary to measure all the components of net emissions and mitigation actions with an acceptable degree of accuracy and to characterize the associated uncertainty. Third, an understanding of how timing affects value and use of C sinks in agriculture is crucial, especially because agricultural sinks may not be permanent. And fourth, an effective GHG-mitigation strategy in agriculture must alter farmers' behaviors relevant to the adoption of improved conservation and land-use practices. Acceptance of agricultural sinks will required the design of policies that can convincingly induce such change.

Full Greenhouse gas accounting

Implementation of effective GHG-sequestration policies will require meaningful, full accounting for GHG emissions in two respects: across GHGs and across locations. In regard to full accounting across gases, agricultural actions may influence more than one GHG. For example, increasing biomass production through fertilizer use will increase C sequestration but also will increase N_2O. Likewise, adoption of conservation tillage increases soil C and decreases fuel use.

The second full accounting issue is whether all land use will be accounted for in meeting a country's obligations or whether only a subset of the land participating in a C sequestration program will be included. Clearly, in a national or a global accounting system in which the national government is responsible for meeting a target, all land whose net emission is nonzero should be included. Lack of total accounting, or a partial program, will raise accountability issues. For example, it will be difficult for a country to claim GHG credit from a program that credits farmers adopting conservation tillage but does not debit farmers converting grassland to cropland. Total land and GHG accounting may or may not be required for implementation of a domestic agricultural policy or a voluntary policy. If the policy performance measure is not aggregate decrease in GHGs, then partial accounting may be acceptable. For example, a voluntary program may be based on the amount of C sequestered by participants, without regard to nonparticipants.

Measurement of sequestration and emission rates

A second substantive issue in developing policy options concerns the ability to observe and to credit sequestered GHGs appropriately. Land based emissions of GHGs are considered nonpoint source pollutants because individual levels of emissions are difficult to observe. Policies for controlling and monitoring nonpoint source pollution with agricultural sources have received considerable attention (e.g., Griffin and Bromley 1982, Millock et al. 2000, Segerson 1988). In most applications of other non-point source pollution, such as agricultural runoff, aggregate pollution levels are observable but individual contributions are not. Control programs thus could be based on knowledge of aggregate pollution and observable individual actions. In theory, the observability of aggregate pollution allows policy makers to modify the level of individual actions until desired aggregate water quality is achieved (Segerson 1988). Alternatively, direct control, or taxation, of inputs into the production process can be brought to yield efficient pollution levels (Griffin and Bromley 1982, Holterman 1976, Shortle and Dunn 1986).

Permanence

Despite the potential of C sinks that have been identified and the fact that the Kyoto Protocol permits their use as credible methods of decreasing C[1], there is concern about how effective these sinks can be and whether they can contribute meaningfully to decreases in the build-up of GHGs. After all, terrestrial sinks eventually will saturate. Further, unlike permanent abatement measures, C sequestration practices can be reversed, releasing possibly all of the stored C. For example, trees can be cut; and farming practices such as no till or reduced till, required for soil sinks, also can be reversed. Given this possibly temporary nature and finite holding capacity, what is the value of temporary C storage? This issue will be discussed from two perspectives: pollution damage control and abatement cost savings. A related question that is addressed is how to consider the value of a ton of GHG sequestered today in relation to a ton sequestered in the future.

Certain groups entertain misconceptions about the value of C sinks. One view is that temporary storage has value mainly because the public discounts future pollution damage. This argument proceeds by noting that when the pollutant is stored now, current pollution damage decreases, but when the pollutant is released from storage, future pollution damage increases by the same amount; if the damage increase in the future equals the current decrease, storage has no value unless the future damage increase is discounted. The logic associated with the argument is not flawed inherently, for it would be quite accurate if the damages from GHGs came about primarily from the flow of GHGs, i.e., from the amount produced each year, not from the accumulated amount. Carbon, however, is essentially a stock pollutant, and so the damage it does depends on the total stock of effluent accumulated over time.

In the instance of a stock pollutant, quite a different story pertains, and it turns out that temporary storage has value even when the social discount rate is zero. The reason for this difference is that a sink decreases the accumulated stock for the period during which pollutants are stored, thereby decreasing damage. Thus, there clearly is a gain during the period in which the sink is in operation, with no associated damage beyond what would have been present in the absence of the sink when the period ends.

So far, we have discussed the value of C sinks in terms of the decreased damage from atmospheric GHG levels. Another perspective in assessing the value of sinks is that, at least in the short run, they may exhibit cost advantages over permanent decreases for certain levels of decreased GHG. If GHG levels are to be decreased by a large amount and if the cost of emissions decrease by industry such as the energy sector rises rapidly as the required decrease

[1]Currently, the Kyoto Protocol allows credit for C sequestration by forestry but also leaves the door open to other sinks such as agricultural soil.

increases, then shifting some of storage will decrease the total cost of decreasing GHGs.[2] According to this argument, low cost sinks such as some in forestry and/or agriculture may be valuable as permanent tools.

Additionally, from a more dynamic perspective, sinks may be useful temporary relief if technological progress decreases the future costs of emission decreases by industry. This argument is often referred to as "buying time." That is, temporary storage allows time for emitting industries to develop innovative methods of decreasing emissions at lower costs. The buying time argument is relevant only if new technologies will be invented and adopted by polluting industries. One concern is that use of C sinks will decrease industry incentives to develop and to adopt newer technologies, though the degree to which this effect may be a factor is difficult to assess.

The net value of agricultural sinks depends on their costs and their benefits. The damages avoided by decreasing GHG emissions by a ton is the same, regardless of the source, e.g., agricultural sink, energy conservation, decreased CH_4 emissions, though the potential number of tons from these sources may differ greatly. Cost per unit of decrease also may be quite different, and so it is desirable to choose the method resulting in the most damage avoided at the least cost.

Adoption

Farmers will participate in an agricultural soils-sink program only if sufficient incentives are provided. It is crucial, therefore, for policy makers to understand the economics behind individual farmer decision-making habits. A key element in the design of contracts for sequestration or any other activity is the concept of incentive compatibility. Farmers will respond to incentives contained in a contract. A contract is incentive compatible when this response is accounted for in contract design.

Generally, farmers respond to increased profit possibilities. In GHG transactions, profit consists of market revenue less cost plus net payment from a GHG contract. When a decision affects the future, farmers may evaluate profit streams discounted into the present. This strategy is of special relevance to soil-sequestration policy makers because it entails soil C stock management over time.

Alternative Policy Designs

Many alternative program designs for decreasing GHG emissions by means of agricultural sinks exist. There is much talk of "carbon trading" and of the buying and selling of C permits and various ways in which actual implementation of such trading schemes could be accomplished are recognized. As has been noted, appropriate design will depend on the scenario under which sinks are established. Specifically, significant government based ventures, such as the design of an official GHG-trading program, is less likely to come to pass unless there is an international accord allowing agricultural sinks to count toward treaty commitments to decrease GHG emissions. In contrast, an international accord allowing agricultural sinks to count toward a country's GHG reductions will require adoption and implementation of a national policy making sinks a meaningful strategy.

[2]In economist's jargon, if the marginal cost of decreasing emissions is higher than that of storing C, total cost will be lower if storage is used, until the two marginal costs are equal.

For an effective program to be implemented, many details concerning the mechanisms for implementing agricultural-sink GHG policy must be worked out. The important dimensions of program design are (1) the definition of the commodity to be regulated or targeted; (2) the organizational structure of the program; (3) the enumeration of payment rules, including timeframe and reversibility issues; and (4) the monitoring and verification of GHG reductions.

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