V. Agriculture

Section V presents international emission baselines and marginal abatement curves (MACs) for all significant agricultural non-CO_2 sources. There are subsections that address emissions and mitigation options for croplands, rice cultivation, and livestock. These sources are associated with methane (CH_4) and nitrous oxide (N_2O) emissions, as well as soil carbon. MAC data are focused on percentage reduction values from baseline emissions. These data can be downloaded in spreadsheet format from the USEPA's Web site at <http://www.epa.gov/nonco2/econ-inv/international.html>.

Section V—Agriculture is organized as follows:

V.1 Introduction and Background

Agricultural activities currently generate the largest share, 63 percent, of the world's anthropogenic non-carbon dioxide (non-CO_2) emissions (84 percent of nitrous oxide [N_2O] and 52 percent of methane [CH_4]), and make up roughly 15 percent of all anthropogenic greenhouse gas emissions (U.S. Environmental Protection Agency [USEPA], 2006; Prentice et al., 2001).[1] Agricultural greenhouse gas emissions are projected to increase significantly over the next 20 years, especially in Asia, Latin America, and Africa, because of increased demand for agricultural products as a result of population growth; rising per capita caloric intake; and changing diet preferences, such as an increased consumption of meat and dairy products over grains and vegetables (see Food and Agriculture Organization [FAO], 2002). Agricultural soil N_2O emissions are projected to increase 37 percent by 2020 compared with 2000 levels, enteric livestock CH_4 emissions are projected to increase 30 percent, manure CH_4 and N_2O to increase 24 percent,[2] and rice CH_4 to increase 22 percent (USEPA, 2006).

The agricultural sector presents unique challenges to developing greenhouse gas mitigation cost estimates at regional and international scales. First, there is a high degree of spatial and temporal heterogeneity in biophysical and management conditions and thus in resulting greenhouse gas emissions, which are rarely directly monitored. This fact makes it challenging to extrapolate the greenhouse gas and cost implications of farm-level mitigation analyses, the scale at which much of the literature on this subject is found. Any large-scale mitigation analysis should emphasize the broad trends and direction and magnitude of changes, which requires some trade-off in accuracy for very small spatial (e.g., individual farms) and temporal (e.g., days and seasons) scales. Second, there is a paucity of regional cost data from which one can estimate the implications of implementing greenhouse gas mitigation practices, in terms of changes in inputs, revenue, and labor. Third, estimating the expected level of adoption of the mitigation options in response to financial incentives (e.g., carbon price) or, alternatively, in response to extension services with greenhouse gas reduction objectives, is difficult given the information and cultural barriers to adoption in different regions.

Nevertheless, agricultural net greenhouse gas and non-CO_2 mitigation analyses have been developed for several countries and the world. Some analyses include a relatively comprehensive set of greenhouse gas mitigation options with a dynamic economic and biophysical representation of the agricultural and forest sectors (see USEPA [2005a] for the United States). Others target individual agricultural emissions sources with static, engineering mitigation estimation methods (see Kroeze and Mosier [1999] for global cropland N_2O and enteric CH_4 emissions and Reimer and Freund [1999] for global rice emissions; see also Table 3.27 in Moomaw et al. [2001] of IPCC Working Group III). The USEPA supported the development of global mitigation estimates for cropland N_2O, livestock enteric and manure CH_4, and rice CH_4 (DeAngelo et al., 2006) that were then incorporated into the Energy Modeling Forum-21 (EMF-21) study of global multigas mitigation options (van Vuuren et al. [2006]). This report improves on the agricultural analysis conducted for EMF-21 in a number of areas.

---

[1] This value compares the International Panel on Climate Change (IPCC) (Prentice et al., 2001) estimate of gross annual CO_2 emissions from fossil fuel combustion, cement manufacturing, and land-use change with the USEPA (2006) estimate of all anthropogenic non-CO_2 emissions. Fossil fuel CO_2 emissions associated with agriculture (e.g., on-farm equipment, fertilizer production) are not assigned to the agricultural sector in this estimate.

[2] The estimated increase of manure CH_4 and N_2O emissions represents a joint estimate based on CO_2 equivalent units using global warming potentials (GWPs) from the IPCC Second Assessment Report.

V.1.1 Brief Points of Comparison with Other Non-CO_2 Emissions Sectors

A few points about how baseline assumptions and methods for agriculture compare with those in other non-CO_2 sectors of this report are in order. First, baseline emissions projections used in this section are not entirely consistent with baseline projections developed by the USEPA (2006). This is the case for cropland N_2O and rice CH_4 emissions, where separate baseline emissions projections are developed with process-based models. These models, described later in this section, are also used for the mitigation scenarios, so that assumptions and all underlying activity data on both the baseline and mitigation sides of the equation are consistent.

Second, although the focus of this report is on the non-CO_2 greenhouse gases, soil carbon is included in the agricultural analysis. Including soil carbon is important for agriculture because it provides a more comprehensive picture of the net greenhouse gas effects of mitigation options that primarily target N_2O and CH_4.

Third, the agricultural analysis, like other sectors in this report, presents marginal abatement curves (MACs) by region, for the 2000 to 2020 period, showing the technical, net greenhouse gas mitigation potential at various levels of U.S. dollars (USD) per tonne of CO_2 equivalent ($/t$CO_2$eq), representing the breakeven price of each mitigation option. The approach used to estimate the technical mitigation potential is similar to that used in other sectors—a bottom-up, engineering approach. However, the agricultural analysis illustrates the sensitivity of the mitigation estimates to potential economic market feedbacks as a result of adopting the mitigation options (i.e., showing the effects of simultaneous changes in crop yields, livestock productivity, commodity prices, cropland area, livestock herd size, and emissions).

V.1.2 Previous Estimates for EMF-21 and New Improvements

Previously, the USEPA helped produce a non-CO_2 mitigation analysis for world agriculture (DeAngelo et al., 2006) to assist climate-economic and integrated assessment modelers who participated in the EMF-21 study represent the agricultural sector. The study generated MACs by major world regions for cropland N_2O, livestock enteric CH_4, manure CH_4, and rice CH_4 for 2010. This analysis used a static, engineering approach by relying on literature sources to identify the non-CO_2 reductions associated with each mitigation option, extrapolating those results beyond their original scale of analysis (farm, region, or nation) to other world regions, estimating regionally specific changes in input costs with FAOSTAT and other data sources, and adjusting the extent to which each mitigation option applied to different regions. Summary results of this previous analysis and how they compare with the current analysis are presented in Appendix P.

The current analysis uses new approaches to improve on the previous EMF-21 study in a number of areas. First, biophysical, process-based models (DAYCENT and DNDC) are used to better capture the net greenhouse gas and yield effects of the cropland and rice emissions baseline and mitigation scenarios. The previous analysis estimated the single, dominant gas effects only (e.g., no N_2O or soil carbon effects for rice CH_4 mitigation practices). Furthermore, process-based models better reflect the heterogeneous emissions and yield effects over space and time of adopting mitigation practices, whereas the previous analysis usually assumed a uniform percentage change in emissions and/or yields across regions. The process-based models also ensure greater consistency in underlying assumptions and activity data between baseline and mitigation scenarios. For example, when emissions projections are estimated with IPCC Tier I default methodologies, it is not always possible to identify what underlying management practices are taking place, which in turn makes it difficult to ascertain if the chosen mitigation options are indeed additional to baseline management practices.

New mitigation options are assessed (e.g., slow-release fertilizers, nitrogen inhibitors, and no till), and more detailed, less aggregated results are provided for individual crop types (e.g., maize, wheat, and soybeans) under both irrigated and rain-fed conditions. Lastly, sensitivity experiments using a global agricultural trade model (IMPACT of the International Food Policy Research Institute [IFPRI]) are conducted to assess the agricultural commodity market effects of adopting the mitigation options.

V.2 Emissions Characterization, Baselines, and Mitigation Scenarios

V.2.1 Croplands (N_2O and Soil Carbon)

V.2.1.1 Cropland N_2O and Soil Carbon Emissions Characterization

N_2O is typically the dominant greenhouse gas source from agricultural systems and is produced naturally in soils through the processes of nitrification and denitrification. These are soil microbial processes whereby ammonium (NH_3) is reduced to nitrate (NO_3) under aerobic or oxygen-rich conditions (nitrification), and nitrate is reduced to molecular nitrogen (N_2) under anaerobic or oxygen-poor conditions (denitrification). A number of activities add nitrogen to soils, thereby increasing the amount available for nitrification and denitrification, and ultimately the amount of N_2O emitted to the atmosphere. Activities may add nitrogen to soils either directly or indirectly. Direct additions occur through nitrogen fertilizer use, application of managed livestock manure and sewage sludge, production of nitrogen-fixing crops and forages, retention of crop residues, and cultivation of histosols (i.e., soils with high organic-matter content, also known as organic soils). Indirect emissions occur through volatilization and subsequent atmospheric deposition of applied nitrogen, as well as through surface runoff and leaching of applied nitrogen into groundwater and surface water.

Other soil management activities, such as irrigation, drainage, tillage practices, and fallowing of land, can also affect fluxes of N_2O, as well as soil carbon and fossil fuel CO_2 emissions. Fossil fuel CO_2 emissions can be generated on-farm by agricultural equipment and off-farm or upstream through the energy-intensive production of fertilizers.[3] These fossil fuel CO_2 emissions are not included in this study; thus some net emissions reduction benefits of the mitigation options are likely to be underestimated in this report.[4]

Agricultural soil carbon emissions and/or sequestration tend to be less dominant than N_2O emissions in terms of the net greenhouse gas picture under baseline conditions; however, enhancing soil carbon sequestration represents a significant greenhouse gas mitigation option, potentially more viable than N_2O reductions (see USEPA [2005a]). Croplands often emit CO_2 as a result of conventional tillage practices and other soil disturbances. This occurs when soils containing organic matter that would otherwise be protected by vegetative cover are exposed to the air through tillage disturbances and become susceptible to decomposition. Conservation tillage—defined in the United States as any tillage system that maintains at least 30 percent of ground covered by crop residue after planting (Conservation Technology Information Center [CTIC], 1994)—eliminates one or several practices associated with conventional tillage, such as turning soils over with a moldboard plow and mixing soils with a disc plow (Lal et al.,

[3] Under IPCC greenhouse gas inventory reporting guidelines and in the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* reported by the USEPA, these fossil fuel CO_2 emissions are reported as energy-sector not agricultural-sector emissions.

[4] In the USEPA (2005a), the FASOM-GHG model of U.S. forestry and agriculture shows that on-farm and upstream fossil fuel CO_2 emissions associated with crop production are roughly 40 percent of the size of the joint CH_4 and N_2O emissions in agriculture, on a CO_2-equivalent basis. The DAYCENT modelers for this report assumed that for every unit of nitrogen fertilizer applied, 0.8 units of CO_2 were generated from fertilizer manufacturing, though these numbers were intentionally excluded from this report to maintain consistency across emissions categories.

1998). Conservation tillage, including no-till, allows crop residues to remain on the soil surface as protection against erosion.

Lastly, seasonal temperature and precipitation changes, as well as regional climate variability, influence rates of both soil N_2O and carbon emissions.

V.2.1.2 DAYCENT Baseline Estimates of Cropland N_2O, Soil Carbon, and Yields

The DAYCENT model is used to estimate baseline and mitigation scenario emissions of N_2O and soil carbon for a significant share of the world's nonrice croplands. (DAYCENT, rather than IPCC default values, is also the tool now used to estimate the majority of agricultural soil N_2O emissions for the annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, reported by the USEPA). Use of DAYCENT offers the advantage of a consistent methodology and tool across regions and between the baseline and mitigation scenarios. The DAYCENT model and emissions baseline methodologies are described briefly here, and further details are provided in Appendix Q.

The DAYCENT model (Del Grosso et al., 2001; Parton et al., 1998) is a process-based model that simulates crop growth, soil organic-matter decomposition, greenhouse gas fluxes, nitrogen deposited by grazing animals, and other biogeochemical processes using daily climate data, land management information, and soil physical properties. N_2O emissions estimated by DAYCENT account for nitrogen additions, crop type, irrigation, and other factors and capture both direct (through fertilizer applications) and indirect (through volatilization and leaching) N_2O emissions.

Global baseline N_2O emissions for this report are estimated from DAYCENT to be 799 $MtCO_2eq$ in 2000, 795 $MtCO_2eq$ in 2010, and 859 $MtCO_2eq$ in 2020. With the net effects of soil carbon, global net greenhouse gas estimates are 839 $MtCO_2eq$, 830 $MtCO_2eq$, and 893 $MtCO_2eq$ for 2000, 2010, and 2020, respectively. These estimates represent the mean of decadal averages (e.g., 1996 to 2005 mean for reported year 2000). Emissions estimates for individual key countries and regions are provided in Table 1-1 (see Section V.1.3.2 for additional baseline data).

Table 1-1: DAYCENT N_2O and Soil Carbon Estimates for 2000, 2010, and 2020 by Key Region ($MtCO_2eq/yr$)

	2000		2010		2020	
Region	N_2O	Soil Carbon	N_2O	Soil Carbon	N_2O	Soil Carbon
United States	164	3	176	2	197	3
EU-15	95	–4	98	–5	107	–6
Eastern Europe	37	2	37	2	39	2
FSU	187	26	127	30	126	36
Mexico	14	1	16	1	17	>0
Brazil	28	0	30	0	30	0
India	69	–3	74	–4	78	–5
China	84	7	95	3	105	–1

EU-15 = European Union; FSU = Former Soviet Union.
Note: Negative numbers indicate net sequestration.

As described below, the cropland coverage for the DAYCENT simulations is incomplete. Therefore, the baseline estimates from DAYCENT are intended to serve as the foundation from which to assess the general implications of mitigation scenarios. The DAYCENT baseline estimates are not intended to serve as independent national and global inventory estimates, which can be found elsewhere in the literature (USEPA 2006; USEPA 2005b; Robertson 2004; IPCC 2001; Ehhalt et al., 2001; Mosier et al., 1998).

Appendix S describes how the DAYCENT N_2O emissions baseline estimates compare with the USEPA's (2006) more comprehensive estimates.

DAYCENT explicitly simulates the major crop types only: maize, spring and winter wheat, and soybeans. However, analogous crops are added to these major crop types (e.g., rye, barely, and oats with wheat; millet and sorghum with maize) to increase the coverage of cropland area and to capture a higher portion of nitrogenous fertilizer applications. Grazing-land emissions are not included, and emissions due to residue burning are not included. For these reasons, the DAYCENT baseline N_2O estimates are generally lower than other published inventory studies for national and world total N_2O emissions.

DAYCENT simulations for maize, wheat, and soybean areas are run under both irrigated and rain-fed conditions.[5] The relative portion of maize, wheat, and soybean areas under irrigated and rain-fed conditions are provided by IFPRI and vary by region and over time.

Underlying data for the emissions estimates include global data sets of weather, soils, cropland area, and native vegetation, mapped to an approximate 2° × 2° resolution. Daily weather data (i.e., precipitation and maximum and minimum temperatures) from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction for the 1991 to 2000 period are used under both baseline and mitigation options; therefore, there is no explicit assumption about anthropogenic climate change for the 2000 to 2020 period. Soils data include texture percentages of clay, sand, and silt and come from FAO/UNESCO (1996). Histosols, a source of N_2O, are not included in the simulations. Cropland distribution and the fractional area of specific crops are taken from both the International Geosphere Biosphere Programme (IGBP) land cover classification (Belward et al., 1999; Belward, 1996) and the Global Land Cover (GLC) data set of Leff et al. (2004).

Cropland area is assumed to remain constant over time in the DAYCENT simulations under both baseline and mitigation options (the same assumption is held for rice areas with the DNDC simulations). The subject of changing area in response to market feedbacks due to the implementation of mitigation options is discussed in Section V.1.3.6.

Box 1-1: DAYCENT Estimates of U.S. Agricultural N_2O Emissions in This Report versus Inventory

The annual *Inventory of Greenhouse Gas Emissions and Sinks*, reported by the USEPA, now uses the DAYCENT model to estimate the majority of agricultural soil N_2O emissions. Though DAYCENT is used in this report and provides estimates for U.S. agricultural soil N_2O emissions under baseline and mitigation scenarios, the U.S. estimates in this report are not the same as the U.S. estimates in the Inventory. This is because the Inventory uses input data specific to the United States, while the input data used by DAYCENT in this report come from global data sets to provide as much consistency as possible across regions, including the United States.

In addition to simulating N_2O emissions from mineral cropland soils, a DAYCENT simulation was performed for those same areas as though they were covered by native vegetation and never cultivated (using *potential* vegetation from Cramer et al. [1999] and Melillo et al. [1993]), so that anthropogenic emissions are isolated from natural background emissions. Therefore, all reported emissions estimates

[5] Rain-fed conditions mean that the crop receives no extra water in addition to rainfall and the resultant water stored in the soil. To simulate irrigation, extra water is added, if necessary, to bring soil water content to field capacity once per week for 20 weeks during the growing season. This minimizes or eliminates plant water stress and is an assumption consistent with the fact that farmers typically irrigate only when necessary because irrigation requires resources.

under both baseline and mitigation scenarios from croplands represent anthropogenic emissions separated from natural background emissions.[6]

Synthetic nitrogenous fertilization rates are based on globally uniform relationships with current and projected production of the major crop types by region. Current and historic nitrogenous fertilization data for each region are from FAOSTAT (2004b) and the International Fertilizer Industry Association (IFA) (2002). Current nitrogenous fertilization rates (kg/hectare) were assumed to be the same as 1998 levels, and projected rates were scaled from this base. Projected fertilization rates for wheat and maize were taken from regression equations based on crop production from FAO (2000); for soybeans, an analogous regression equation was developed using a combination of FAOSTAT (2004b) and IFA (2002) (see Appendix Q). Regionally specific projections of crop yields from IFPRI for 2010 and 2020 are used with these equations to derive future fertilization rates. Crop area is assumed to remain constant for the DAYCENT simulations. Increases in N_2O out to 2020 for most regions (see Table 1-1) are therefore the result of increasing rates of fertilization based on yield projections. All baseline fertilizer applications for all regions are assumed to be administered in one application.

Organic-matter fertilizer additions are assumed to be a function of animal numbers by region. Historical trends in organic fertilizer use were calculated from animal numbers reported by FAOSTAT (2004a), using IPCC default factors concerning region-specific average nitrogen excretion per animal, and the percentage of nitrogen distributed among waste management practices (see Appendix Q for IPCC default factors). Projections of manure nitrogen are taken from underlying activity data used for USEPA (2006).

Nonspatial data (such as planting date and fertilizer application rates) were assigned as point values for each region or country and were assumed to be the same within each region. Global maps of 2° × 2° resolution for baseline N_2O emissions estimated by DAYCENT for areas of wheat, maize, and soybeans are presented in Appendix Q (under rain-fed conditions only).

V.2.1.3 Mitigation Options for Cropland N_2O and Soil Carbon Emissions

Mitigation options for croplands have been identified that could decrease N_2O emissions, often the result of applying fertilizer that exceeds crop demand, while maintaining yields (e.g., Mosier et al., 2002). Mitigation options are chosen with this goal in mind. Options are listed in Table 1-2. The soil N_2O mitigation options involve either more efficient (or simply reduced) application of nitrogen-based fertilizers (e.g., adding nitrification inhibitors; using split fertilization; reducing baseline nitrogen fertilization by 10, 20, or 30 percent) or adoption of no-till cultivation methods. Because the focus of this report is on the non-CO_2 greenhouse gas emissions, additional options that might increase soil carbon (e.g., reduced fallow periods, different cropping mix) are not considered.

These mitigation options are simulated by DAYCENT and resulting crop yields (of wheat, maize, and soybeans), and emissions effects are compared with the DAYCENT baseline, as described above. Though all mitigation options are represented in the final MACs, DAYCENT simulates only one mitigation option at a time, assuming that each mitigation option is implemented on all croplands in 2000 and continuously until 2020. No mitigation options are implemented simultaneously on the same croplands, or on different portions of the croplands, within DAYCENT.

[6] This approach of isolating anthropogenic emissions from natural background emissions is also used when the DAYCENT model is applied to estimate anthropogenic N_2O emissions from agricultural soils for the *Inventory of U.S. Greenhouse Gas Emissions and Sinks,* reported by the USEPA.

Table 1-2: Cropland N_2O and Soil Carbon Mitigation Options Run Through DAYCENT

Mitigation Option	Description	Greenhouse Gas Effects
Split fertilization	Application of same amount of nitrogen fertilizer as in baseline but divided into three smaller increments during crop uptake period to better match nitrogen application with crop demand and reduce nitrogen availability for leaching, nitrification, denitrification, and volatilization.	N_2O, some soil carbon
Simple fertilization reduction—10 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 10 percent.	N_2O, some soil carbon
Simple fertilization reduction—20 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 20 percent.	N_2O, some soil carbon
Simple fertilization reduction—30 percent	Reduction of nitrogen-based fertilizer from one-time baseline application of 30 percent.	N_2O, some soil carbon
Nitrification inhibitor	Reduces conversion of ammonium to NO_3, which slows the immediate availability of nitrate (nitrate is water soluble). The inhibition of nitrification reduces nitrogen loss and increases overall plant uptake.	N_2O, some soil carbon
No-till	Conversion from conventional tillage to no till, where soils are disturbed less and more crop residue is retained.	Soil carbon, some N_2O

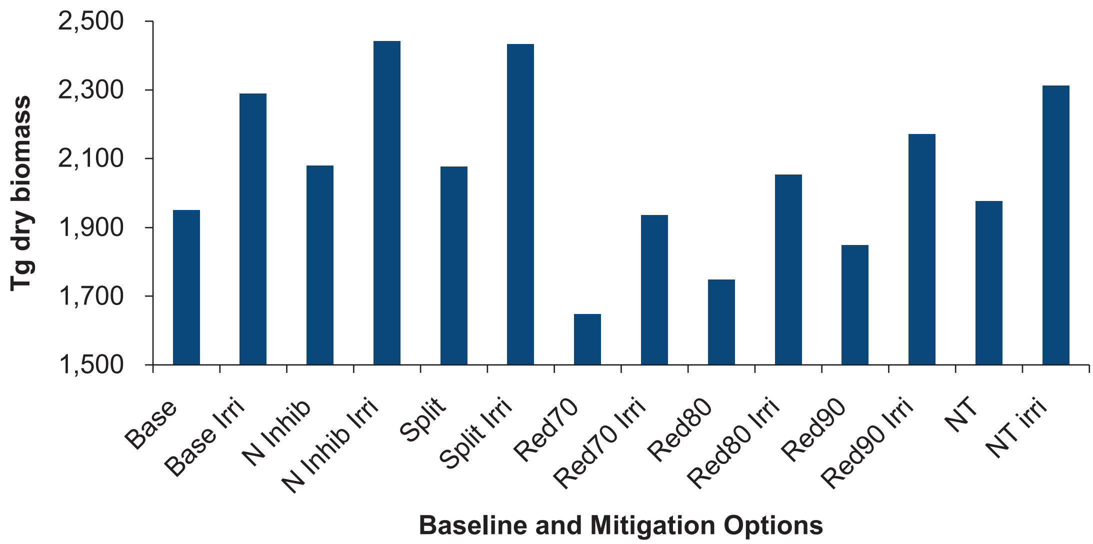
As in the baseline scenario, each DAYCENT mitigation simulation is run according to the relative portions of maize, wheat, and soybean areas under either irrigated or rain-fed management.

A number of mitigation options are found to increase net greenhouse gas emissions relative to the baseline depending on crop, management, region, and time period. These options are removed to estimate and construct the abatement curves. The number of options that increase net emissions grows from the 2000 to the 2010 to the 2020 period. All of these options occur on either wheat or maize croplands, are spread over most regions of the world, and predominantly involve reducing baseline nitrogen fertilizers. The primary reason why decreasing nitrogen fertilizer use leads to an increase in net GHG in some regions is a decrease in soil carbon—due to lower plant growth from the fertilizer reductions and hence less residue returning to the soil—which more than compensates for the lower N_2O emissions. A small number of Asian regions experience an increase in emissions for the split-fertilization option, which can occur if more frequent (but smaller) fertilizer applications coincide with rainy periods; however, the timing of the applications for this option was assumed to be uniform across regions. In practice, farmers would time fertilizer applications based on their local weather conditions and on plant growth stages. In addition, some of the no-till scenarios in Western Europe increase net emissions; this is primarily because no till allows for greater soil water content and enhances denitrification to produce N_2O emissions.

V.2.1.4 DAYCENT Results for Changes in Cropland N_2O, Soil Carbon, and Yields

Figure 1-1 summarizes total global production of the major crops of wheat, maize, and soybeans under baseline and mitigation scenarios, holding area constant. DAYCENT simulations were performed for both irrigated and nonirrigated conditions. In every case, production is higher with irrigation, as expected. All three of the options that were effective in reducing emissions (i.e., nitrification inhibitors, split-fertilization, and conversion to no till) simultaneously increased production. The three options that involved reduced fertilization, on the other hand, resulted in substantial reductions in production.

Figure 1-1: Global Cropland Yields for Baseline and Mitigation Options Estimated by DAYCENT, 2010[a]



Note: This figure shows total global production of wheat, maize, and soybeans—the three major crops modeled using DAYCENT—simulated under the baseline and mitigation options.

[a] Ninhib—addition of nitrification inhibitor (irrigated and nonirrigated).

Split—split fertilization, dividing fertilizer applications into three smaller increments.

Red70—reduction of nitrogen-based fertilizer to 70 percent of baseline.

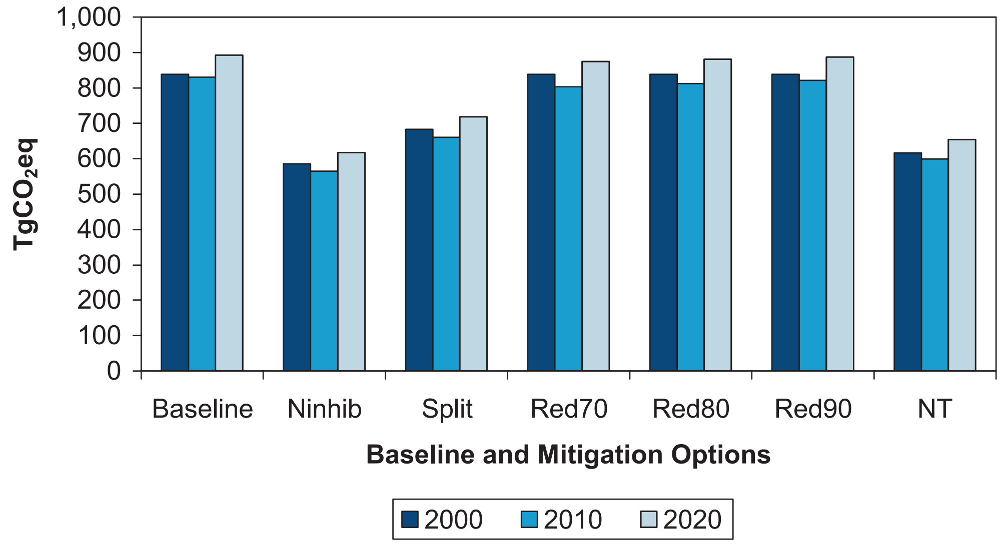
Red80—reduction of nitrogen-based fertilizer to 80 percent of baseline.

Red90—reduction of nitrogen-based fertilizer to 90 percent of baseline.

Reduced nitrogen fertilizer leads to reduced yields because plant growth rates, and hence crop yields, are highly sensitive to nutrient supply in DAYCENT. That is, DAYCENT assumes that plant growth is limited by nutrient availability, as well as by water and temperature. Nitrification inhibitors and split fertilizer caused the largest increase in yields because both of these options maintain higher nitrogen availability for plants. Nitrification inhibitors keep more nitrogen in the root zone for two reasons: less nitrogen is lost from the soil as nitrogen gas and, because the conversion of ammonium (NH_4) to NO_3 is inhibited, less NO_3 is leached below the root zone. Split-nitrogen application increases plant-available nitrogen, because nitrogen supply is more synchronized with plant-nitrogen demand. Higher plant-nitrogen uptake also reduces nitrogen losses from nitrification, denitrification, and leaching, although to a lesser extent than the nitrification inhibitor, for the reasons discussed above.

As shown in Figure 1-2, DAYCENT simulations for corn, soy, and wheat suggest that using nitrification inhibitors and no-till cultivation lead to the largest reduction in net greenhouse gas emissions at the global scale. Surprisingly, reduced nitrogen fertilizer leads to net emissions similar to the baseline scenario. The decrease in crop production associated with reduced fertilizer applications leads to reduced

Figure 1-2: Global Net Greenhouse Gas (N_2O and Soil Carbon) Cropland Emissions Estimated by DAYCENT under Baseline and Mitigation Scenarios[a]



[a] Ninhib—addition of nitrification inhibitor.
Split—split fertilization, dividing fertilizer applications into three smaller increments.
Red70—reduction of nitrogen-based fertilizer to 70 percent of baseline.
Red80—reduction of nitrogen-based fertilizer to 80 percent of baseline.
Red90—reduction of nitrogen-based fertilizer to 90 percent of baseline.
NT—conversion from conventional tillage to no-till.

soil inputs and, hence, reduced soil carbon. Observations show that soil carbon levels are sensitive to changes in crop residue inputs (e.g., Peterson et al. [1998]); however, the degree to which a particular soil responds to changes in crop residue inputs depends on many factors, such as the history of land-use management. The soil carbon reduction offsets the reduced N_2O emissions to varying degrees. The net emissions for the three different fertilizer reduction amounts (10, 20, and 30 percent) are similar. This suggests that, at the global scale, the amount of soil carbon lost and the amount of N_2O reduced respond roughly linearly and equally to fertilizer inputs.

An additional consideration regarding potential trade-offs between N_2O emissions and soil carbon is that N_2O reductions are long lasting, whereas soil carbon accumulation is reversible through future changes in management. The reversibility of soil carbon accumulation is not accounted for in this analysis, because all changes in management are assumed to occur immediately and continuously through to 2020.

The nitrification inhibitor leads to the largest reduction in net emissions because it directly decreases emissions from nitrification. Split fertilization also leads to significant net reductions, but it is possible that the DAYCENT simulation is underestimating the mitigation potential of this option. This is because the three separate fertilizer applications are occurring on the same day, regardless of the timing and amount of rainfall represented in the model. If heavy rains happen to fall a couple of weeks after the second fertilizer application, N_2O may be higher than if all of the fertilizer were applied when the crop was planted.

No-till cultivation leads to a large reduction in net emissions primarily because of increased carbon storage in soil and surface residue, although this option also decreases N_2O by a small amount at the global scale. However, DAYCENT does project higher N_2O emissions under no till for certain locations, which is consistent with data showing higher N_2O emissions under no till, particularly in humid environments (Smith and Conen, 2004). Because the majority of the reduced greenhouse gas emissions from the no-till option are from carbon storage, it should be noted that this benefit is transitory, because the capacity of soils to store carbon is finite and most soils are likely to reach equilibrium within approximately 50 years of land management change. Also, if cultivation intensity is increased in the future, then much of the carbon that was stored is likely to be respired and returned to the atmosphere. However, the reduced N_2O emissions associated with applying nitrification inhibitors and split fertilizer are irreversible and likely to persist indefinitely.

To estimate the breakeven $/t$CO_2$eq of these mitigation options, DAYCENT results for the change (from baseline) in net emissions, yields, and fertilizer applications are used in combination with crop and fertilizer price information, as well as assumptions about other input costs and labor changes. The change in crop revenue is estimated with DAYCENT changes in yields and IFPRI's current and projected region-specific baseline prices for wheat, maize, and soybeans. Likewise, IFPRI price information for change in fertilizer costs is used. Appendix T provides details on IFPRI's commodity prices.

No capital costs are assumed for any cropland mitigation options.[7] The nitrification inhibitor option is assumed to incur an additional input cost of $20 per hectare (Scharf et al., 2005), which is scaled from the United States to other regions. Only two of the options are assumed to incur labor changes. Split fertilization is assumed to require an increase in labor and no till a decrease in labor.[8] These percentage changes in labor are assumed to be uniform across regions; however, data from the Global Trade Analysis Project (GTAP, 2005) database are used to calculate the share of output attributable to labor costs by crop for each region. This share is used to calculate baseline labor costs per hectare from the estimated value of output per hectare by crop and by region. Labor rates are taken from IFPRI's IMPACT model to calculate the implied number of labor hours per hectare consistent with the labor cost per hectare, as a validity check on the labor costs being estimated. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.2 Rice (CH_4, N_2O, and Soil Carbon)

V.2.2.1 Rice CH_4, N_2O, and Carbon Emissions Characterization

Most rice in Asia and the rest of the world is grown in flooded paddy fields (less than 10 percent of the rice in Asia is grown in upland conditions). When fields are flooded, decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions

[7] No-till options would require purchasing no-till equipment for direct planting. However, if this equipment is purchased in place of equipment used for traditional tillage, there may be little incremental capital costs associated with no till. Some crop budgets actually indicate lower capital costs for no till because of the need for fewer passes over the field, which leads to reduced equipment depreciation. Thus, no incremental capital costs for the no-till option are assumed.

[8] Split fertilization is assumed to require 14 percent more labor, assuming one additional pass over the fields, where, for this purpose, seven passes per year are assumed in the baseline (i.e., for tilling, planting, fertilizing, applying herbicide, applying pesticide, and harvesting, some of which may not be done on all fields but may require more than one pass on some farms). The biophysical modeling in DAYCENT assumes a one-time fertilizer application in the baseline and two applications with split fertilization. No till is assumed to decrease labor requirements based on a U.S. Department of Agriculture (USDA) Agricultural Resource Management Survey (ARMS) survey, which provides labor estimates for conventional and conservation tillage on both irrigated and rain-fed land by major crop.

in the soil to develop. Anaerobic decomposition of soil organic matter by methanogenic bacteria generates CH_4. Varying amounts up to 90 percent of the CH_4 is oxidized by aerobic methanotrophic bacteria in the soil (Krüger et al., 2002; Holzapfel-Pschorn et al., 1985; Sass et al., 1990). Some of the CH_4 is also leached away as dissolved CH_4 in floodwater that percolates from the field. The remaining unoxidized CH_4 is transported from the soil to the atmosphere, primarily through the rice plants themselves. Minor amounts of CH_4 also escape from the soil via diffusion and bubbling through floodwaters.

The water management system under which rice is grown is therefore one of the most important factors affecting CH_4 emissions. The amount of available carbon susceptible to decomposition is also critical. Some flooded fields are drained periodically during the growing season, either intentionally or accidentally. If water is drained and soils are allowed to dry sufficiently, CH_4 emissions decrease or stop entirely. This is due to soil aeration, which not only causes existing soil CH_4 to oxidize but also inhibits further CH_4 production in soils.

Field measurements in China indicate, however, that midseason drainage, while significantly reducing CH_4, actually increases N_2O emissions (Zheng et al., 1997, 2000; Cai et al., 1999). One of the key processes controlling CH_4 and N_2O production/consumption in paddy soils is the reduction potential (Eh) dynamics. Methane and N_2O are produced during different stages of soil redox potential fluctuations.

In addition to water management, other practices (e.g., tillage, fertilization, manure amendments) will alter the soil environmental conditions (e.g., temperature, moisture, pH) and hence affect the soil carbon- and nitrogen-driving processes such as decomposition, nitrification, and denitrification. The changes in the soil biogeochemical processes will finally affect the availability of soil nitrogen and water to the crops and hence alter the crop yields. Because crop residue is the major source of soil organic carbon, the change in crop yield and litter will redefine the soil organic-matter balance, which is one of the most important factors determining the CH_4, soil CO_2, and N_2O emissions (Li et al., 2006).

Soil temperature is also known to be an important factor regulating the activity of methanogenic bacteria and, therefore, the rate of CH_4 production.

V.2.2.2 DNDC Baseline Estimates of Rice CH_4, N_2O, Soil Carbon, and Yields

The DNDC model, in particular the paddy-rice version of the model (DNDC 8.6; Li et al., 2004; Li et al., 2002; Cai et al., 2003; Zhang et al., 2002), was used to estimate baseline and mitigation scenario emissions of CH_4, N_2O, and soil carbon, as well as yield and water resource changes, for Asian rice systems. Greenhouse gas emissions from non-Asian rice systems, which represent about 10 percent of the world's total rice area (Wassmann et al., 2000), are excluded, primarily because data for these areas were not available at the time of the DNDC modeling. The DNDC model and emissions baseline methodologies are briefly described here, and further details are provided in Appendix R. Appendix S summarizes differences between the baseline rice GHG emissions used in this analysis and USEPA (2006).

DNDC is a soil biogeochemical model that simulates both aerobic and anaerobic soil conditions and estimates crop yields based on a detailed crop physiology-phenology model. It is designed for assessing the impact of different management strategies on short-term and long-term soil organic carbon dynamics and emissions of CH_4, N_2O, nitric oxide (NO), and NH_3 from both upland and wetland agricultural ecosystems. DNDC requires data on soils (e.g., pH, soil carbon, bulk density, and soil texture), rice cropping areas and systems (e.g., single rice, double rice, rice rotated with upland crops), climate, and management practices (e.g., fertilizer use, planting and harvesting dates, tillage, water use). DNDC runs on a daily time step and can therefore capture temporal, as well as spatial, heterogeneity in emissions processes.

DNDC has been tested against several CH_4 and N_2O flux data sets for wetland rice systems in different regions of the world, and overall results indicate that DNDC is capable of estimating the seasonal patterns and magnitudes of CH_4 and N_2O fluxes. In some cases (less than 20 percent of the sites tested), there were discrepancies between modeled and observed patterns of CH_4 and N_2O fluxes. In these cases, minor modifications to capture unique local management conditions, rice varieties, and anaerobic processes resulted in good estimates of greenhouse gas emissions from all rice systems tested (Li et al., 2006; Cai et al., 2003; Zhang et al., 2002; see also Appendix R).

DNDC simulates rice growth and yield by tracking heat (i.e., daily temperature) accumulation, water availability, and nitrogen availability. If there is any stress in heat, water, or nitrogen detected by DNDC, the yield will be reduced accordingly. The impacts of farming practices on yield are modeled based on the effects of the practices on water and nitrogen (it is assumed the practices have little effect on heat flux).

China is the core focus of the rice component of this study because China contains roughly 20 percent of the world's rice paddies and generates 31 percent of the world's rice production (FAOSTAT, 2004a); furthermore, previous DNDC modeling efforts had already collected a detailed database for Chinese rice systems at the county scale. This Chinese rice component of the analysis is described in Li et al. (2006) and briefly summarized here.

Table 1-3 contains DNDC estimates of rice emissions for China, individual water basin regions within China, and other Asian countries (see Section V.1.3.3 for additional baseline summary information). Methane emissions tend to increase over time because of soil carbon accumulation. N_2O emissions tend to decline, also because of the soil carbon accumulation, coupled with an assumed constant rate of fertilization (which increases total denitrification).

Data on rice cropping systems, soils, climate, water management, residue management, fertilizer, and optimum yield profiles are incorporated into DNDC for each of the approximately 2,500 Chinese counties. County data are aggregated to water basin regions within China. Maximum and minimum values of soil texture, pH, bulk density, and soil organic carbon content are derived for each county. These factors are used to determine the most sensitive factors to estimate uncertainty in emissions estimates within each county. Based on sensitivity tests (Li et al., 2004), the most sensitive factors for CH_4 and N_2O emissions from rice paddies are soil texture and soil organic carbon. By varying soil texture and soil organic carbon over the ranges reported in the county-scale database, a range of CH_4 and N_2O emissions for each cropping system in each county is estimated. All emissions estimates from DNDC in this study represent the midpoints of those ranges.

There are 11 different crop rotations, including single rice, double rice, rice-winter wheat, rice-rapeseed, and rice-rice-vegetable. The area occupied by each rotation in each county is quantified by combining the county-scale statistical database of crop-sown areas with a Landsat land-cover map for mainland China (Frolking et al., 2002). Total rice area is assumed to remain fixed over the 2000 to 2020 period under both baseline and mitigation scenarios, though regional changes in rice area are certainly expected to occur; the subject of changing rice area in response to implementing the mitigation options is discussed in Section V.1.3.6.

Table 1-3: Rice-Only Baseline CH_4, N_2O, and Soil Carbon Estimates for 2000, 2010, and 2020 by Asian Region (Midpoints from DNDC in $MtCO_2eq/yr$; Negative Carbon Numbers Indicate Net Sequestration)

	2000			2010[a]			2020[b]		
Region	CH_4	N_2O	Soil Carbon	CH_4	N_2O	Soil Carbon	CH_4	N_2O	Soil Carbon
China	211	199	–25	217	132	–48	223	114	–35
Huaihe	41	23	–4	43	18	–6	44	15	–4
Haihe	3	2	–1	3	1	–1	4	1	–0
Huanghe	2	1	–1	2	1	–0	2	1	–0
Changjian	87	104	–18	90	65	–24	92	56	–18
Songliao	23	8	6	24	6	–2	24	6	–1
Inland	1	0	–0	1	0	–0	1	0	–0
Southwest	1	2	1	1	1	–1	1	1	–0
ZhuJiang	33	38	–2	34	25	–10	35	21	–8
Southeast	19	20	–6	20	15	–5	20	13	–4
Bangladesh	41	4	13	45	2	–1	47	2	–2
India	103	5	19	111	10	–9	117	15	–10
Indonesia[c]	131	36	257	139	5	78	150	4	65
Philippines	58	7	36	60	2	7	64	2	6
Thailand	66	6	70	69	3	14	73	3	12
Vietnam	45	6	40	73	3	7	80	3	6

[a] Average of 2006–2010.
[b] Average of 2016–2020.
[c] Indonesia has exceptionally large baseline decreases in soil carbon because it is starting from a very high initial soil carbon content (about 7 percent).

Total emissions are estimated from total sown area, including all rice systems that capture more than one rice crop (i.e., double rice) for multiple growing seasons over the course of a year. Rice yields in DNDC, however, are estimated from single-rice systems only and are assumed to be representative of other types of rice systems (i.e., double rice and rice-winter wheat).[9]

Daily weather data (i.e., maximum and minimum air temperatures and precipitation) for 1990 from 610 weather stations in China were acquired from the National Center for Atmospheric Research (http://dss.ucar.edu/datasets/ds485.0/). Climate data for 1990 are used for baseline and mitigation scenarios; thus, as with the DAYCENT modeling runs, there is no explicit assumption about anthropogenic climate change out to 2020. Climate, biophysical, and management conditions are assumed to be the same within each county but vary across counties.

Midseason drainage is assumed to be a baseline management practice for a fixed percentage (80 percent) of Chinese paddies currently and out to 2020; the remaining 20 percent is assumed to be under continuous flooding. Shen et al. (1998) estimate that 80 percent of Chinese rice systems have made the

[9] There are plans to modify the DNDC model so that yields for multiple types of rice cropping systems, in addition to single-rice systems, can be tracked separately.

conversion from continuous flooding to midseason drainage, a practice that decreases CH_4 emissions because it decreases the period over which anaerobic conditions occur. Under midseason drainage, three drainage events are assumed to be carried out for each rice-growing season.

Optimal Chinese rice yields in DNDC were set to increase by 1 percent per year over the 2000 to 2020 period to match yield projections from IFPRI's IMPACT model. As a result, realized yields in DNDC do increase over time but fall short of the prescribed optimal yields due to nutrient limitations, primarily insufficient nitrogen availability.

Fertilizer applications are assumed to be 140 kgN/hectare (70 kgN of urea and 70 kgN of ammonium bicarbonate) for each rice-growing season. These rates remain fixed over the 2000 to 2020 period. Rice straw (1,000 kg-C) is also amended at the beginning of each rice-growing season. No manure is applied.

Less detailed DNDC analyses are carried out for other Asian regions. These emissions analyses are not intended to serve as national inventory studies but rather to provide a basis from which to assess the effects of the different mitigation options. DNDC is run for individual sites under both rain-fed and irrigated conditions in Bangladesh, India, Indonesia, Japan, the Philippines, Thailand, and Vietnam. For each site, soil and climate data were compiled from several sources (Global Soil Data Task Group, 2000; Kistler et al., 2001; Webb et al., 2000). To estimate national-level emissions, the simplified assumption is made that the site-level conditions are representative of the entire country. Therefore, net emissions (CH_4, N_2O, soil carbon) rates per hectare from these test sites are multiplied by the number of hectares under either irrigated or rain-fed conditions in each country, according to data from the International Rice Research Institute (IRRI). These areas also remain fixed over the 2000 to 2020 period. Like the DNDC simulations in China, optimal yield projections out to 2020 from IFPRI (see Appendix R) are used to allow annual baseline yields in DNDC to increase at different rates in different countries.

Midseason drainage is currently not widely practiced outside of China; for this reason, the dominant baseline management condition assumed in these other Asian regions is continuous flooding under either irrigated or rain-fed conditions. Fertilization types and rates are assumed to be the same as in China. DNDC simulations were not carried out for Malaysia, Myanmar, South Korea, and other Southeast Asian countries, but nationally averaged emissions and yield results from DNDC in neighboring regions are used as proxies (see Appendix R).

V.2.2.3 Mitigation Options for Rice CH_4, N_2O, and Soil Carbon Emissions

The mitigation options chosen for rice emissions have been identified as viable options in the literature (e.g., Wassmann et al. [2000]; Van der Gon et al. [2001]). Table 1-4 lists these mitigation options, which include changes in water management that reduce the time over which flooding conditions occur (to reduce anaerobic conditions), use of alternative fertilizers and changes in the timing of organic amendments (to inhibit methanogenesis), or switching from flooded to upland rice to eliminate anaerobic conditions.

Unlike China, most other Asian countries have larger fractions of rice areas under rain-fed management conditions. Mitigation options requiring a change in water management are not simulated on rain-fed areas because these systems are water limited and rely only on precipitation. Mitigation options involving fertilizer management and conversion to upland rice are assessed on all rice areas.

All mitigation options are intended primarily to reduce baseline CH_4 emissions, but N_2O emissions and soil carbon are affected as well. Emissions reductions represented in the final cost estimates represent these net greenhouse gas effects. The mitigation options are simulated by DNDC, and resulting rice crop yields and emissions effects are compared with the DNDC baseline, as described above. Although all

Table 1-4: Rice CH_4, N_2O, and Soil Carbon Mitigation Options Run Through DNDC

Mitigation Option	Description	Greenhouse Gas Effects
Full midseason drainage	In China, shift from 80 percent to 100 percent adoption of midseason drainage. In rest of Asia, conversion from 0 percent to 100 percent. Rice fields are dried three times within a growing season and surface water layer is 5 to 10 cm for remaining, flooded period. Not applied on rain-fed areas.	CH_4, N_2O, soil carbon
Shallow flooding	Assumes rice paddies are marginally covered by flood water, with the water table fluctuating 5 to 10 cm above and below soil surface. Not applied on rain-fed areas.	Same
Off-season straw	Shifting straw amendment from in-season to off-season can reduce availability of dissolved organic carbon and; thus, methanogens. Assumes rice straw is applied 2 months before rather than at beginning of rice-growing season.	Same
Ammonium sulfate	Baseline fertilizers, urea, and ammonium bicarbonate, replaced with 140 kg/hectare of ammonium sulfate. Sulfate additions to soil can elevate reduction potential, which suppresses CH_4 production.	Same
Slow-release fertilizer	Nitrogen is slowly released from coated or tablet fertilizer over a 30-day period following application. Applied in the same amount and at the same time as in baseline case. Increases fertilizer-use efficiency.	Same
Upland rice	Assumes upland rice replaces existing paddy rice areas and that fields do not receive any flood water.	Same

mitigation options are represented in the final MACs, DNDC simulates only one mitigation option at a time, assuming that each mitigation option is implemented on all rice lands in 2000 and continuously until 2020. No mitigation options are implemented simultaneously on the same rice lands or on different portions of the rice lands within DNDC.

Unlike the options with DAYCENT, no options that were found to increase net emissions relative to baseline are removed from the rice portion of the analysis, because these net emissions increases were generally small or temporary (i.e., occurring only in the later years of the analysis).

V.2.2.4 DNDC Estimates for Changes in Rice CH_4, N_2O, Soil Carbon, and Yields

Results here provide the most detail for China because that is the country for which the most detailed DNDC modeling runs were carried out. Table 1-5 provides net greenhouse gas results aggregated to the Chinese national level for the baseline and mitigation scenarios, averaged over the entire 2000 to 2020 period. The midpoint estimates from DNDC are those carried forward in the MAC calculations.

Table 1-5: DNDC Estimates of Net Greenhouse Gas Results for Baseline and Mitigation Scenarios for China (Annual Averages in $MtCO_2eq/yr$ over 2000–2020)

Estimate	Baseline	Midseason Drainage	Shallow Flooding	Off-Season Straw	Ammonium Sulfate	Slow-Release Fertilizer	Upland Rice
Midpoint[a]	315	296	140	298	235	326	41
High estimate	484	445	232	468	379	454	71
Low estimate	146	148	47	128	90	199	11

Source: Li et al., 2006.

[a] The high, mid, and low estimates are the results of most sensitive factor (MSF) estimates carried out with the DNDC model.

Table 1-6 shows individual greenhouse gas changes from the baseline, as well as the net greenhouse gas and yield changes, at the Chinese national level on a per-hectare basis; change in water-use requirements are also shown but are not used in the final cost estimates because water is not a priced commodity in these rice systems.

Table 1-6: Changes from Baseline in Greenhouse Gas Emissions, Crop Yields, and Water Consumption for China (Annual Averages over 2000–2020; Negative Numbers Indicate Decreases Relative to the Baseline)

Management Option	CH_4 ($kgCO_2eq/ha$)	N_2O ($kgCO_2eq/ha$)	CO_2 ($kgCO_2/ha$)	Net Greenhouse Gas ($kgCO_2eq/ha$)	Yield (kg C/ha)	Water (mm/yr)
Midseason drainage	–2,411	1,283	–1	–1,129	81	–9
Shallow flooding	–7,402	–2,440	591	–9,251	134	–248
Off-season straw	–663	–40	21	–682	43	0
Ammonium sulfate	–367	–3,668	–85	–4,120	28	0
Slow-release fertilizer	287	727	–191	823	131	0
Upland rice	–11,794	–3,018	239	–14,573	–381	–566

Source: Li et al., 2006.

As described in Li et al. (2006), despite large-scale adoption of midseason drainage, there is still large technical potential for additional CH_4 reductions from Chinese rice paddies (e.g., over 60 percent reductions are achieved in the shallow flooding scenario over 2000 to 2020). However, management changes that reduce CH_4 emissions simultaneously affect N_2O emissions and soil carbon dynamics such that the net greenhouse gas effects should be considered. Midseason drainage, for example, is an effective CH_4 reduction strategy but can significantly increase N_2O emissions. Ammonium sulfate reduces CH_4 by a small amount but significantly reduces N_2O; these low CH_4 reductions are largely due to the fact that mid-season drainage rather than continuous flooding is the baseline practice (conditions under which sulfate is less effective at reducing CH_4), whereas more significant N_2O reductions occur because ammonium sulfate is less susceptible to volatilization than the urea it is replacing (because all of the nitrogen is already in the ammonium form).

In terms of net greenhouse gas technical mitigation potential only, the most effective mitigation option appears to be shallow flooding, followed by ammonium sulfate, full midseason drainage adoption, and off-season straw amendments; the slow-release fertilizer scenario enhances soil carbon but increases the other gases and thus does not reduce net greenhouse gas emissions compared with the baseline. The upland rice scenario, where it is assumed that existing rice fields receive no flood water, is simulated in DNDC for China and is found to decrease net greenhouse gas emissions by about 87 percent.

The relative order of mitigation across scenarios remains the same even when the proportions of midseason drainage vary (Li and Salas, 2005), suggesting that these results may apply to other regions where midseason drainage has not been widely adopted. Appendix R contains information about the time dynamics of these net greenhouse gas changes for each scenario for 2000 to 2020.

Most mitigation options, including slow-release fertilizer, increase rice yields compared with the baseline. In general, rice yields vary directly with nitrogen availability, assuming no heat stress and sufficient water resources: higher nitrogen availability leads to higher yields. Relative to continuous flooding, midseason drainage or shallow flooding elevates soil aeration and hence accelerates decomposition, which produces more inorganic nitrogen and increases nitrogen availability. Slow-release fertilizer improves the fertilizer use efficiency by extending the period of nitrogen availability for the plants, effectively increasing total nitrogen availability. Similar to the slow-release fertilizer, ammonium sulfate has relatively low solubility compared with baseline fertilizer, urea, and ammonium bicarbonate and thus is less susceptible to leaching. Although theoretically off-season straw may not have a direct effect on yield, it is assumed that early incorporation of straw favored its decomposition because of the high reduction potential conditions before flooding. This higher decomposition rate enhanced yields caused by increased soil nitrogen availability when the rice was transplanted. The yield difference between upland rice and paddy rice is in the rice's genetic characteristics. The current upland rice has genetically low yield. This situation may change if new strains of upland rice are developed. In summary, management practices that increase nitrogen availability (through increased decomposition or better synchronization with plant needs) will typically increase rice yields.

Shifting to full midseason drainage and shallow flooding are also water-saving practices because they significantly decrease water consumption (i.e., evapotranspiration), whereas the other mitigation options, involving only changes in fertilization or straw amendment, have almost no effect on water consumption.

Table 1-7 shows net greenhouse gas results under each mitigation option compared with the baseline for the other Asian countries. The pattern of results observed in China is similar for these other countries. The most effective mitigation options in terms of net greenhouse gas reductions involve a change in water management; the options involving a change in fertilization management are less effective. Slow-release fertilizer is also a particularly poor greenhouse gas reduction strategy in these other Asian countries, often leading to no net greenhouse gas reductions compared with the baseline.

Table 1-7: Net Greenhouse Gas Results for Baseline and Mitigation Options for Other Asian Countries (Annual Averages in $MtCO_2eq/yr$ over 2000–2020)

Country	Baseline	Midseason Drainage	Shallow Flooding	Off-Season Straw	Ammonium Sulfate	Slow-Release Fertilizer	Upland Rice
Bangladesh	47	23	8	32	43	47	21
India	113	60	23	79	101	115	41
Indonesia	237	139	142	193	223	238	190
Japan	29	15	6	22	26	29	10
Philippines	72	40	16	54	65	73	26
Thailand	91	79	74	65	85	91	72
Vietnam	84	71	59	51	78	84	43

To estimate the breakeven $\$/tCO_2eq$ of these mitigation options, DNDC results for the change from baseline in net emissions, yields, and fertilizer applications are used in combination with rice crop and fertilizer price information, as well as assumptions about other input costs and labor changes. Change in crop revenue is estimated with DNDC changes in yields and IFPRI's changes in current and projected region-specific baseline producer prices for rice (see Appendix T). For the ammonium sulfate option, the additional input cost is the extra cost of ammonium sulfate compared with urea and ammonium bicarbonate, based on FAO prices. For the slow-release fertilizer option, the additional input cost is assumed to be $20 per hectare for all regions, based on the cost of using Agrotain, a urease inhibitor thought to be an appropriate proxy.

No one-time capital costs are assumed for any of the rice mitigation options. Three of the options (i.e., midseason drainage, shallow flooding under irrigated conditions, and off-season straw amendments) are assumed to require additional labor compared with baseline practices. The percentage increase in labor for these three options is assumed to be uniform across all regions and is estimated by assuming percentage changes in preharvest labor based on data from Moser and Barrett (2002) for systems of rice intensification as a rough proxy. Preharvest labor is assumed to account for 75 percent of total labor in all regions. GTAP data on value of inputs used in rice production are used to calculate the share of output value attributable to rice labor costs for each region. This share is used to calculate baseline labor costs per hectare from the estimated value of output per hectare by region. Labor rates are taken from IFPRI's IMPACT model to calculate the implied number of labor hours per hectare, consistent with the labor cost per hectare, as a validity check on the labor costs being estimated. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.3 Livestock (CH_4 and N_2O)

V.2.3.1 Livestock Enteric CH_4 Emissions Characterization

Methane is produced as part of the normal digestive process in animals. During digestion, microbes present in an animal's digestive system ferment food consumed by the animal. This microbial fermentation process is referred to as enteric fermentation and produces CH_4 as a by-product, which can be exhaled or eructated by the animal. The amount of CH_4 produced and excreted by an animal depends primarily on the animal's digestive system and the amount and type of feed it consumes.

Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters of CH_4 because of their unique digestive systems. Ruminants possess a rumen, or large fore-stomach, in which microbial fermentation breaks down coarse plant material for digestion. Nonruminant domesticated animals (e.g., swine, horses, mules) also produce CH_4 emissions through enteric fermentation, although this microbial fermentation occurs in the large intestine, where the capacity to produce CH_4 is lower (USEPA, 2005b).

An animal's feed quality and feed intake also affect CH_4 emissions. In general, lower feed quality or higher feed intake lead to higher CH_4 emissions. Feed intake is positively related to animal size, growth rate, and production (e.g., milk production, wool growth, pregnancy, or work). Therefore, feed intake varies among animal types, as well as among different management practices for individual animal types.

Because CH_4 emissions represent an economic loss to the farmer—where feed is converted to CH_4 rather than to product output—viable mitigation options can entail feed efficiency improvements to reduce CH_4 emissions per unit of beef or milk. However, these mitigation options can actually *increase* CH_4 per animal.

V.2.3.2 Livestock Manure CH_4 and N_2O Emissions Characterization

The management of livestock manure can produce both CH_4 and N_2O emissions. Methane is produced by the anaerobic decomposition of manure. Nitrous oxide is produced through the nitrification and denitrification of the inorganic nitrogen derived from livestock manure and urine.

When livestock and poultry manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid or slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH_4. When manure is handled as a solid (e.g., in stacks or pits) or deposited on pasture, range, or paddock lands, it tends to decompose aerobically and produce little or no CH_4 (USEPA, 2005b).

Ambient temperature and manure storage or residency time also significantly affects the amount of CH_4 produced because of influences on the growth of the bacteria responsible for CH_4 formation. For example, CH_4 production generally increases with rising temperature and residency storage time (USEPA, 2005b). Also, for nonliquid-based manure systems, moist conditions (which are a function of rainfall and humidity) favor CH_4 production. Although the majority of manure is handled as a solid, producing little CH_4, the general trend in manure management, particularly for large dairy and swine producers in the United States and other industrialized countries, is one of increasing use of liquid systems.

The composition of the manure also affects the amount of CH_4 produced. Manure composition varies by animal type and diet. In general, the greater the energy content of the feed, the greater the potential for CH_4 emissions. For example, feedlot cattle fed a high-energy grain diet generate manure with a high CH_4-producing capacity, whereas range cattle fed a low-energy diet of forage material produce manure with about half the CH_4-producing potential (USEPA, 2005b). However, some higher-energy feeds also are more digestible than lower quality forages, which can result in less overall waste excreted from the animal.

A small portion of the total nitrogen excreted in manure and urine is expected to convert to N_2O. The production of N_2O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system (USEPA, 2005b). For N_2O emissions to occur, the manure must first be handled aerobically where NH_3 or organic nitrogen is converted to nitrates and nitrites (nitrification) and then handled anaerobically, where the nitrates and nitrites are reduced to nitrogen gas (N_2), with intermediate production of N_2O (i.e., denitrification) (Groffman et al., 2000). These emissions are most likely to occur in dry manure handling systems that have aerobic conditions but that also contain pockets of anaerobic conditions, such as rain events.

V.2.3.3 The USEPA Baseline Estimates of Livestock Enteric CH_4 Emissions

Baseline emissions of and activity data for livestock enteric CH_4 are taken directly from USEPA (2006). Enteric CH_4 emissions from livestock are estimated to be the second largest source of global agricultural non-CO_2. In 2000, global enteric CH_4 emissions were estimated to be 85,648 Gg or 1,799 $MtCO_2eq$ and are projected to increase more than 30 percent by 2020 to 111,633 Gg or 2,344 $MtCO_2eq$ (a 32 percent increase relative to 1990). Livestock enteric CH_4 accounted for 32 percent of global agricultural non-CO_2 emissions in 2000. In the United States, enteric CH_4 accounts for 27 percent of agricultural non-CO_2 and less than 2 percent of all greenhouse gas emissions (USEPA, 2005b).

V.2.3.4 The USEPA Baseline Estimates of Livestock Manure CH_4 and N_2O Emissions

Baseline emissions of and activity data for livestock manure CH_4 and N_2O are taken directly from USEPA (2006). The joint CH_4 and N_2O emissions from livestock manure are estimated to be the fourth largest source of global agricultural non-CO_2 emissions. In 2000, livestock manure emissions were estimated to be 421 $MtCO_2eq$, or 10,732 Gg of CH_4 and 632 Gg of N_2O, and are projected to increase 24 percent by 2020 to 523 $MtCO_2eq$, or 12,832 Gg of CH_4 and 818 Gg of N_2O (a 21 percent increase relative to 1990). Livestock manure emissions accounted for less than 8 percent of global agricultural non-CO_2 emissions in 2000. In the United States, joint CH_4 and N_2O emissions from livestock manure account for 13 percent of agricultural non-CO_2 emissions and less than 1 percent of all greenhouse gas emissions (USEPA, 2005b).

V.2.3.5 Mitigation Options for Livestock Emissions

Non-CO_2 greenhouse gas emissions from livestock can be reduced primarily through either reducing CH_4 emissions that occur during the normal digestive process (i.e., enteric fermentation) or capturing

CH_4 emitted by livestock manure. There is also potential to affect N_2O emissions from manure management, either indirectly through options that target CH_4, but also through mitigation options that primarily target N_2O. However, limited quantitative information is available on the co-effects of CH_4 mitigation options on N_2O or the cost or emissions reductions associated with options focused on N_2O. Thus, the focus here is on options designed to reduce CH_4 but to account for changes in N_2O emissions for those options that change livestock populations by assuming a change in N_2O emissions proportionate to the change in livestock population.

V.2.3.5.1 Mitigation Options for Livestock Enteric CH_4

The enteric CH_4 mitigation options fall into four general categories: (1) improvements to food conversion efficiency by increasing energy content and digestibility of feed, (2) increased animal productivity through the use of natural or synthetic compounds that enhance animal growth and/or lactation (e.g., bovine somatotropin [bST], antibiotics), (3) feed supplementation to combat nutrient deficiencies that prevent animals from optimally using the potential energy available in their feed, and (4) changes in herd management (e.g., use of intensive grazing).[10] Some of these proposed options for enteric fermentation may actually *increase* net greenhouse gas emissions per animal but lead to an even larger increase in productivity. Thus, emissions per unit of product (e.g., meat, milk, or work) decline, and mitigation at the national or regional level requires a sufficient reduction in the number of animals to more than offset the increase in emissions per animal. To capture this issue, two separate estimates of mitigation potential and costs were developed assuming both a constant number of animals and constant production. The static, engineering approach does not allow for simultaneous adjustment in both number of animals and production; however, sensitivity experiments at the end of this section using the global agricultural commodity market model, IMPACT, allow for these dynamic feedbacks to occur.

Table 1-8 summarizes the enteric fermentation options. Most of these options could also be applied to other livestock species (e.g., buffalo, sheep, goats), but no data were available on the emissions reductions or productivity effects that would be expected for those species.

V.2.3.5.2 Mitigation Options for Livestock Manure CH_4 and N_2O

All manure CH_4 mitigation options involve the capture and use of CH_4 through anaerobic digesters. Anaerobic digesters are currently in limited use on large-scale livestock operations in developed regions, often primarily as a means of treating and stabilizing waste and controlling odor, but the CH_4 that is captured is also used as an energy source. Small-scale, ambient temperature digesters are also being used in developing regions, such as China, India, and Vietnam, for household energy generation. The feasibility of digesters depends in part on climate. There are a large number of different types of digesters that can be used, with some being more appropriate for certain climates or livestock species than others. Another important characteristic of digester systems is whether they include engines for electricity generation. Systems generating electricity can potentially create savings by offsetting farm purchases of electricity or even selling the electricity. Systems that do not include electricity generation generally use the heat generated for on-farm use to offset purchases of heating fuels.

[10] Emissions can also be mitigated through other methods, such as improving genetic characteristics, feeding compounds that inhibit rumen methane formation, improving reproduction efficiency, and controlling disease better. However, data are currently insufficient to include estimates for these options.

Table 1-8: Livestock Enteric Fermentation Greenhouse Gas Mitigation Options

Mitigation Option	Description	Greenhouse Gas Effects[a]
Improved feed conversion	Increase the amount of grain fed to livestock to increase the proportion of feed energy being converted to milk, meat, or work instead of animal maintenance. This option tends to increase emissions per animal but reduce emissions per unit output. It is more effective in reducing emissions per unit of production in regions where baseline feed is of relatively low quality. This option is applied to both beef and dairy cattle in all regions, although it was excluded from the MACs for some developed regions where it resulted in slightly higher GHG emissions.	CH_4, some N_2O
Antibiotics	Administer antibiotics (e.g., monensin) to beef cattle to promote faster weight gain, which reduces time to maturity and CH_4 production per kilogram of weight gain. This option is applied in all regions.	CH_4, some N_2O
Bovine somatotropin (bST)	Administer bST to dairy cattle to increase milk production. In many cases, this option increases CH_4 emissions per animal but typically increases milk production sufficiently to lower emissions per kilogram of milk. Because of opposition to the use of bST in many countries, this option was only applied in selected countries that currently approve of the use of bST or are likely to approve its use by 2010.	CH_4, some N_2O
Propionate precursors	Involves administering propionate precursors to animals on a daily basis. Hydrogen produced in the rumen through fermentation can react to produce either CH_4 or propionate. By adding propionate precursors to animal feed, more hydrogen is used to produce propionate and less CH_4 is produced. This option is applied to both beef and dairy cattle in all regions.	CH_4, some N_2O
Antimethanogen	Vaccine in development by Commonwealth Scientific and Industrial Research Organization (CSIRO) that can be administered to animals and will suppress CH_4 production in the rumen. This option is applied to beef and dairy cattle, sheep, and goats in all regions.	CH_4, some N_2O
Intensive grazing	Moving to a more management-intensive grazing system where cattle are frequently rotated between pastures to allow recently grazed pastures time to regrow and to provide cattle with more nutritious pasture grazing that will permit replacement of more feed grains. This option may actually reduce animal yields but will decrease emissions by an even larger percentage. This option is applied to beef and dairy cattle in developed regions and Latin America.	CH_4, some N_2O

[a] For this analysis, effects on N_2O are estimated only for the scenarios where production is held constant and there is a change in livestock population.

The types of digesters are aggregated based on a categorization of representative systems provided by the USEPA's AgStar program (Table 1-9). For most regions, swine and diary cattle account for the majority of greenhouse gas emissions from manure, largely because their manure is often managed in liquid systems under anaerobic conditions. Although CH_4 emissions from manure could potentially be captured from additional species (e.g., beef cattle, buffalo, sheep, goats), these species typically account for much smaller shares of emissions and are often managed on pasture much of the year with solid manure handling. Manure from livestock on pasture does not produce much CH_4 because it decomposes under aerobic conditions, resulting in little to no emissions. Based on IPCC default factors, the CH_4 emissions factor is actually higher for digesters than for dry manure management systems such as pasture.

Complete-mix, plug-flow, fixed-film, and large-scale covered lagoon digesters are applied only in the United States, EU-15, Japan, Australia, other developed countries, Eastern Europe, Central Asia, FSU, China, South Korea, and other East Asian regions, based on climate, environmental regulations, capital costs, and other considerations. The dome, polyethylene bag, small-scale covered lagoon, and flexible-bag digesters are applied in all other world regions. China and other parts of East Asia are the only regions where digesters in both of these groups are applied. Applicability of these options was further refined by allocating the share of baseline emissions to swine and dairy cattle and applying emissions reductions only to those portions of the emissions stream. The share of livestock manure emissions due to dairy and swine is based on USEPA (2006), which relies on both IPCC inventory default methodologies and individual country greenhouse gas inventory reports.

CH_4 reduction efficiencies are assumed to be 85 percent from baseline for the complete-mix, plug-flow, fixed-film, and large-scale covered lagoon digesters based on the difference between IPCC default emissions factors for anaerobic manure management, where CH_4 is released into the atmosphere, and digesters. For the smaller-scale digesters applied in developing countries, the reduction efficiency is assumed to be 50 percent from baseline, where baseline emissions are much lower because of a different distribution of manure management practices and the likelihood of less efficient CH_4 capture.

Capital costs are taken from the USEPA's AgStar program (Roos, personal communication, 2005), which estimates the capital cost per 1,000 pounds of liveweight. These values are combined with the 1996 IPCC guideline values for average liveweight for different species in regions around the world to generate estimates of the capital cost per animal. Because liveweight per animal tends to be much smaller in developing countries, the capital cost per animal ends up being lower than in developed regions. This cost is annualized assuming that the large-scale digesters have an expected useful lifetime of 20 years and the small-scale digesters have an expected useful lifetime of 10 years.

GTAP data on labor cost shares by region for livestock production and IMPACT data on regional agricultural wage rates are used to calculate the baseline labor hours per animal and change in hours to verify the reasonableness of these assumptions, as described above for cropland soil management and rice cultivation. For large-scale digesters, labor requirements for swine farms are assumed to increase by 2 percent for options without engines and 4 percent for those with engines. For dairy farms, labor requirements are assumed to increase by 0.5 percent for options without engines and 1 percent for those with engines. The percentage increase in labor is smaller, because dairy farming is already much more labor intensive and requires much more labor per animal in the baseline. The increase in labor for dairy farms is calculated by assuming 200 hours per year in the United States for digester operation, repairs, management, and typical farm size of 800 cows with 50 hours of labor per head per year in the baseline. For hog farms, it is again assumed that a digester will add about 200 hours of labor per year, but assuming an average of about 5,000 hogs per farm per year, that assumption could potentially add a

Table 1-9: Livestock Manure Management Greenhouse Gas Mitigation Options

Mitigation Option	Description	Greenhouse Gas Effects[a]
Complete-mix digester	These digesters are more common in warmer climates, where manure is flushed out of barns or pens with water, lowering the solids' concentration to a level generally between 3 percent and 10 percent. Often there is a mixing tank where the manure accumulates before entering the digester. These digesters make use of gravity and pumps to move the manure through the system. They are often in the shape of a vertical cylinder and made of steel or concrete with a gas-tight cover. These digesters are typically heated to maintain a constant temperature and constant gas flow.	CH_4
Plug-flow digester	These digesters consist of long and relatively narrow heated tanks, often built below ground level, with gas-tight covers. Plug-flow digesters are only used for dairy manure because they require higher manure solids' content, around 11 percent to 13 percent. As with complete-mix digesters, they are maintained at constant temperatures throughout the year to maintain consistent gas production.	CH_4
Fixed-film digester	This digester option may be appropriate where concentrations of solids are very low, such as in manure management situations where manure is very diluted with water. Fixed-film digesters consist of a tank packed with inert media on which bacteria grow as a biofilm.	CH_4
Covered lagoon digester, large-scale	Covered earthen lagoons are the simplest of the systems used in developed countries and generally the least expensive, though there is quite a bit of variation in the systems that have been built. This system is used with low manure solids' concentration (less than 3 percent) and can be used for swine or dairy cattle. CH_4 is captured by covering the lagoon where manure is stored with a floating cover and piping the gas out to a flare or used on-farm. Because these digesters are not generally heated, the available gas flow varies significantly over the course of the year.	CH_4
Dome digester, cooking fuel and light	These are small-scale, unheated digesters used in some developing nations, including China and India. A typical dome digester is a brick-lined cylinder sunk in the ground with a wall dividing the cylinder in two with inlet and outlet ports connected to the bottom of the tank. Biogas generated is typically used by the household for cooking and other household energy needs.	CH_4
Polyethylene bag digester, cooking fuel and light	This small-scale unheated digester is in use in a variety of developing countries. The digester essentially consists of a hole dug in the ground and covered with a plastic bag, with an area for input of manure and a pipe with a valve for biogas produced. Biogas generated is typically used by the household for cooking and other household energy needs.	CH_4
Covered lagoon, small-scale, for cooking fuel, light, shaft power	This is smaller-scale and much cheaper version of the covered lagoon above, used to generate biogas for household use. Some of these digesters may produce enough energy for shaft power, in addition to household cooking and other uses.	CH_4
Flexible-bag digester, cooking fuel and light	This is another relatively simple and low-cost unheated digester used in developing countries where the biogas is generated and collected within a plastic bag.	CH_4

[a] Unlike options for reducing emissions from enteric fermentation, none of the options included for manure management are expected to affect yields and there are no effects on N_2O currently being estimated.

digester and about 2 hours of labor per hog annually in the baseline. Options with engines and accompanying electricity generation and transfer equipment were assumed to require twice as much labor as those that produce heat only. For the small-scale digesters in developing nations, labor was assumed to increase by 2.5 percent for options without engines and 5 percent for those with engines that rely on manure from either swine or dairy cattle. Many of these digesters are used on operations with only a few animals and often combine manure from multiple species with other household wastes.

None of these manure management options are expected to change livestock yields. Revenues (or cost savings) are generated from using captured CH_4 (essentially natural gas) for either heat or electricity on the farm. Revenues are scaled for other non-U.S. regions based on a U.S. Energy Information Agency (USEIA) electricity price index (2003).

Breakeven prices (\$/tCO_2eq) for these mitigation options are calculated by region and by species using the emissions reductions from baseline, annualized capital costs, changes in labor costs, and energy savings or revenue. Section V.1.3.1 provides additional information on how these individual parameters are used to estimate costs.

V.2.3.6 Changes in Livestock CH_4 and Productivity

Figure 1-3 shows total livestock emissions (enteric fermentation and manure management) associated with the baseline and mitigation scenarios, assuming a constant number of animals, where each option is assumed to be applied to 100 percent of the appropriate livestock species (see Tables 1-8 and 1-9), and appropriate regions. Similarly, Figure 1-4 shows the relative emissions under baseline and the mitigation scenarios, assuming constant production. Because percentage emissions reductions are assumed to be the same across all large-scale digesters and across all small-scale digesters, the individual manure management mitigation options identified in Table 1-9 are aggregated here.

Figure 1-3: Global Net Greenhouse Gas (CH_4 and N_2O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Number of Animals Constant

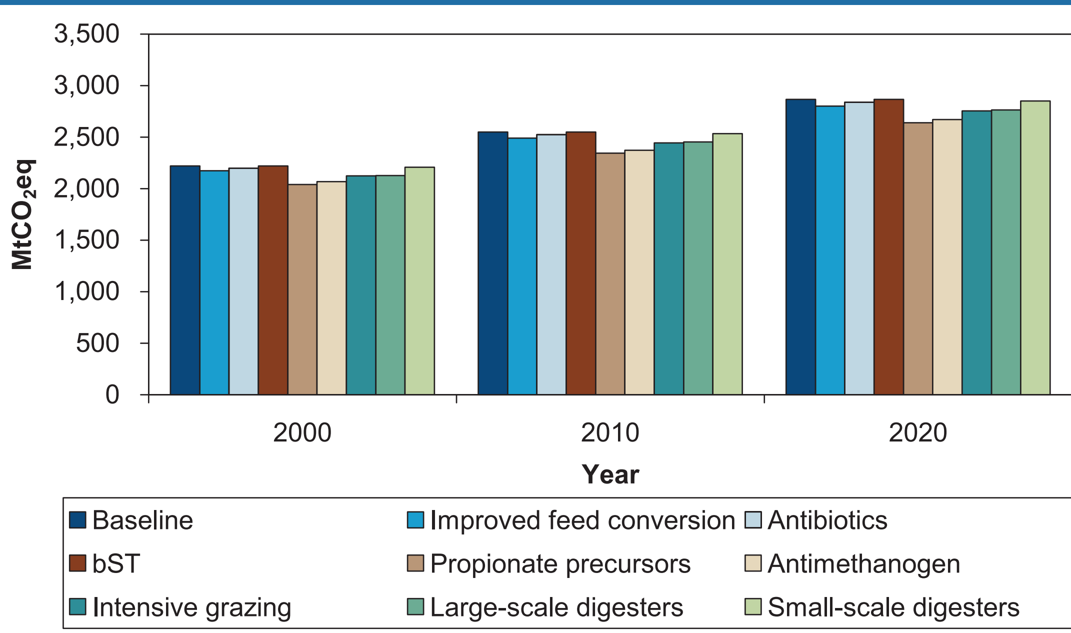
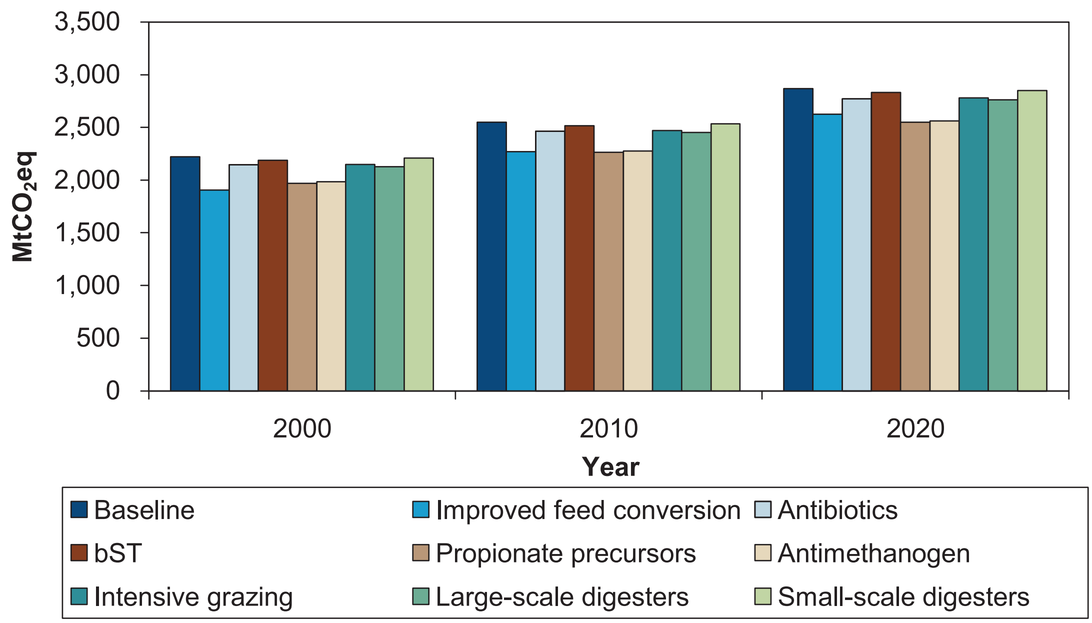


Figure 1-4: Global Net Greenhouse Gas (CH_4 and N_2O) Livestock Emissions under Baseline and Mitigation Scenarios, Assuming Full Adoption of Individual Options and Holding Production Constant



Because some of the enteric fermentation options increase yields in many regions, holding production of meat and milk constant means that there will be fewer animals needed for production. Thus, emissions tend to fall more under the constant production assumption than the constant animals assumption. For instance, improved feed conversion has such large positive yield impacts that emissions under full adoption of that option are about 250 $MtCO_2eq$ less annually when holding production constant and reducing the number of livestock, than when the number of animals is held constant. Section V.1.3.6 presents results that reflect adjustments for market impacts where there are simultaneous changes in the number of animals and in production. In practice, a combination of mitigation options would be adopted and no single option would be adopted for all production. In Section V.1.3.4, MACs are presented that assume partial adoption of each of the available options in each region. However, Figures 1-3 and 1-4 are included to give a sense of the relative emissions that would occur under different production scenarios.

Holding the number of animals constant, emissions are lowest under intensive grazing, followed by propionate precursors, antimethanogen, large-scale digesters, improved feed conversion, small-scale digesters, antibiotics, and bST. However, when production is held constant, the order differs, with improved feed conversion followed by propionate precursors, antimethanogen, intensive grazing, large-scale digesters, antibiotics, small-scale digesters, and bST.

As mentioned above, an important component of these options that will influence net emissions is the change in yield corresponding to each of these options. For some options (e.g., improved feed conversion), the yield effects vary substantially across regions because of widely differing baseline conditions. To summarize the primary overall yield effects, Figures 1-5 and 1-6 show the difference in global production of beef and milk from dairy cattle under full adoption of each of these options, holding the number of animals constant.

Figure 1-5: Global Beef Production under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant

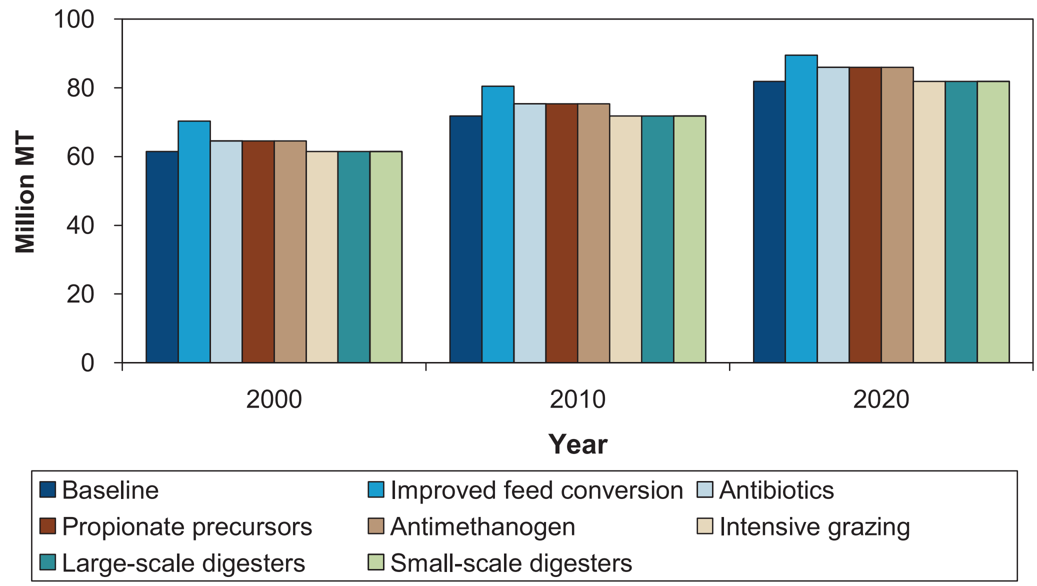
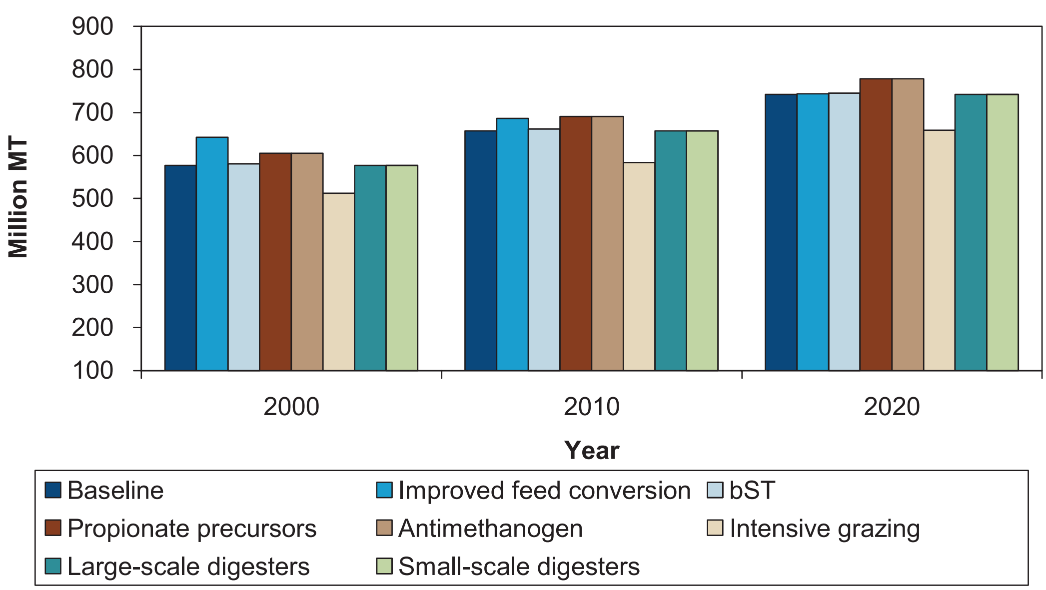


Figure 1-6: Global Production of Milk from Dairy Cattle under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant



For both beef and milk from dairy cattle, the largest yield increases are for improved feed conversion in 2000. Yield increases relative to baseline are smaller in future years, largely because productivity is improving rapidly under the baseline.[11] Improved feed conversion remains the option with the largest average global yield improvement for beef production in all years. Antibiotics, propionate precursors, and antimethanogen all increase beef yield by a similar amount, while intensive grazing, large-scale digesters, and small-scale digesters are assumed to have no impact on beef yield. For milk yield, propionate precursors and antimethanogen lead to similar increases in yield, which become greater than improved feed conversion by 2010. The use of bST leads to a small increase in yield, which would be larger were it not for assumptions that many regions will not adopt this option. Large-scale and small-scale digesters are assumed to have no impact on milk yield. Intensive grazing has a negative effect on milk yield.

[11] The percentage increase in yield attributable to the mitigation option for improved feed conversion is calculated for each year by netting out the percentage increase in baseline yield projected by IMPACT. This is done to reflect improved practices expected to be adopted in the baseline and avoid double-counting improvements in yield.

V.3 Results

V.3.1 Estimating Average Costs and Constructing Abatement Curves

The methods used to estimate the average cost of each mitigation option and construct the MACs in the agricultural sector follow the general methodology described in Section I. This section shows additional baseline emissions data (as described in Section V.1.2), the average costs of the mitigation options for key countries, and the MACs for key countries and world totals.

The average cost for each mitigation option represents the present-value breakeven price, expressed as 2000$ t/CO_2eq, where total benefits equal total costs. The $/t$CO_2$eq is estimated according to

$$\sum_{t=1}^{T}\left[\frac{(P\times ER)(1-TR)+R(1-TR)+TB}{(1+DR)^t}\right]=CC_0+\sum_{t=1}^{T}\left[\frac{RC(1-TR)}{(1+DR)^t}\right] \tag{1.1}$$

where

P	=	The breakeven price of the option in dollars per metric ton of CO_2 equivalent ($/t$CO_2$eq).
ER	=	The emissions reduction achieved by the technology (MtCO_2eq).
R	=	The revenue generated from energy production (scaled based on regional energy prices) or change in agricultural commodity prices ($).
T	=	The option lifetime (years).
DR	=	The selected discount rate (10%).
CC	=	The one-time capital cost of the option ($).
RC	=	The recurring (operation and maintenance [O&M]) cost of the option (portions of which may be scaled based on regional labor costs) ($/year).
TR	=	The tax rate (40%).
TB	=	The tax break equal to the capital cost divided by the option lifetime, multiplied by the tax rate ($).

Assuming that the emissions reduction, *ER*, the recurring costs, *RC*, and the revenue generated *R* do not change on an annual basis, then we can rearrange this equation to solve for the breakeven price, *P*, of the option for a given year as follows:

$$P=\frac{CC}{(1-TR)ER\sum_{t=1}^{T}\frac{1}{(1+DR)^t}}+\frac{RC}{ER}-\frac{R}{ER}-\frac{CC}{ER\cdot T}\cdot\frac{TR}{(1-TR)} \tag{1.2}$$

The cost estimate takes into account greenhouse gas reductions, revenue effects (e.g., positive or negative changes in yield), any required capital costs (e.g., anaerobic digesters), labor requirements, and changes in other input costs (e.g., increase or decrease in fertilizer applications), all relative to baseline conditions. Section V.1.2 above describes the individual mitigation options; the methods for estimating their associated effects on greenhouse gas emissions and yields; and the assumptions used for other input, capital, and labor costs.

MACs showing greenhouse gas reductions, in terms of percentage reductions from the baseline in 2010 and 2020, are estimated for key regions and world totals. Emphasis is placed on percentage reductions from the baseline, rather than on absolute emissions reduction numbers, because the overall trends are most important to convey for this analysis. Furthermore, the baselines for croplands and rice cultivation are not comprehensive greenhouse gas inventory estimates so that the percentage changes from these baselines are viewed as more transferable to other kinds of analyses.

To construct the MAC, lines are essentially drawn to connect the points representing the average cost of each mitigation option (where the X axis is MtCeq mitigated and the Y axis is $/t$CO_2$eq). The following general factors are estimated to ensure the MAC can represent simultaneous adoption of all mitigation options. First, a technical applicability fraction is estimated to ensure the mitigation option is applied only to the correct portion of baseline emissions. For example, options to reduce dairy cattle emissions can only be applied to the fraction of livestock emissions attributable to dairy cattle. Second, an implied adoption rate is estimated by segmenting the applicable baseline emissions into uniform fractions based on the number of mitigation options. For example, if 10 mitigation options could technically be applied to reduce cropland N_2O emissions, then each mitigation option is assumed to apply to only 10 percent of baseline emissions. This is a simplistic method to avoid double counting among mitigation options, but unfortunately it does not allow lower-cost options to out-compete higher-cost options. Other factors in addition to cost (e.g., adoption feasibility and implementation barriers) can of course determine the extent to which one mitigation option is adopted over another. Because such factors are not included, this static approach of allowing each mitigation option to be applied equally is viewed as a conservative approach to estimate the technical mitigation potential.

All mitigation options are assumed to be implemented immediately (i.e., in the first data year, 2000), but only for appropriate regions, and are assumed to remain in place continuously until 2020. Therefore, the MACs presented in 2010 represent the emissions reductions and associated costs that occur in year 2010, assuming that all mitigation options have been implemented since 2000. The emissions reductions represented in 2010 are estimated relative to the 2010 emissions baseline under the assumption that no mitigation options have been implemented since 2000.

Two general approaches are used to calculate all MACs in the agricultural sector. The first approach keeps cropland area, rice area, and livestock populations constant over time, allowing total production to change as yields per hectare and productivity per animal change as a result of the mitigation options. The biophysical modeling in DAYCENT and DNDC also holds land area constant over time. The second approach holds crop production, rice production, and livestock production (e.g., production of milk and beef) constant over time, allowing land area and animal populations to change (postprocess). In this case, land area is changed for each region by scaling the revised per-hectare yield numbers to maintain the same regional crop or rice production as in the baseline. Livestock population numbers are changed in a similar way. This latter approach is particularly important for the livestock sector, because many proposed enteric fermentation mitigation options actually *increase* CH_4 emissions per animal but decrease CH_4 emissions per unit product. Results are shown for both approaches.

V.3.2 Baselines, Mitigation Costs and MACs for Croplands

Table 1-10 presents the baseline net GHG emissions (N_2O and soil carbon) from croplands management by region by year used in this analysis. These are the values to which all estimated percentage reductions in croplands emissions were applied.

Table 1-10: Baseline Net GHG Emissions from Croplands from DAYCENT Estimates ($MtCO_2eq$)

Country/Region	2000	2010	2020
Africa	29	32	36
Annex I	**508**	**484**	**521**
Australia/New Zealand	13	17	17
Brazil	27	30	30
China	91	97	104
Eastern Europe	38	39	41
EU-15	91	93	101
India	66	69	73
Japan	0	0	0
Mexico	14	16	28
Non-OECD Annex I	**171**	**123**	**124**
OECD	**313**	**338**	**373**
Russian Federation	171	123	124
South & SE Asia	25	26	28
United States	167	179	200
World Total	**839**	**830**	**893**

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.
Note: These emissions include only croplands used for wheat, maize, or soybean production.
Note: Combinations of countries included in regions available from DAYCENT are not identical to those included in regions presented in this report, but were aggregated to approximate these regions as closely as possible.

Table 1-11 shows information on the yield effects, emissions reductions, and costs associated with individual croplands mitigation options for the United States, EU-15, Brazil, China, and India.

Table 1-12 provides estimates of the percentage reduction in net GHG emissions (relative to the croplands baseline used in this analysis) that could potentially be achieved at prices between $0/$tCO_2eq$ and $60/$tCO_2eq$ for both 2010 and 2020 in major regions around the world.

Figure 1-7 shows the globally aggregated MAC for cropland greenhouse gas mitigation for 2000, 2010, and 2020, in terms of percentage emissions reductions from baseline over the applicable carbon price range. With no price signal (i.e., at $0/$tCO_2eq$), approximately 15 percent of cropland net GHG (N_2O and soil carbon) can be mitigated. More than 190 million tCO_2eq (about 22 percent to 23 percent of baseline emissions, depending on which year is analyzed) are mitigated at less than $45/$tCO_2eq$ in 2010 and 2020, but costs begin to rise rapidly beyond that point. Mitigation levels do not substantially increase at higher prices, given the mitigation options considered here.

Negative costs result from options with cost savings because of lower applications of fertilizers while maintaining yields, whereas high-cost options are those where revenues decline as yields decline in response to suboptimal fertilizer applications. Negative cost options are consistent with previous studies, finding large potential agricultural mitigation from “no-regret” options. The fact that farmers are not adopting options that seemingly would increase profitability indicates that this analysis may not capture some costs barriers to adoption exist, such as increased variability of profits or complexity of management requirements.

Table 1-11: Croplands Mitigation Option Detail for Key Regions

Croplands	United States				EU-15				Brazil			
	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)
Nitrogen inhibitor—wheat–rf	6.6%	$26	2.33	1.3%	9.6%	–$13	2.568	2.8%	11.7%	$27	0.029	0.1%
Nitrogen inhibitor—wheat–irri	7.4%	$11	0.17	0.1%	10.0%	–$18	1.107	1.2%	11.9%	$25	0.000	0.0%
Nitrogen inhibitor—maize–rf	3.6%	$9	2.99	1.7%	2.7%	$15	0.171	0.2%	25.5%	$21	1.180	4.0%
Nitrogen inhibitor—maize–irri	3.4%	$2	0.58	0.3%	2.3%	$13	0.061	0.1%	NA	NA	NA	NA
Nitrogen inhibitor—soybean–rf	0.6%	$210	0.53	0.3%	0.4%	$384	0.001	0.0%	2.4%	$125	0.231	0.8%
Nitrogen inhibitor—soybean–irri	0.5%	$210	0.05	0.0%	0.3%	$323	0.000	0.0%	NA	NA	NA	NA
Split fertilization—wheat–rf	8.6%	–$64	2.00	1.1%	2.7%	$48	0.542	0.6%	19.8%	–$69	0.039	0.1%
Split fertilization—wheat–irri	8.3%	–$67	0.14	0.1%	3.0%	$44	0.214	0.2%	19.3%	–$70	0.000	0.0%
Split fertilization—maize–rf	9.4%	–$38	7.59	4.2%	3.8%	$13	0.154	0.2%	11.4%	–$60	0.173	0.6%
Split fertilization—maize–irri	8.9%	–$38	1.60	0.9%	4.3%	$5	0.077	0.1%	NA	NA	NA	NA
Split fertilization—soybean–rf	1.0%	$188	0.33	0.2%	0.0%	$190,338	0.000	0.0%	0.6%	$76	0.081	0.3%
Split fertilization—soybean–irri	0.8%	$298	0.03	0.0%	0.0%	$366,480	0.000	0.0%	NA	NA	NA	NA
Reduce fertilizer to 70% of base—wheat–rf	–16.6%	$267	0.81	0.5%	–19.1%	$114	0.798	0.9%	–12.2%	$69	0.008	0.0%
Reduce fertilizer to 70% of base—wheat–irri	–16.3%	$296	0.06	0.0%	–19.0%	$170	0.260	0.3%	–12.2%	$76	0.000	0.0%
Reduce fertilizer to 70% of base—maize–rf	–23.6%	–$613	–1.12	–0.6%	–15.9%	–$22,944	–0.001	0.0%	–23.7%	$109	–0.062	–0.2%
Reduce fertilizer to 70% of base—maize–irri	–22.7%	–$553	–0.28	–0.2%	–15.4%	–$445	–0.018	0.0%	NA	NA	NA	NA
Reduce fertilizer to 70% of base—soybean–rf	–0.6%	–$44	0.33	0.2%	0.0%	–$64	0.000	0.0%	–0.5%	–$14	0.088	0.3%
Reduce fertilizer to 70% of base—soybean–irri	–0.5%	–$43	0.03	0.0%	0.0%	–$40	0.000	0.0%	NA	NA	NA	NA
Reduce fertilizer to 80% of base—wheat–rf	–11.0%	$249	0.57	0.3%	–13.0%	$117	0.553	0.6%	–8.1%	$70	0.005	0.0%
Reduce fertilizer to 80% of base—wheat–irri	–10.9%	$293	0.04	0.0%	–12.9%	$174	0.176	0.2%	–8.2%	$76	0.000	0.0%
Reduce fertilizer to 80% of base—maize–rf	–15.8%	–$766	–0.60	–0.3%	–10.4%	$1,231	0.010	0.0%	–16.3%	$71	–0.057	–0.2%
Reduce fertilizer to 80% of base—maize–irri	–15.2%	–$628	–0.17	–0.1%	–10.3%	–$635	–0.009	0.0%	NA	NA	NA	NA
Reduce fertilizer to 80% of base—soybean–rf	–0.4%	–$45	0.22	0.1%	0.0%	–$57	0.000	0.0%	–0.4%	–$14	0.059	0.2%

(continued)

Table 1-11: Croplands Mitigation Option Detail for Key Regions (continued)

	United States				EU-15				Brazil			
Croplands	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)
Reduce fertilizer to 80% of base—soybean–irri	–0.3%	–$45	0.02	0.0%	0.0%	–$46	0.000	0.0%	NA	NA	NA	NA
Reduce fertilizer to 90% of base—wheat–rf	–5.6%	$264	0.28	0.2%	–6.5%	$116	0.284	0.3%	–4.1%	$69	0.003	0.0%
Reduce fertilizer to 90% of base—wheat–irri	–5.4%	$275	0.02	0.0%	–6.5%	$174	0.090	0.1%	–4.1%	$74	0.000	0.0%
Reduce fertilizer to 90% of base—maize–rf	–7.9%	–$1,037	–0.22	–0.1%	–5.1%	$606	0.009	0.0%	–8.4%	$50	–0.035	–0.1%
Reduce fertilizer to 90% of base—maize–irri	–7.6%	–$759	–0.07	0.0%	–5.1%	–$941	–0.003	0.0%	NA	NA	NA	NA
Reduce fertilizer to 90% of base—soybean–rf	–0.2%	–$47	0.11	0.1%	0.0%	–$65	0.000	0.0%	–0.2%	–$15	0.029	0.1%
Reduce fertilizer to 90% of base—soybean–irri	–0.1%	–$46	0.01	0.0%	0.0%	–$40	0.000	0.0%	NA	NA	NA	NA
Convert coventional tillage to no-till—wheat–rf	1.5%	–$63	2.10	1.2%	1.2%	$17	–7.160	–7.7%	0.6%	–$24	0.015	0.0%
Convert coventional tillage to no-till—wheat–irri	0.9%	–$80	0.11	0.1%	0.3%	$12	–3.977	–4.3%	0.4%	–$24	0.000	0.0%
Convert coventional tillage to no-till—maize–rf	1.6%	–$87	4.14	2.3%	0.1%	$135	–0.221	–0.2%	0.5%	–$15	0.369	1.3%
Convert coventional tillage to no-till—maize–irri	0.9%	–$89	0.61	0.3%	–2.5%	$40	–0.137	–0.1%	NA	NA	NA	NA
Convert coventional tillage to no-till—soybean–rf	0.2%	–$154	1.37	0.8%	0.5%	–$317	0.005	0.0%	0.1%	–$103	0.237	0.8%
Convert coventional tillage to no-till—soybean–irri	0.3%	–$46	0.12	0.1%	0.6%	–$135	0.001	0.0%	NA	NA	NA	NA

EU-15 = European Union; NA = Data unavailable.

(continued)

Table 1-11: Croplands Mitigation Option Detail for Key Regions (continued)

	China				India			
Cropland	Change in Output Yield (% from baseline)	Breakeven Cost ($/tCO$_2$eq)	Emissions Reduction (Absolute, MtCO$_2$eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/tCO$_2$eq)	Emissions Reduction (Absolute, MtCO$_2$eq)	Emissions Reduction (% from baseline)
Nitrogen inhibitor—wheat–rf	5.0%	$58	0.282	0.3%	2.5%	$208	0.070	0.1%
Nitrogen inhibitor—wheat–irri	5.6%	$31	1.051	1.1%	3.9%	$84	0.519	0.8%
Nitrogen inhibitor—maize–rf	2.2%	$49	0.788	0.8%	26.0%	$9	2.513	3.6%
Nitrogen inhibitor—maize–irri	2.3%	$39	0.569	0.6%	24.2%	$10	0.694	1.0%
Nitrogen inhibitor—soybean–rf	0.3%	$175	0.074	0.1%	5.6%	$85	0.129	0.2%
Nitrogen inhibitor—soybean–irri	0.2%	$147	0.076	0.1%	5.4%	$94	0.010	0.0%
Split fertilization—wheat–rf	3.6%	–$1	0.102	0.1%	2.3%	$21	0.027	0.0%
Split fertilization—wheat–irri	4.1%	–$14	0.405	0.4%	3.6%	–$5	0.335	0.5%
Split fertilization—maize–rf	1.7%	$51	0.340	0.3%	12.7%	–$24	0.848	1.2%
Split fertilization—maize–irri	1.8%	$32	0.381	0.4%	12.7%	–$34	0.219	0.3%
Split fertilization—soybean–rf	0.3%	$534	0.018	0.0%	0.0%	$0	—	0.0%
Split fertilization—soybean–irri	0.3%	$449	0.025	0.0%	0.0%	$0	—	0.0%
Reduce fertilizer to 70% of base—wheat–rf	–11.5%	$30	0.321	0.3%	–8.6%	$7	0.193	0.3%
Reduce fertilizer to 70% of base—wheat–irri	–13.4%	$104	0.643	0.7%	–13.6%	$208	0.282	0.4%
Reduce fertilizer to 70% of base—maize–rf	–16.0%	–$226	–0.479	–0.5%	–7.9%	$41	0.255	0.4%
Reduce fertilizer to 70% of base—maize–irri	–15.7%	–$206	–0.424	–0.4%	–8.2%	$53	0.082	0.1%
Reduce fertilizer to 70% of base—soybean–rf	–0.4%	–$37	0.142	0.1%	0.0%	$0	—	0.0%
Reduce fertilizer to 70% of base—soybean–irri	–0.3%	–$39	0.118	0.1%	0.0%	$0	—	0.0%
Reduce fertilizer to 80% of base—wheat–rf	–7.5%	$29	0.217	0.2%	–5.6%	$6	0.129	0.2%
Reduce fertilizer to 80% of base—wheat–irri	–8.9%	$103	0.432	0.4%	–9.3%	$229	0.175	0.3%
Reduce fertilizer to 80% of base—maize–rf	–10.5%	–$249	–0.286	–0.3%	–5.3%	$43	0.167	0.2%
Reduce fertilizer to 80% of base—maize–irri	–10.5%	–$223	–0.262	–0.3%	–5.5%	$55	0.054	0.1%
Reduce fertilizer to 80% of base—soybean–rf	–0.3%	–$36	0.096	0.1%	0.0%	$0	—	0.0%
Reduce fertilizer to 80% of base—soybean–irri	–0.2%	–$38	0.080	0.1%	0.0%	$0	—	0.0%
Reduce fertilizer to 90% of base—wheat–rf	–3.8%	$28	0.110	0.1%	–2.8%	$6	0.065	0.1%
Reduce fertilizer to 90% of base—wheat–irri	–4.4%	$101	0.220	0.2%	–4.7%	$247	0.083	0.1%
Reduce fertilizer to 90% of base—maize–rf	–5.2%	–$276	–0.127	–0.1%	–2.7%	$45	0.081	0.1%
Reduce fertilizer to 90% of base—maize–irri	–5.2%	–$240	–0.121	–0.1%	–2.8%	$59	0.026	0.0%
Reduce fertilizer to 90% of base—soybean–rf	–0.1%	–$36	0.049	0.1%	0.0%	$0	—	0.0%
Reduce fertilizer to 90% of base—soybean–irri	–0.1%	–$38	0.040	0.0%	0.0%	$0	—	0.0%
Convert coventional tillage to no-till—wheat–rf	1.4%	–$65	0.283	0.3%	2.7%	–$29	0.150	0.2%
Convert coventional tillage to no-till—wheat–irri	2.0%	–$69	1.046	1.1%	5.5%	–$61	0.954	1.4%
Convert coventional tillage to no-till—maize–rf	1.4%	–$86	1.143	1.2%	2.7%	–$23	1.294	1.9%
Convert coventional tillage to no-till—maize–irri	1.3%	–$84	0.654	0.7%	2.0%	–$23	0.329	0.5%
Convert coventional tillage to no-till—soybean–rf	0.0%	–$168	0.152	0.2%	1.3%	–$70	0.131	0.2%
Convert coventional tillage to no-till—soybean–irri	0.0%	–$41	0.136	0.1%	1.3%	–$23	0.010	0.0%

EU-15 = European Union; NA = Data unavailable.

Table 1-12: Croplands: Percentage Reductions from Baselines at Different $/tCO$_2$eq Prices

	2010					2020				
Country/Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	11.1%	12.8%	13.9%	14.5%	14.5%	10.6%	13.5%	13.6%	14.0%	14.2%
Annex I	**20.6%**	**23.2%**	**29.7%**	**30.2%**	**30.9%**	**19.6%**	**20.7%**	**24.2%**	**28.6%**	**29.2%**
Australia/New Zealand	21.2%	21.2%	24.9%	34.7%	34.7%	21.9%	21.9%	26.1%	36.1%	36.1%
Brazil	5.3%	5.3%	13.3%	13.3%	13.3%	4.5%	4.5%	12.3%	12.4%	12.4%
China	6.4%	6.4%	6.7%	10.1%	12.7%	5.8%	6.3%	7.3%	10.5%	12.5%
Eastern Europe	14.6%	18.8%	21.0%	21.5%	24.1%	13.5%	17.9%	20.8%	20.8%	20.8%
EU-15	11.9%	12.7%	13.0%	13.7%	15.5%	10.8%	10.8%	11.4%	11.7%	13.8%
India	6.2%	11.4%	11.4%	12.0%	12.4%	5.8%	11.5%	11.5%	11.5%	11.5%
Japan	11.8%	11.8%	11.8%	11.8%	12.5%	11.0%	11.0%	11.0%	11.6%	11.6%
Mexico	10.8%	14.3%	23.4%	23.4%	23.4%	10.5%	23.2%	23.2%	23.2%	23.2%
Non-OECD Annex I	**28.3%**	**28.3%**	**47.8%**	**47.9%**	**48.3%**	**28.0%**	**28.0%**	**31.7%**	**47.5%**	**47.9%**
OECD	**18.0%**	**21.4%**	**23.8%**	**24.5%**	**25.0%**	**17.0%**	**18.7%**	**22.0%**	**22.9%**	**23.5%**
Russian Federation	28.3%	28.3%	47.8%	47.9%	48.3%	28.0%	28.0%	31.7%	47.5%	47.9%
South & SE Asia	8.1%	8.3%	9.6%	13.5%	14.4%	8.3%	8.4%	11.0%	14.0%	14.3%
United States	21.7%	25.9%	28.5%	28.5%	28.5%	20.3%	21.0%	26.5%	26.5%	26.5%
World Total	15.4%	17.6%	22.0%	23.1%	24.0%	14.6%	16.2%	18.8%	22.0%	22.7%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 1-7: Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, 2000–2020

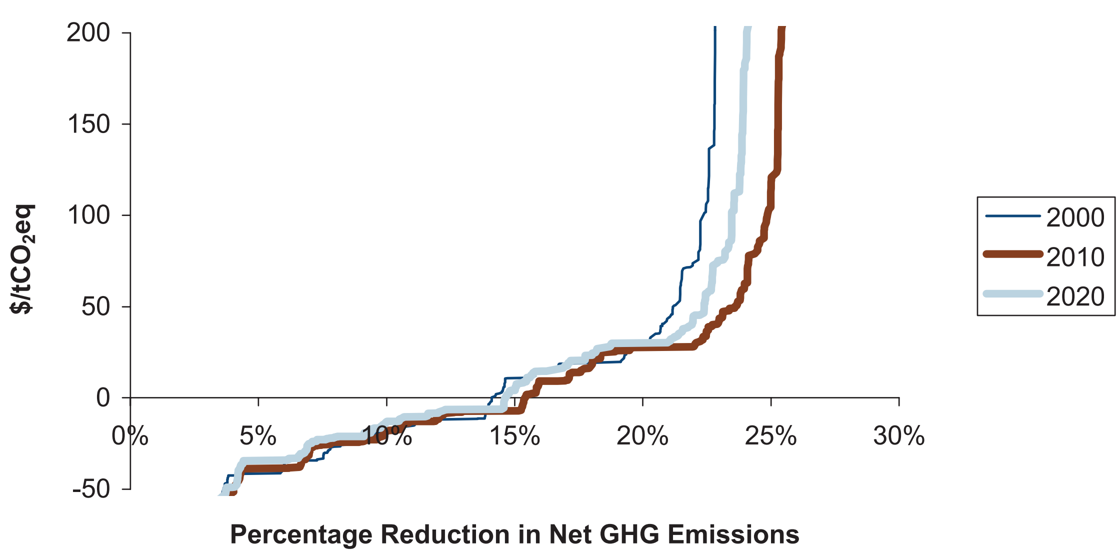
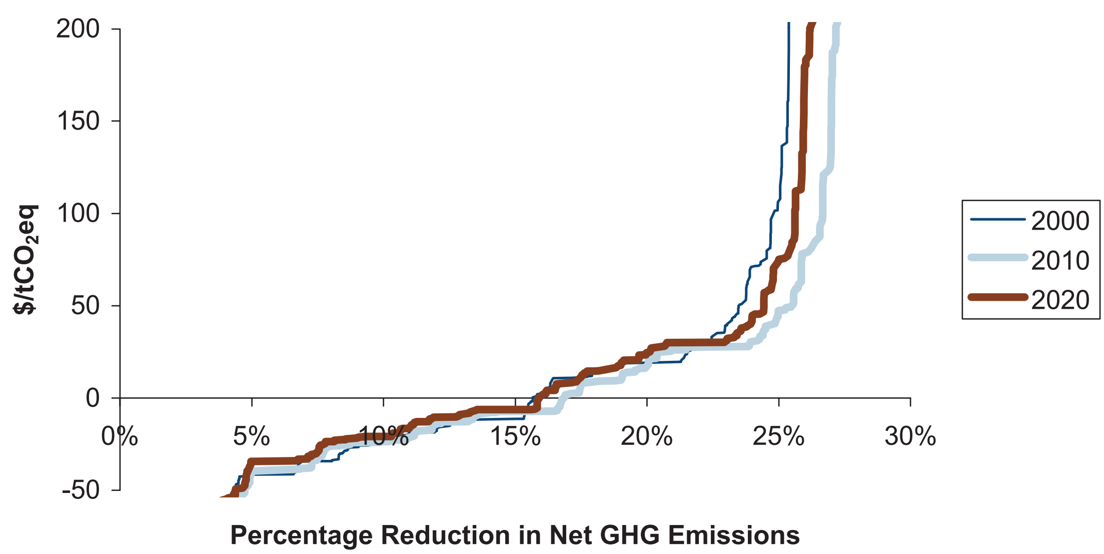


Figure 1-8 shows the sensitivity of the global cropland MAC when only the three options that were most effective at mitigating net GHGs (nitrogen inhibitors, split fertilization, and no till) are applied. The excluded options (reducing baseline levels of nitrogen fertilizer by varying amounts) had little impact on net emissions at the global scale. As expected, the MAC with only the three most effective options—where these options are each essentially applied to one-third of the cropland base—shows greater mitigation.

Figure 1-8: Global MAC for Net Greenhouse Gas Emissions from Croplands, Holding Area Constant, Allocating Adoption of Mitigation Strategies to the Three Most Effective Options Only, 2000–2020



Figures 1-9, 1-10, 1-11, and 1-12 show the MACs for four major regions of the world—the United States, EU-15, FSU, and China. Each of those figures show simulated mitigation potential assuming equal adoption of the six mitigation options included for croplands. If mitigation strategies were limited to the three most effective options for emissions reductions, excluding the fertilizer reduction options that have little to no impact on net greenhouse gas in our DAYCENT model runs, total mitigation potential would increase. This is analogous to the change at the global level, observed in Figures 1-7 and 1-8. Percentage emissions reductions vary substantially, from less than 15 percent for China up to almost 50 percent in FSU. Among these four regions, the FSU has the largest emissions reduction potential, followed closely by the United States: both have emissions reductions above 50 $MtCO_2eq$ at less than \$50/tCO_2eq. EU-15 and China have less than one-third of the emissions reductions of the FSU or United States, with potential reductions of 10 $MtCO_2eq$ to 15 $MtCO_2eq$ at \$50/tCO_2eq.

Figure 1-9: MAC for Net Greenhouse Gas Emissions from Cropland Management in the United States, Holding Area Constant, 2000–2020

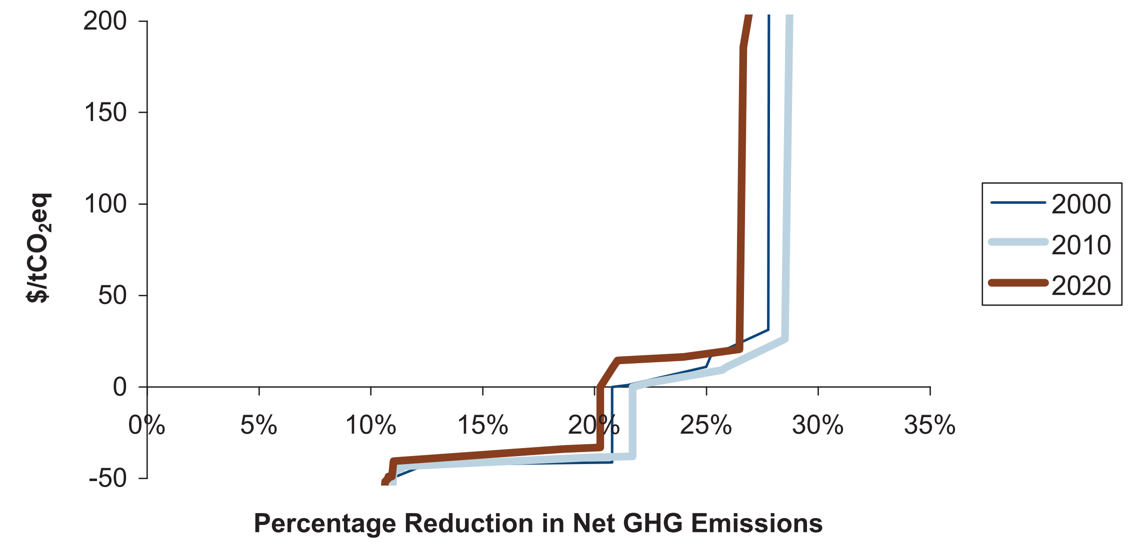


Figure 1-10: MAC for Net Greenhouse Gas Emissions from Cropland Management in the EU-15, Holding Area Constant, 2000–2020

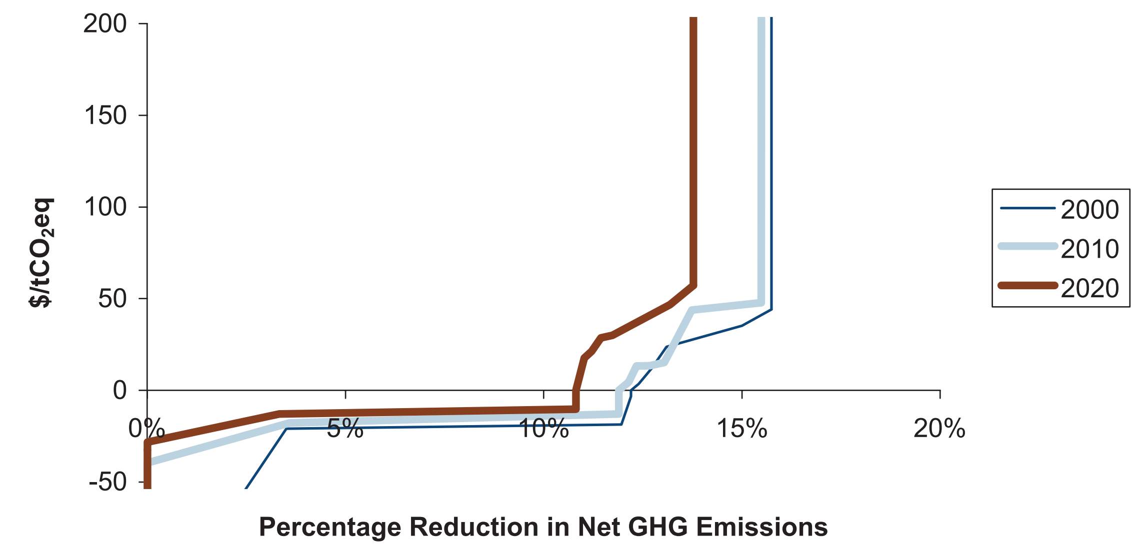


Figure 1-11: MAC for Net Greenhouse Gas Emissions from Cropland Management in the FSU, Holding Area Constant, 2000–2020

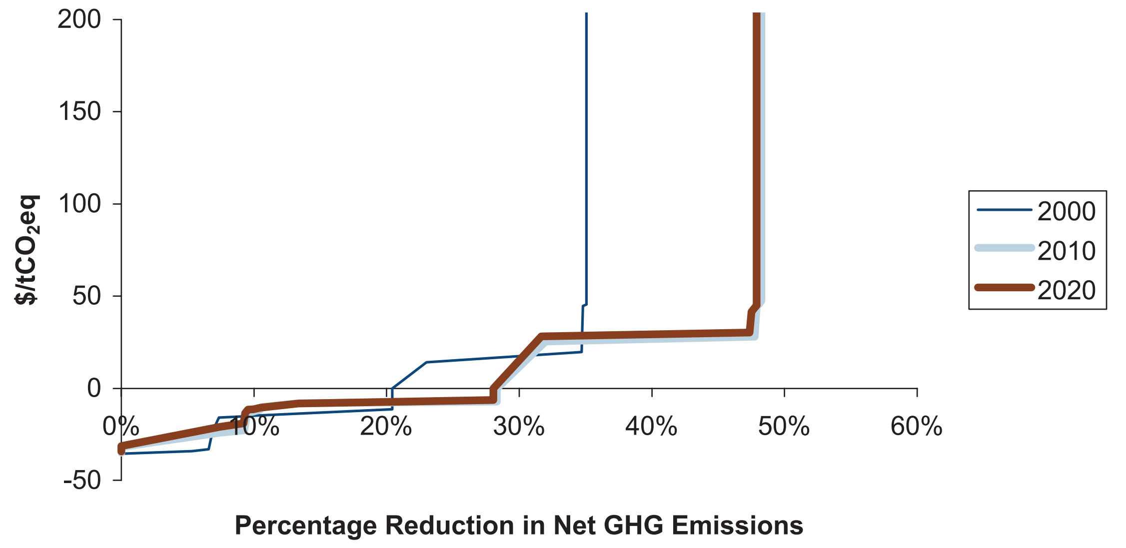
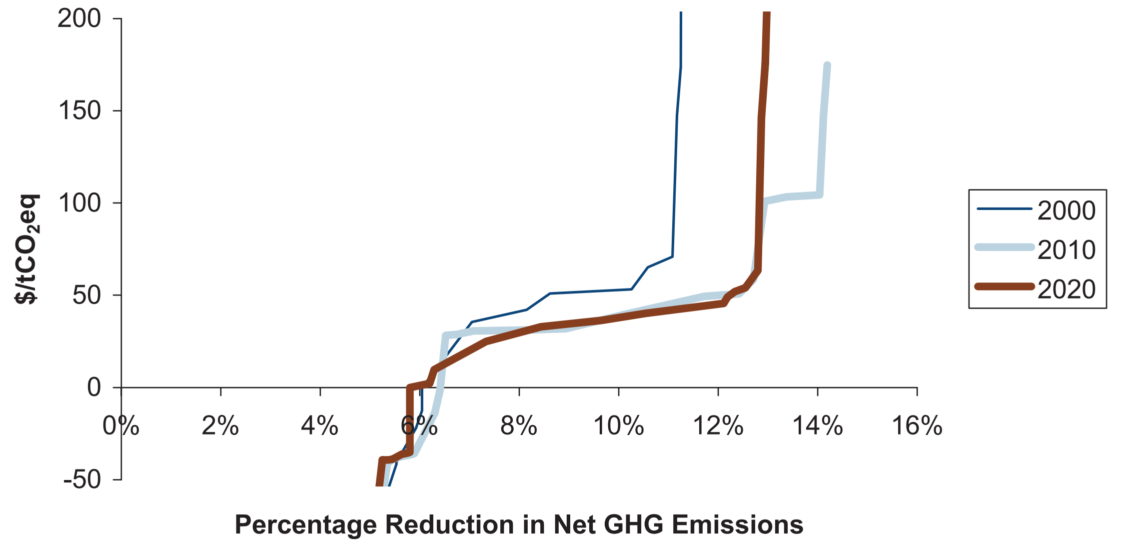


Figure 1-12: MAC for Net Greenhouse Gas Emissions from Cropland Management in China, Holding Area Constant, 2000–2020



V.3.3 Baselines, Mitigation Costs, and MACs for Rice Cultivation

Table 1-13 presents estimates of baseline net GHG emissions from rice cultivation by region by year used in this analysis. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-13: Baseline Emissions from Rice Cultivation from DNDC Estimates ($MtCO_2eq$)

Country/Region	2000	2010	2020
Africa	—	—	—
Annex I	**45**	**28**	**27**
Australia/New Zealand	—	—	—
Brazil	—	—	—
China	385	301	302
Eastern Europe	—	—	—
EU-15	—	—	—
India	127	111	122
Japan	45	28	27
Mexico	—	—	—
Non-OECD Annex I	**—**	**—**	**—**
OECD	**63**	**43**	**43**
Russian Federation	—	—	—
South & SE Asia	929	583	594
United States	—	—	—
World Total	**1,504**	**1,038**	**1,062**

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-14 presents information on the yield effects, emissions reductions, and costs associated with individual rice cultivation mitigation options for China and India.

Table 1-15 provides estimates of the percentage reduction in net GHG emissions (relative to the rice cultivation baseline used in this analysis) that could potentially be achieved at prices between $0/tCO_2eq and $60/tCO_2eq for both 2010 and 2020 in major regions around the world.

Figure 1-13 shows the MACs estimated for 2000, 2010, and 2020. This outward shift in the curve reflects changes in baseline emissions, commodity prices, labor rates, and other factors over time. Total global mitigation for rice CH_4 is estimated to be around 3 percent at negative or zero cost and about 13 percent at $45/tCO_2eq in 2000. After that level, costs rise very rapidly. By 2010, global mitigation is estimated to have increased to about 11 percent at negative or zero cost and 24 percent at $45/tCO_2eq. Between 2010 and 2020, there is little change in the MAC throughout most of its range.

Figures 1-14 and 1-15 display the MACs for the key rice-producing regions of India and China, respectively. In both regions, the percentage emissions reduction is higher in 2010 than in 2000, but the curve shifts inward in 2020. This is largely due to substantial changes in the baseline emissions over time that are changing the reductions in net GHG relative to baseline conditions available. For instance, baseline emissions from China are projected to decline substantially over time, leaving fewer emissions to be abated in future years. DNDC simulations project baseline emissions from rice cultivation in China to fall by 21.5 percent between 2000 and 2020, from 384.9 $MtCO_2eq$ in 2000 to 302.1 $MtCO_2eq$ by 2020.

Table 1-14: Rice Cultivation Mitigation Option Detail for Key Regions

	China				India			
Option Labels	Breakeven Cost ($\$tCO_2eq$)	Emission Reduction (absolute, $MtCO_2eq$)	Emission Reduction (1% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($\$tCO_2eq$)	Emission Reduction (absolute, $MtCO_2eq$)	Emission Reduction (1% from baseline)	Change in Output Yield (% from baseline)
Midseason drainage—rice(rf)	NA	NA	NA	NA	NA	NA	NA	NA
Midseason drainage—rice(irri)	3.2%	–$11.4	3.5	1.2%	0.7%	4	8.9	8.0%
Shallow flooding—rice(rf)	NA	NA	NA	NA	NA	NA	NA	NA
Shallow flooding—rice(irri)	5.5%	–$1.9	28.6	9.5%	0.3%	7	14.9	13.4%
Offseason straw—rice(rf)	NA	NA	NA	NA	0.0%	81	0.3	0.3%
Offseason straw—rice(irri)	2.1%	–$3.6	2.2	0.7%	0.0%	9	5.7	5.2%
Sulfate fertilizer—rice(rf)	NA	NA	NA	NA	0.0%	89	0.3	0.3%
Sulfate fertilizer—rice(irri)	1.8%	–$2.9	13.1	4.4%	–0.3%	19	2.0	1.8%
Slow-release fertilizers—rice(rf)	NA	NA	NA	NA	0.0%	248	0.3	0.2%
Slow-release fertilizer—rice(irri)	5.4%	$27.9	–2.3	–0.8%	–0.3%	–319	–0.3	–0.2%
Switch to upland rice—rice(rf)	NA	NA	NA	NA	6.1%	21	–3.9	–3.5%
Switch to upland rice—rice(irri)	–15.0%	$10.1	45.1	15.0%	–32.9%	62	15.7	14.1%

NA = Data unavailable.

Table 1-15: Rice Cultivation: Percentage Reductions from Baseline at Different $/tCO$_2$eq Prices

	2010					2020				
Country/Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Annex I	**1.6%**	**24.1%**	**24.1%**	**24.1%**	**24.1%**	**1.6%**	**24.4%**	**24.4%**	**24.4%**	**24.4%**
Australia/New Zealand	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Brazil	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
China	15.8%	30.8%	30.0%	30.0%	30.0%	13.1%	26.3%	27.0%	27.0%	27.0%
Eastern Europe	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
EU-15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
India	–0.2%	26.4%	24.7%	24.7%	24.7%	–0.3%	25.9%	25.9%	25.9%	25.9%
Japan	1.6%	24.1%	24.1%	24.1%	24.1%	1.6%	24.4%	24.4%	24.4%	24.4%
Mexico	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Non-OECD Annex I	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**	**NA**
OECD	**4.0%**	**19.5%**	**24.8%**	**24.8%**	**24.8%**	**4.4%**	**25.0%**	**25.0%**	**25.0%**	**25.0%**
Russian Federation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
South & SE Asia	10.4%	16.6%	16.8%	20.7%	22.3%	12.1%	19.1%	19.1%	22.7%	22.7%
United States	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
World Total	10.5%	21.9%	21.8%	24.0%	24.9%	10.7%	22.1%	22.4%	24.4%	24.4%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development; NA = Data unavailable.

Figure 1-13: Global MAC for Net Greenhouse Gas Emissions from Rice Cultivation, Holding Area Constant, 2000–2020

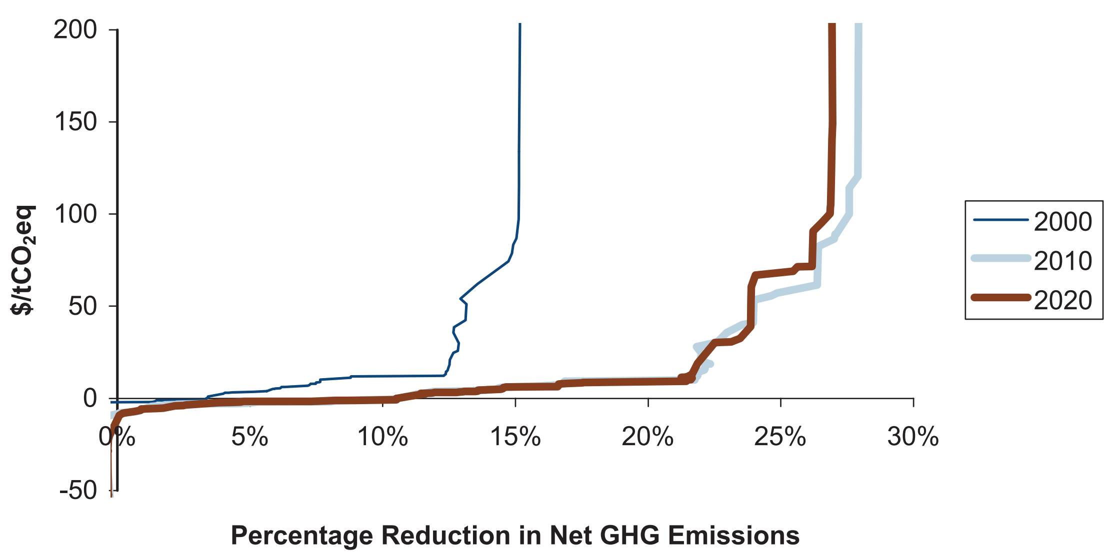


Figure 1-14: MAC for Net Greenhouse Gas Emissions from Rice Cultivation in India, Holding Area Constant, 2000–2020

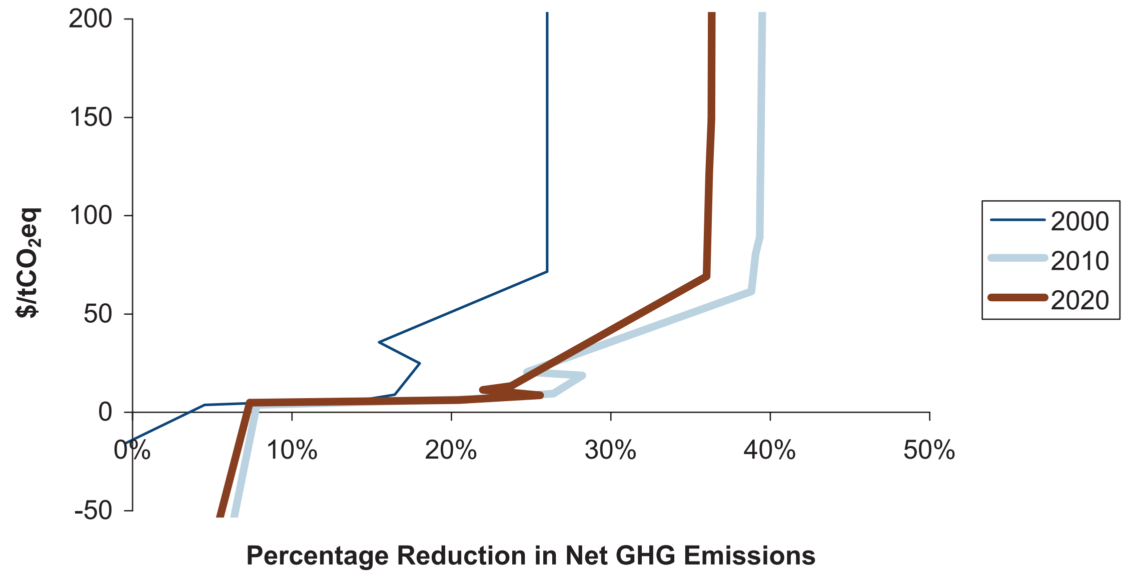
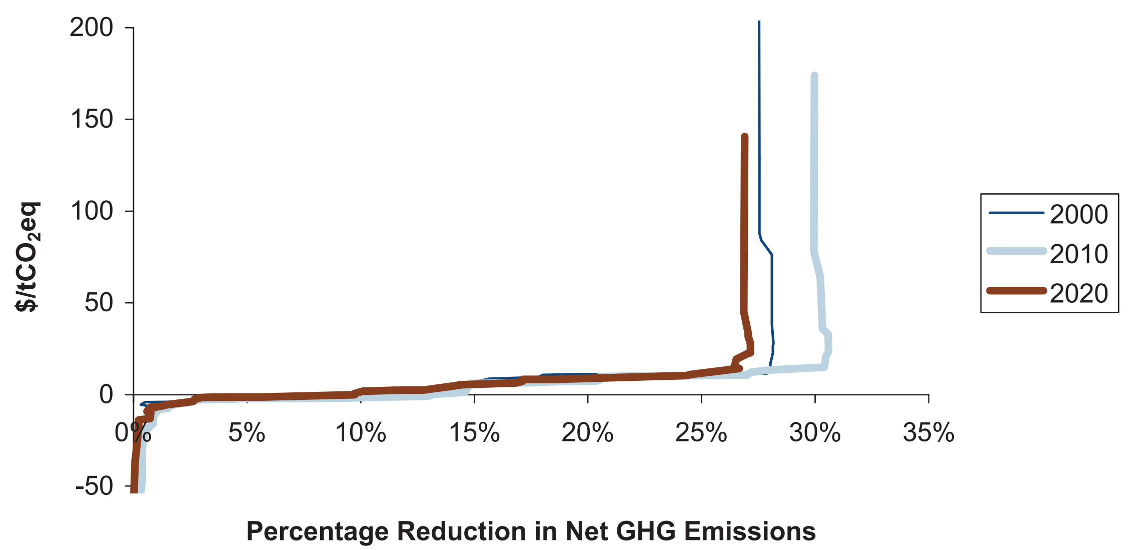


Figure 1-15: MAC for Net Greenhouse Gas Emissions from Rice Cultivation in China, Holding Area Constant, 2000–2020



V.3.4 Baselines, Mitigation Costs, and MACs for Livestock Management

Table 1-16 presents estimates of baseline net GHG emissions from livestock enteric fermentation and manure management by region and by year. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-17 presents information on the yield effects, emissions reductions, and costs associated with individual livestock management mitigation options for the USA, EU-15, Brazil, China, and India.

Table 1-16: Baseline Emissions from Livestock Management from USEPA (2006) ($MtCO_2eq$)

Country/Region	2000	2010	2020
Africa	271	332	395
Annex I	**704**	**718**	**748**
Australia/New Zealand	91	93	94
Brazil	222	263	297
China	313	392	470
Eastern Europe	48	54	58
EU-15	222	203	202
India	224	260	286
Japan	20	21	22
Mexico	43	50	57
Non-OECD Annex I	**111**	**131**	**150**
OECD	**642**	**644**	**663**
Russian Federation	66	78	91
South & SE Asia	187	232	276
United States	171	173	171
World Total	**2,220**	**2,548**	**2,867**

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Table 1-17: Livestock Mitigation Option Detail for Key Regions

	United States				EU-15				Brazil			
Livestock	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)
Improved feed conversion—beef	0.2%	–$1,126	–0.2	–0.1%	7.7%	$238	–0.1	–0.1%	2.5%	$102	1.3	0.5%
Improved feed conversion—dairy	0.0%	–$655	–0.7	–0.4%	0.0%	$5,335	0.1	0.0%	87.9%	$187	–2.6	–1.0%
Antibiotics—beef	5.0%	–$265	0.5	0.3%	5.0%	–$121	0.7	0.4%	5.0%	–$31	0.9	0.3%
bST—dairy	11.2%	$888	–0.1	–0.1%	12.5%	–$5,597	0.0	0.0%	12.5%	–$1,097	–0.6	–0.2%
Propionate precursors—beef	5.0%	$89	1.6	1.0%	5.0%	$81	1.2	0.6%	5.0%	$50	4.0	1.5%
Propionate precursors—dairy	5.0%	–$68	1.4	0.8%	5.0%	$183	2.1	1.0%	5.0%	$322	1.6	0.6%
Antimethanogen—beef	5.0%	–$60	1.6	1.0%	5.0%	–$53	1.2	0.6%	5.0%	$0	4.0	1.5%
Antimethanogen—sheep & goats	5.0%	$184	0.1	0.1%	5.0%	$327	1.5	0.8%	5.0%	$131	0.4	0.2%
Antimethanogen—dairy	5.0%	–$430	0.5	0.3%	5.0%	–$288	0.8	0.4%	5.0%	$20	0.7	0.3%
Intensive grazing—beef	0.0%	–$70	2.2	1.3%	0.0%	$24	1.7	0.8%	0.0%	–$14	5.4	2.1%
Intensive grazing—dairy	–11.2%	$371	0.8	0.5%	–11.2%	$725	1.3	0.6%	–11.2%	$78	1.0	0.4%
Complete-mix digester with engine—hogs	0.0%	$25	2.5	1.4%	0.0%	$7	3.9	1.9%	NA	NA	NA	NA
Complete-mix digester with engine—dairy	0.0%	$12	1.7	1.0%	0.0%	–$21	1.4	0.7%	NA	NA	NA	NA
Plug-flow digester with engine—dairy	0.0%	$8	1.7	1.0%	0.0%	–$40	1.4	0.7%	NA	NA	NA	NA
Fixed-film digester with engine—hogs	0.0%	$31	2.5	1.4%	0.0%	$15	3.9	1.9%	NA	NA	NA	NA
Fixed-film digester with engine—dairy	0.0%	$16	1.7	1.0%	0.0%	–$2	1.4	0.7%	NA	NA	NA	NA
Complete-mix digester without engine—hogs	0.0%	$39	2.5	1.4%	0.0%	$46	3.9	1.9%	NA	NA	NA	NA
Complete-mix digester without engine—dairy	0.0%	$23	1.7	1.0%	0.0%	$115	1.4	0.7%	NA	NA	NA	NA
Plug-flow digester without engine—dairy	0.0%	$20	1.7	1.0%	0.0%	$103	1.4	0.7%	NA	NA	NA	NA
Fixed-film digester without engine—hogs	0.0%	$43	2.5	1.4%	0.0%	$51	3.9	1.9%	NA	NA	NA	NA
Fixed-film digester without engine—dairy	0.0%	$25	1.7	1.0%	0.0%	$127	1.4	0.7%	NA	NA	NA	NA
Covered lagoon with engine—hogs	0.0%	–$7	2.5	1.4%	0.0%	–$30	3.9	1.9%	0.0%	–$101	0.2	0.1%
Covered lagoon with engine—dairy	0.0%	$5	1.7	1.0%	0.0%	–$59	1.4	0.7%	0.0%	–$447	0.2	0.1%

(continued)

Table 1-17: Livestock Mitigation Option Detail for Key Regions (continued)

	United States				EU-15				Brazil			
Livestock	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/t$CO_2$eq)	Emissions Reduction (Absolute, MtCO_2eq)	Emissions Reduction (% from baseline)
Covered lagoon without engine—hogs	0.0%	$18	2.5	1.4%	0.0%	$22	3.9	1.9%	0.0%	$23	0.2	0.1%
Covered lagoon without engine—dairy	0.0%	$18	1.7	1.0%	0.0%	$90	1.4	0.7%	0.0%	$402	0.2	0.1%
Domes cook fuel, light—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$135	0.1	0.0%
Domes cook fuel, light—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$2,145	0.1	0.1%
Polyethylene bags cook fuel, light—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$92	0.1	0.0%
Polyethylene bags cook fuel, light—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$553	0.1	0.1%
Covered lagoon cook fuel, light, shaft power—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$77	0.1	0.0%
Covered lagoon cook fuel, light, shaft power—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$345	0.1	0.1%
Flexible bag (pilot)—hogs	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$70	0.1	0.0%
Flexible bag (pilot)—dairy	NA	NA	NA	NA	NA	NA	NA	NA	0.0%	–$251	0.1	0.1%

EU-15 = European Union; NA = Data unavailable.

(continued)

Table 1-17: Livestock Mitigation Option Detail for Key Regions (continued)

	China				India			
Livestock	Change in Output Yield (% from baseline)	Breakeven Cost ($/tCO$_2$eq)	Emissions Reduction (Absolute, MtCO$_2$eq)	Emissions Reduction (% from baseline)	Change in Output Yield (% from baseline)	Breakeven Cost ($/tCO$_2$eq)	Emissions Reduction (Absolute, MtCO$_2$eq)	Emissions Reduction (% from baseline)
Improved feed conversion—beef	46.6%	–$143	2.9	0.7%	69.0%	–$382	0.7	0.3%
Improved feed conversion—dairy	6.2%	$567	0.6	0.1%	16.9%	$62	1.3	0.5%
Antibiotics—beef	5.0%	–$41	0.6	0.1%	5.0%	–$8	0.2	0.1%
bST—dairy	12.5%	–$5,807	–0.2	–0.1%	12.5%	–$6,438	–0.4	–0.2%
Propionate precursors—beef	5.0%	$82	4.0	1.0%	5.0%	$126	2.2	0.8%
Propionate precursors—dairy	5.0%	$1,668	0.6	0.2%	5.0%	$1,258	2.0	0.8%
Antimethanogen—beef	5.0%	$5	4.0	1.0%	5.0%	$15	2.2	0.8%
Antimethanogen—sheep & goats	5.0%	$229	5.0	1.3%	5.0%	$322	1.7	0.7%
Antimethanogen—dairy	5.0%	$205	0.2	0.1%	5.0%	$29	0.8	0.3%
Intensive grazing—beef	NA	NA	NA	NA	NA	NA	NA	NA
Intensive grazing—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Complete-mix digester with engine—hogs	0.0%	$13	1.3	0.3%	NA	NA	NA	NA
Complete-mix digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Plug-flow digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Fixed-film digester with engine—hogs	0.0%	$27	1.3	0.3%	NA	NA	NA	NA
Fixed-film digester with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Complete-mix digester without engine—hogs	0.0%	$94	1.3	0.3%	NA	NA	NA	NA
Complete-mix digester without engine—dairy	0.0%	$956	0.1	0.0%	NA	NA	NA	NA
Plug-flow digester without engine—dairy	0.0%	$851	0.1	0.0%	NA	NA	NA	NA
Fixed-film digester without engine—hogs	0.0%	$103	1.3	0.3%	NA	NA	NA	NA
Fixed-film digester without engine—dairy	0.0%	$1,062	0.1	0.0%	NA	NA	NA	NA
Covered lagoon with engine—hogs	0.0%	–$55	1.3	0.3%	NA	NA	NA	NA
Covered lagoon with engine—dairy	NA	NA	NA	NA	NA	NA	NA	NA
Covered lagoon without engine—hogs	0.0%	$50	1.3	0.3%	0.0%	$11	0.3	0.1%
Covered lagoon without engine—dairy	0.0%	$745	0.1	0.0%	0.0%	$448	0.7	0.3%
Domes cook fuel, light—hogs	0.0%	–$101	0.8	0.2%	0.0%	–$105	0.2	0.1%
Domes cook fuel, light—dairy	0.0%	–$1,968	0.1	0.0%	0.0%	–$4,508	0.4	0.2%
Polyethylene bags cook fuel, light—hogs	0.0%	–$68	0.8	0.2%	0.0%	–$74	0.2	0.1%
Polyethylene bags cook fuel, light—dairy	0.0%	–$469	0.1	0.0%	0.0%	–$1,165	0.4	0.2%
Covered lagoon cook fuel, light, shaft power—hogs	0.0%	–$36	0.8	0.2%	0.0%	–$65	0.2	0.1%
Covered lagoon cook fuel, light, shaft power—dairy	0.0%	–$85	0.1	0.0%	0.0%	–$936	0.4	0.2%
Flexible bag (pilot)—hogs	0.0%	–$21	0.8	0.2%	0.0%	–$61	0.2	0.1%
Flexible bag (pilot)—dairy	0.0%	$89	0.1	0.0%	0.0%	–$832	0.4	0.2%

EU-15 = European Union; NA = Data unavailable.

Table 1-18 provides estimates of the percentage reduction in net GHG emissions (relative to the livestock emissions baseline used in this analysis) that could potentially be achieved at prices between \$0/tCO_2eq and \$60/tCO_2eq for both 2010 and 2020 in major regions around the world.

Table 1-18: Livestock Management: Percentage Reductions from Baselines at Different \$/tCO_2eq Prices

	2010					2020				
Country/Region	**\$0**	**\$15**	**\$30**	**\$45**	**\$60**	**\$0**	**\$15**	**\$30**	**\$45**	**\$60**
Africa	0.7%	2.1%	2.6%	3.5%	3.6%	0.5%	2.1%	2.6%	3.5%	3.6%
Annex I	**5.0%**	**6.9%**	**10.1%**	**11.3%**	**12.5%**	**4.9%**	**7.4%**	**10.3%**	**11.9%**	**12.7%**
Australia/New Zealand	4.1%	4.3%	6.8%	7.5%	8.4%	4.2%	4.6%	7.2%	7.7%	8.7%
Brazil	2.9%	4.5%	4.9%	4.9%	6.5%	2.9%	4.5%	4.9%	4.9%	6.5%
China	2.0%	3.4%	3.7%	3.7%	4.1%	2.0%	3.4%	3.7%	3.7%	4.0%
Eastern Europe	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	2.7%	3.5%
EU-15	**6.3%**	**10.1%**	**13.0%**	**13.0%**	**16.9%**	**6.4%**	**10.3%**	**12.2%**	**15.2%**	**17.1%**
India	1.2%	2.1%	2.5%	2.5%	2.5%	1.2%	2.5%	2.5%	2.5%	2.5%
Japan	4.0%	4.0%	4.4%	4.4%	4.4%	4.1%	4.1%	4.1%	4.4%	4.4%
Mexico	3.3%	3.3%	3.3%	3.4%	3.4%	3.3%	3.3%	3.3%	3.4%	3.4%
Non-OECD Annex I	**2.5%**	**2.5%**	**2.5%**	**2.5%**	**2.5%**	**2.4%**	**2.4%**	**2.4%**	**2.4%**	**3.0%**
OECD	**5.4%**	**7.4%**	**11.1%**	**12.5%**	**13.8%**	**5.3%**	**8.1%**	**11.4%**	**13.3%**	**14.0%**
Russian Federation	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.4%	2.9%
South & SE Asia	3.9%	5.3%	6.1%	6.2%	6.6%	3.5%	4.6%	6.0%	6.0%	6.5%
United States	6.4%	9.4%	17.2%	21.4%	21.4%	6.3%	11.8%	19.8%	23.0%	23.0%
World Total	3.0%	4.4%	5.6%	6.1%	6.8%	2.9%	4.4%	5.5%	6.1%	6.7%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Total global mitigation for livestock management in 2020, holding the number of animals constant, is estimated to be 3 percent at negative or zero cost, reaching about 7 percent at \$60/tCO_2eq (Figure 1-16). Figure 1-17 shows the global MAC, holding production constant. The percentage of baseline emissions mitigated at \$60/tCO_2eq increases from just under 7 percent with a constant number of animals to over 10 percent with constant production. If other greenhouse gas benefits were included (e.g., soil carbon increases, cropland N_2O reductions for less feed), the estimates of greenhouse gas mitigation would be higher, but no model was identified to allow estimation of multigas impacts for livestock analogous to the DNDC and DAYCENT models used for cropland management and rice cultivation.

Figures 1-18, 1-19, 1-20, and 1-21 show the MACs for mitigation of greenhouse gas emissions from livestock management for the United States, China, India, and Brazil, respectively, holding the number of animals constant. Among these four regions, the United States has the greatest potential for relatively low-cost reductions in emissions in this sector, followed by China, Brazil, and India.

Because some options for mitigating emissions from enteric fermentation rely on improvements in yield resulting in fewer animals to achieve emissions reductions, assumptions about changes in livestock populations and production are important to examine for this sector. Thus, MACs are presented for the United States, China, India, and Brazil, assuming that production remains constant (Figures 1-22, 1-23, 1-24, and 1-25) to show the impact of this assumption. The differences between the two sets of graphs

Figure 1-16: Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Number of Animals Constant, 2000–2020

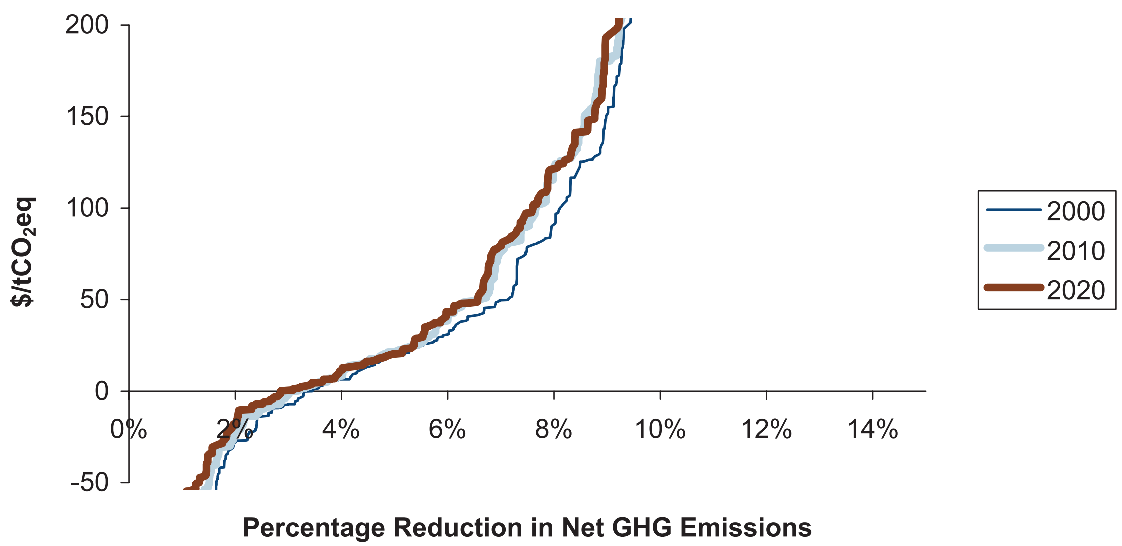


Figure 1-17: Global MAC for Greenhouse Gas Emissions from Livestock Management, Holding Production Constant, 2000–2020

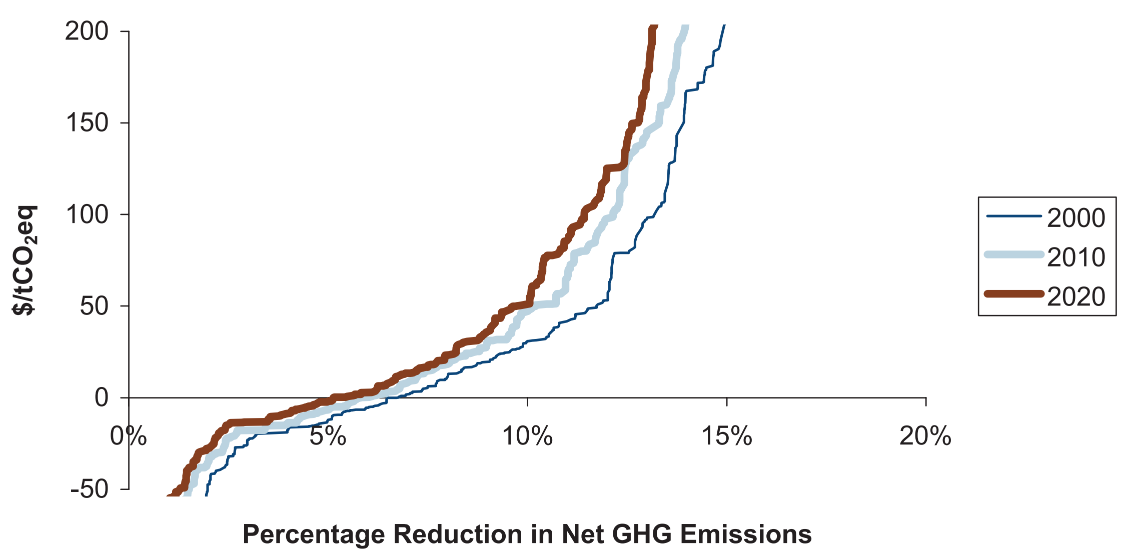


Figure 1-18: MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Number of Animals Constant, 2000–2020

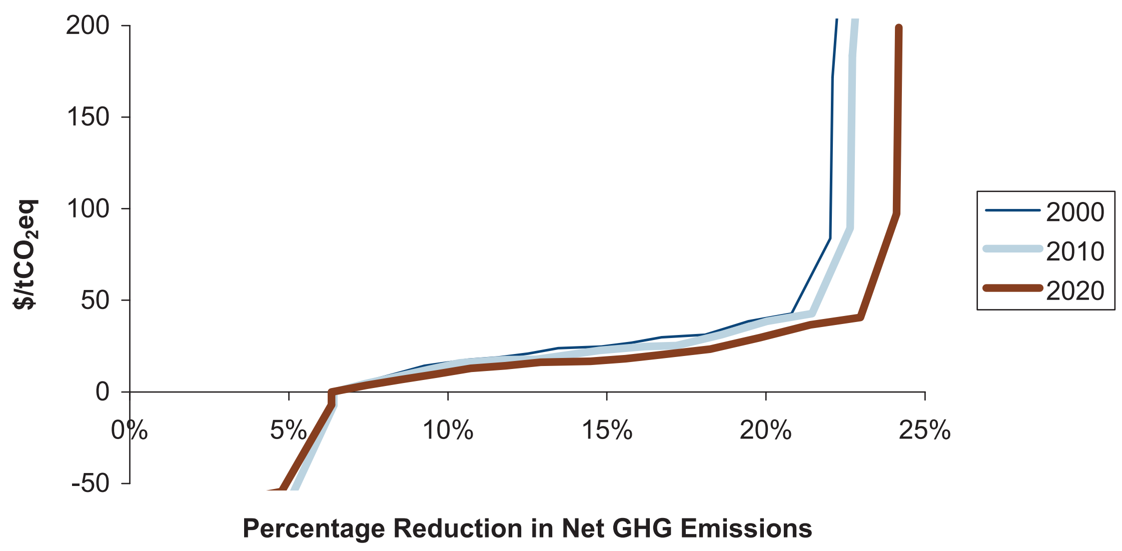


Figure 1-19: MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Number of Animals Constant, 2000–2020

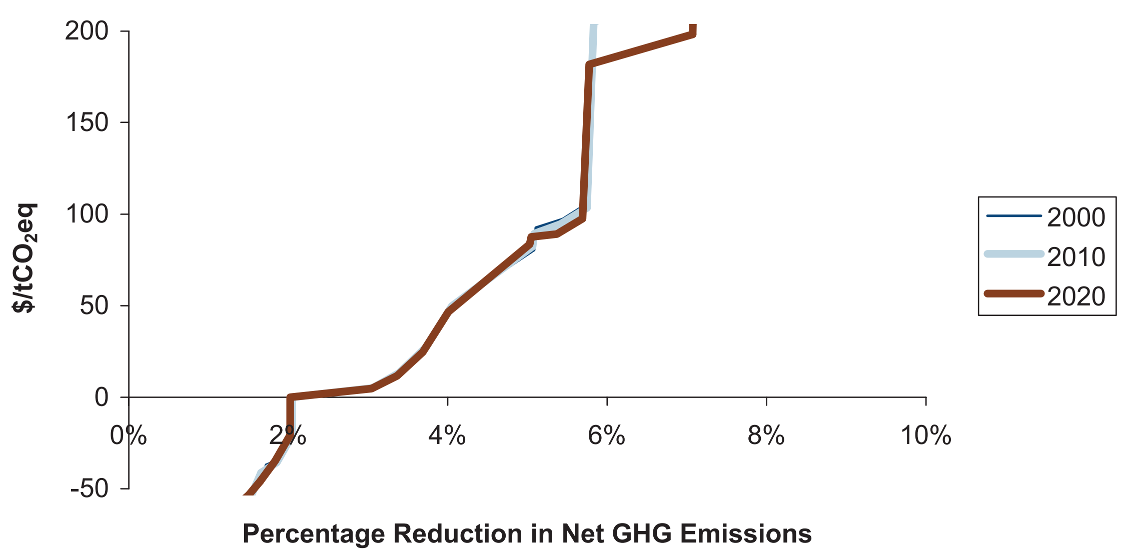


Figure 1-20: MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Number of Animals Constant, 2000–2020

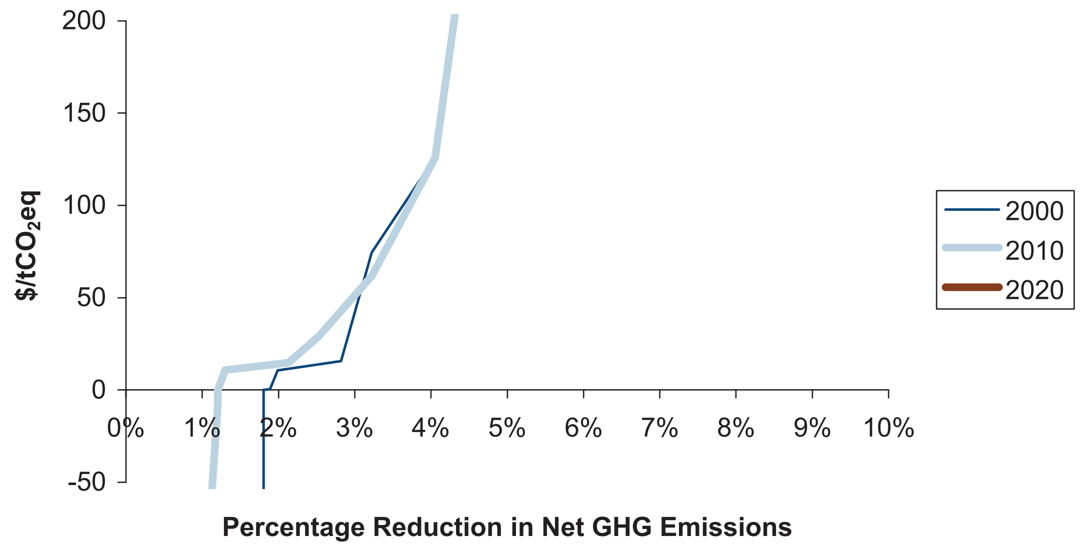


Figure 1-21: MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Number of Animals Constant, 2000–2020

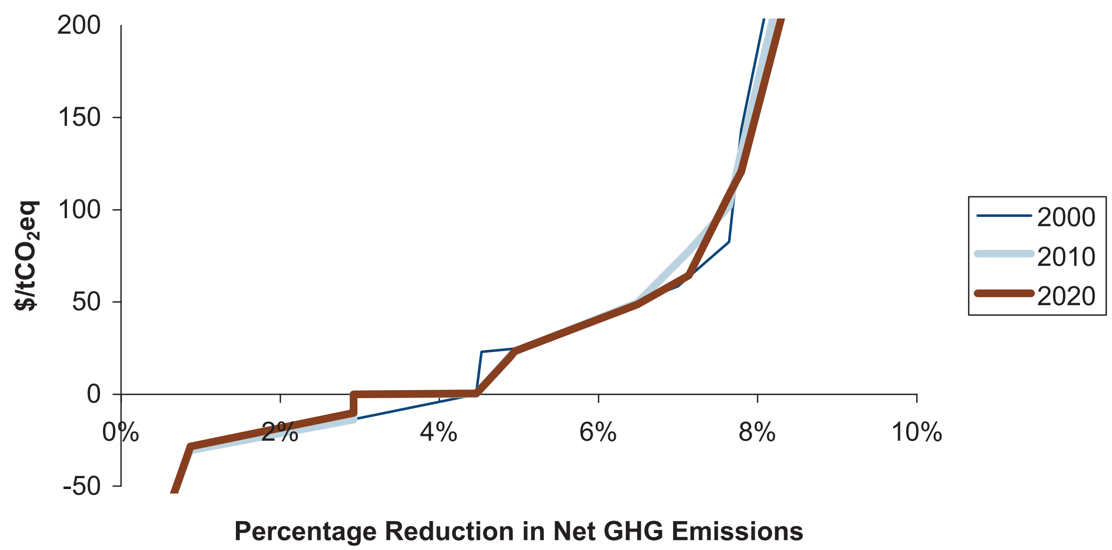


Figure 1-22: MAC for Greenhouse Gas Emissions from Livestock Management in the United States, Holding Production Constant, 2000–2020

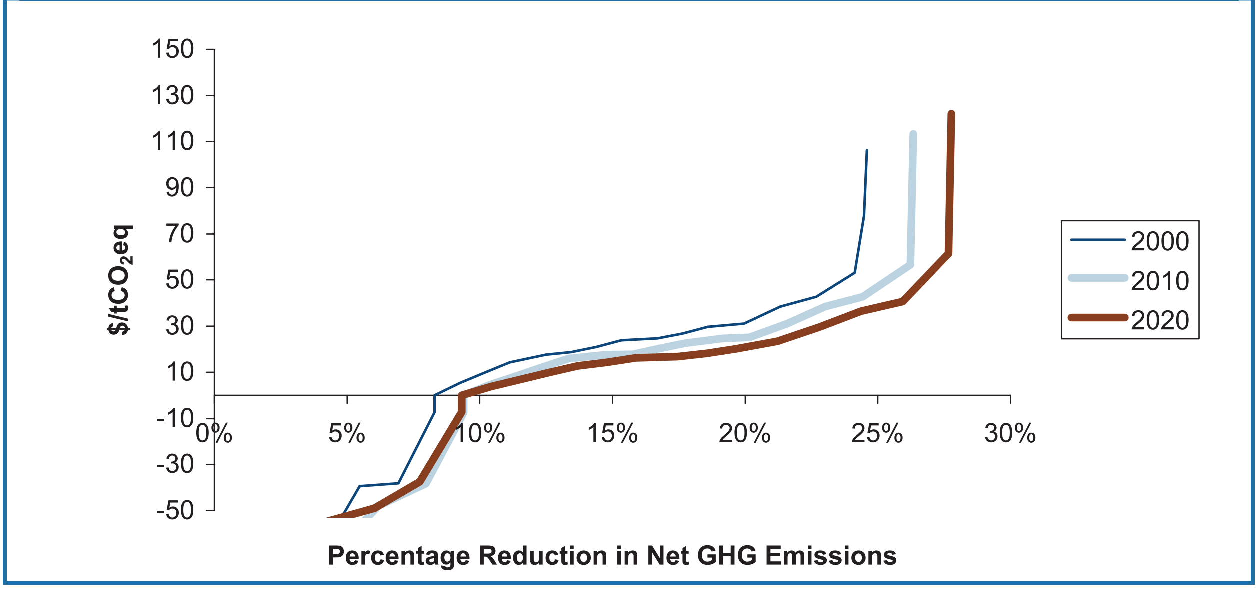


Figure 1-23: MAC for Greenhouse Gas Emissions from Livestock Management in China, Holding Production Constant, 2000–2020

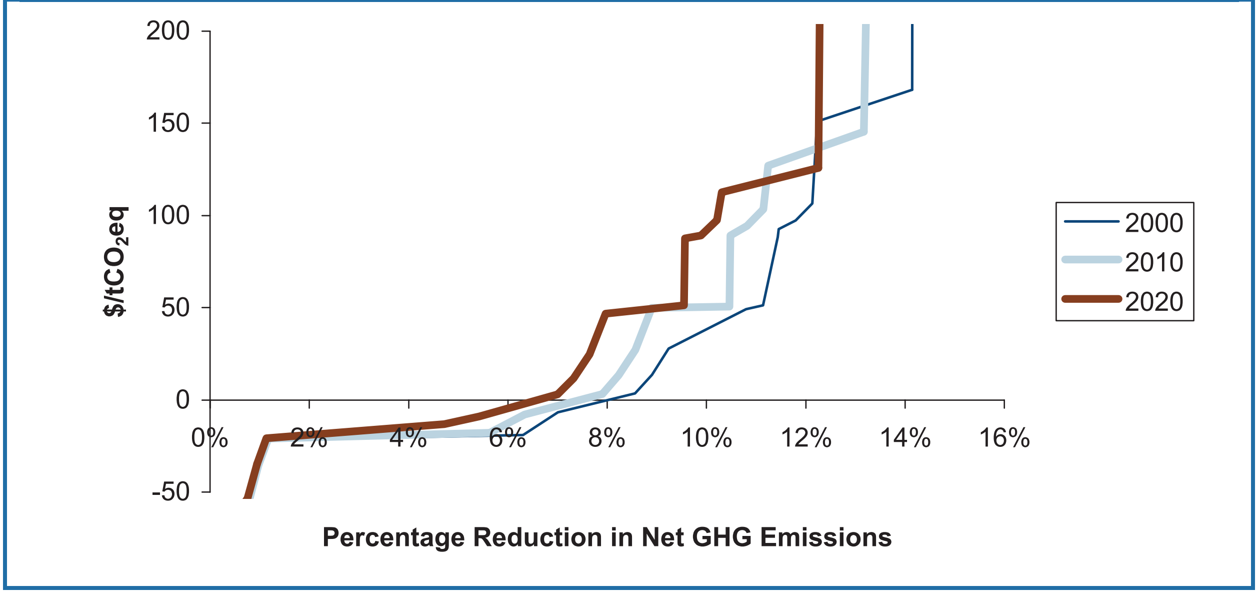


Figure 1-24: MAC for Greenhouse Gas Emissions from Livestock Management in India, Holding Production Constant, 2000–2020

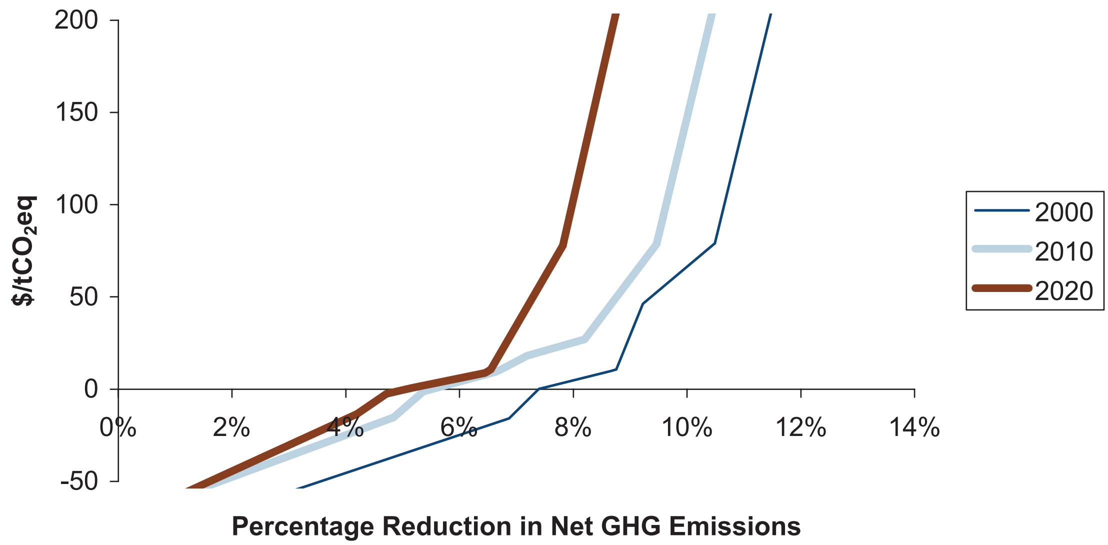
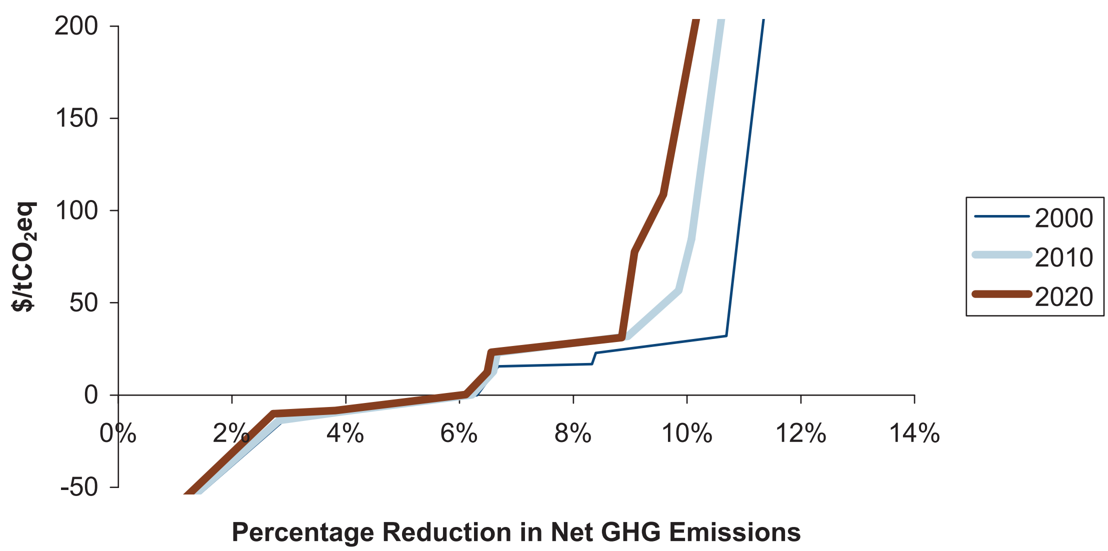


Figure 1-25: MAC for Greenhouse Gas Emissions from Livestock Management in Brazil, Holding Production Constant, 2000–2020



reveal the importance of this assumption, because total mitigation is substantially larger at any given price when production is assumed to remain constant. For those options that increase yields, constant production can be maintained while reducing the number of livestock by an amount corresponding to the increase in productivity. These reductions in the number of livestock can have a sizable impact on emissions. With an assumption that the number of animals remains constant, emissions tend to fall less because the reductions in emissions only come from the change in emissions per animal with no change in emissions due to a change in population. Some mitigation options even increase net greenhouse gas emissions per animal but increase productivity by an even greater proportion, leading to lower emissions per unit of output. If a constant number of animals is assumed, however, then these options will lead to an increase in emissions.

V.3.5 Baselines, Mitigation Costs, and MACs for Total Agriculture

Table 1-19 presents estimates of baseline net GHG emissions from agriculture, aggregated across croplands management, rice cultivation, and livestock management by region by year used in this analysis. These are the values to which all estimated percentage reductions in emissions were applied.

Table 1-19: Baseline Emissions from All Agriculture Used in This Report ($MtCO_2eq$)

Country/Region	2000	2010	2020
Africa	301	364	431
Annex I	**1,258**	**1,230**	**1,297**
Australia/New Zealand	104	109	111
Brazil	249	292	327
China	789	791	876
Eastern Europe	86	93	99
EU-15	313	296	303
India	417	441	480
Japan	65	49	50
Mexico	57	67	85
Non-OECD Annex I	**282**	**254**	**274**
OECD	**1,018**	**1,026**	**1,080**
Russian Federation	237	201	215
South & SE Asia	1,141	842	898
United States	338	351	370
World Total	**4,563**	**4,417**	**4,822**

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.
Note: These emissions reflect the baseline emissions used in calculating agricultural mitigation.

Table 1-20 provides estimates of the percentage reduction in net GHG emissions (relative to the aggregated agricultural emissions baseline used in this analysis) that could potentially be achieved at prices between $0/$tCO_2$eq and $60/$tCO_2$eq for both 2010 and 2020 in major regions around the world.

Figures 1-26 and 1-27 present MACs for global agriculture, aggregated across croplands management, rice cultivation, and livestock management, for assumptions of constant area and number of animals and constant production, respectively.

Table 1-20: Total Agriculture: Percentage Reductions from Baseline at Different $/tCO_2$eq Prices

	2010					2020				
Country/Region	**$0**	**$15**	**$30**	**$45**	**$60**	**$0**	**$15**	**$30**	**$45**	**$60**
Africa	1.6%	3.1%	3.6%	4.5%	4.5%	1.4%	3.0%	3.5%	4.4%	4.4%
Annex I	**11.1%**	**13.7%**	**18.1%**	**19.1%**	**20.0%**	**10.8%**	**13.1%**	**16.2%**	**18.9%**	**19.6%**
Australia/New Zealand	6.7%	6.9%	9.5%	11.6%	12.4%	6.9%	7.3%	10.2%	12.1%	12.9%
Brazil	3.2%	4.5%	5.8%	5.8%	7.2%	3.1%	4.5%	5.6%	5.6%	7.0%
China	7.8%	14.2%	14.1%	14.5%	15.0%	6.3%	11.6%	12.1%	12.5%	12.9%
Eastern Europe	7.7%	9.5%	10.4%	10.7%	11.7%	7.2%	9.0%	10.3%	10.3%	10.7%
EU-15	**8.1%**	**10.9%**	**13.0%**	**13.3%**	**16.4%**	**7.9%**	**10.5%**	**12.0%**	**14.0%**	**16.0%**
India	1.6%	9.7%	9.5%	9.6%	9.7%	1.5%	9.3%	9.3%	9.3%	9.3%
Japan	2.7%	15.5%	15.6%	15.6%	15.6%	2.8%	15.5%	15.5%	15.7%	15.7%
Mexico	5.2%	6.0%	8.3%	8.3%	8.3%	5.0%	8.0%	8.0%	8.0%	8.0%
Non-OECD Annex I	**15.0%**	**15.0%**	**24.4%**	**24.5%**	**24.7%**	**14.0%**	**14.0%**	**15.7%**	**22.9%**	**23.3%**
OECD	**9.5%**	**12.5%**	**15.8%**	**16.9%**	**17.9%**	**9.3%**	**12.4%**	**15.6%**	**17.0%**	**17.7%**
Russian Federation	18.2%	18.2%	30.1%	30.2%	30.4%	17.2%	17.2%	19.3%	28.4%	28.9%
South & SE Asia	8.5%	13.3%	13.7%	16.4%	17.7%	9.2%	14.1%	14.6%	17.0%	17.2%
United States	14.2%	17.8%	22.9%	25.0%	25.0%	13.8%	16.8%	23.4%	24.9%	24.9%
World Total	7.1%	11.0%	12.5%	13.5%	14.3%	6.7%	10.4%	11.6%	13.0%	13.4%

EU-15 = European Union; OECD = Organisation for Economic Co-operation and Development.

Figure 1-26: Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Area/Animals Constant, 2000–2020

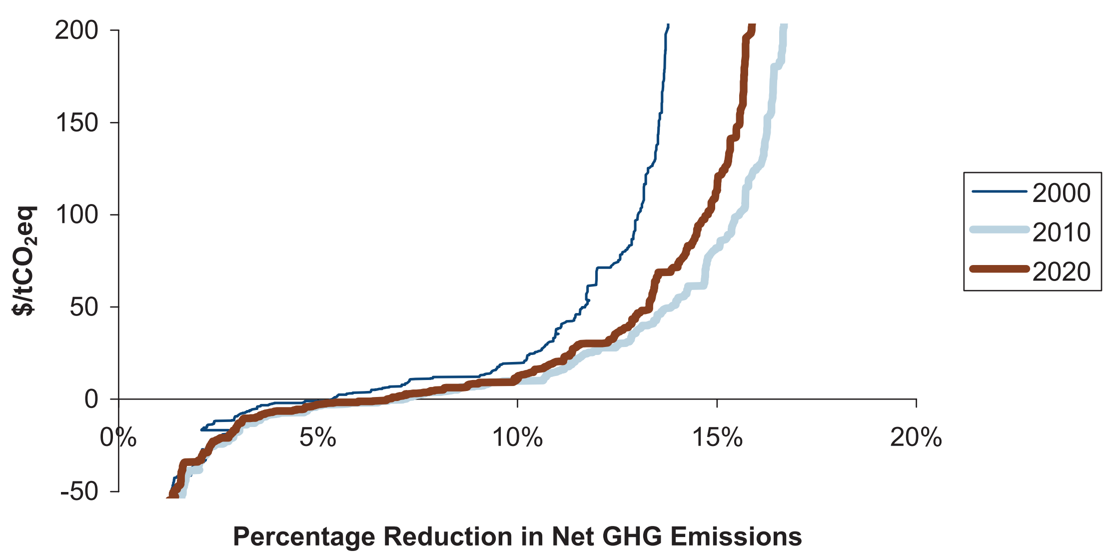
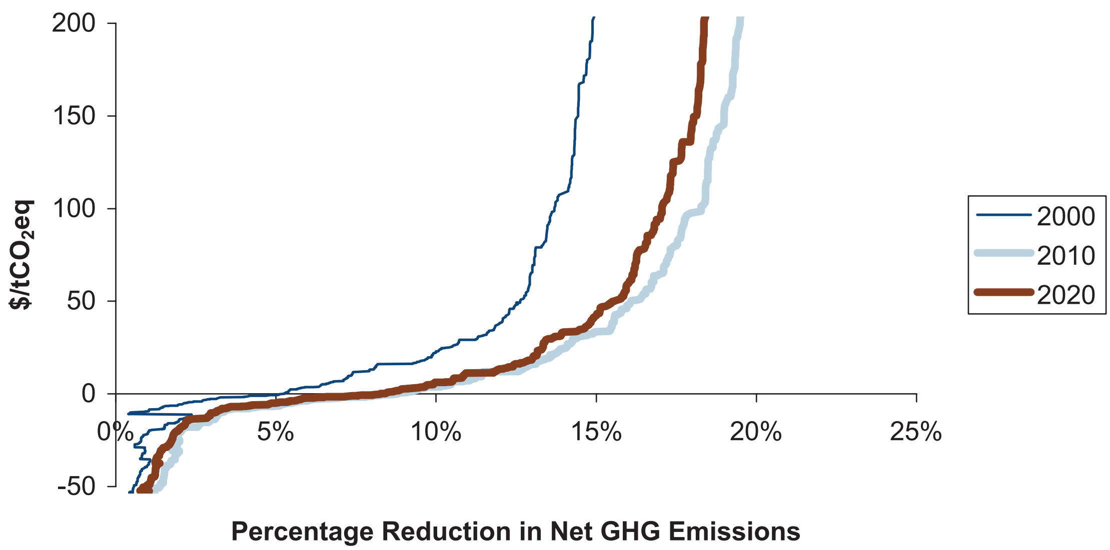


Figure 1-27: Global MAC for Net Greenhouse Gas Emissions from Agriculture, Holding Production Constant, 2000–2020



V.3.6 Agricultural Commodity Market Impacts of Adopting Mitigation Options: Use of the IMPACT Model

Many of the mitigation options considered for the agricultural sector have substantial impacts on agricultural productivity and/or the cost of production. As a result, any significant adoption of these options is expected to shift the market supply curves and move agricultural commodity markets to new equilibrium points. Increases in productivity will have positive supply shifts and will tend to increase market equilibrium quantity and reduce market prices, whereas increases in production costs will have the opposite effect, reducing market quantity and putting upward pressure on market prices. Thus, market equilibrium price and quantity could be either higher or lower than current and projected baseline levels, depending on the net effects of the mitigation options. Not only do these market-level impacts affect the cost of greenhouse gas mitigation, they also affect total mitigation, because emissions are generally tied to the quantity of output produced. For instance, there may be an option that reduces net greenhouse gas emissions per hectare of cropland but through broader market effects then leads to an increase in equilibrium cropland area. With a large enough increase in area, total emissions from adopting the option may actually increase because additional emissions from the larger area more than offset the reduction in emissions per hectare.

To examine the magnitude of these market-level effects in agricultural markets, IFPRI's IMPACT model is used. IMPACT models world supply and demand for agricultural products for 36 world regions, as well as trade between regions. The model is capable of incorporating shifts in supply and/or demand in one or more commodities in one or more regions and then solving for a new global equilibrium in all commodities.

For cropland and rice cultivation options, estimated percentage changes in yield (kg/hectare) and percentage changes in production costs per unit of output ($/metric ton) for each mitigation option were provided as inputs to the IMPACT model. Similarly, percentage changes in milk or meat production per animal (kg/head) and production costs per unit of output ($/metric ton) estimated for each enteric fermentation option were provided as inputs to IMPACT. Manure management greenhouse gas mitigation options were assumed to have no impact on livestock productivity and were not run through the IMPACT model.

Applying the percentage changes in productivity and costs implied by the mitigation options to the baseline levels of these variables in the IMPACT model, the model moves to a new equilibrium. The values for key variables in the baseline and mitigation scenario are then compared to determine the incremental impacts of adopting the mitigation option. Mitigation options are run through the model independently from other options, but each option is applied simultaneously to all regions where that option was believed to be feasible.

Two illustrative examples are presented to show the market adjustments being captured in the IMPACT model and the influence of those adjustments on the abatement curves. The first examines the effects of global adoption of the antimethanogen vaccine option on beef, dairy, and sheep and goat meat markets relative to baseline values. As shown in Figure 1-28, world prices are reduced for all three of the primary livestock categories that may adopt this mitigation option, with reductions ranging from about 4 percent to 9 percent. Figure 1-29 presents the effects on global production, where production increases by 2 percent to 4 percent for each product. In Figure 1-30, the impacts on global animal numbers are shown. The IMPACT model estimates reductions in the number of animals of approximately 0.5 percent to 2 percent for each livestock category included. These changes in prices, production, and animal numbers are attributable to the increase in productivity associated with this option. Although there are costs of purchasing and administering the vaccine, the increase in productivity more than offsets these costs in most regions, leading to more production from fewer animals. The resulting positive supply shift decreases equilibrium market price.

Figure 1-28: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on World Prices Using the IMPACT Model

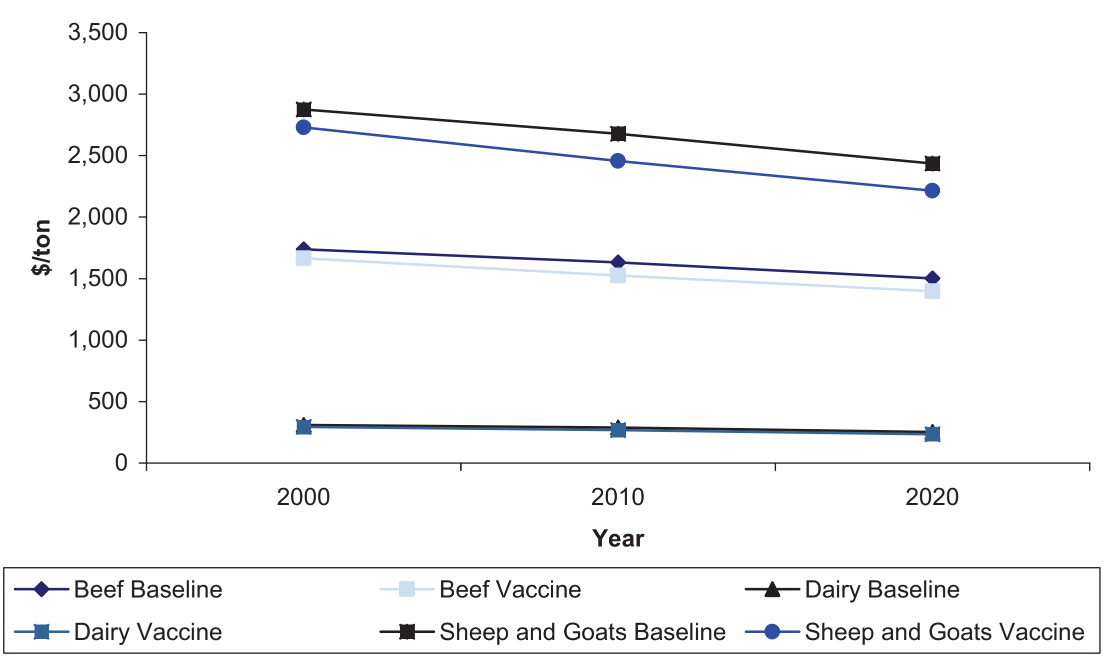


Figure 1-29: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Production Using the IMPACT Model

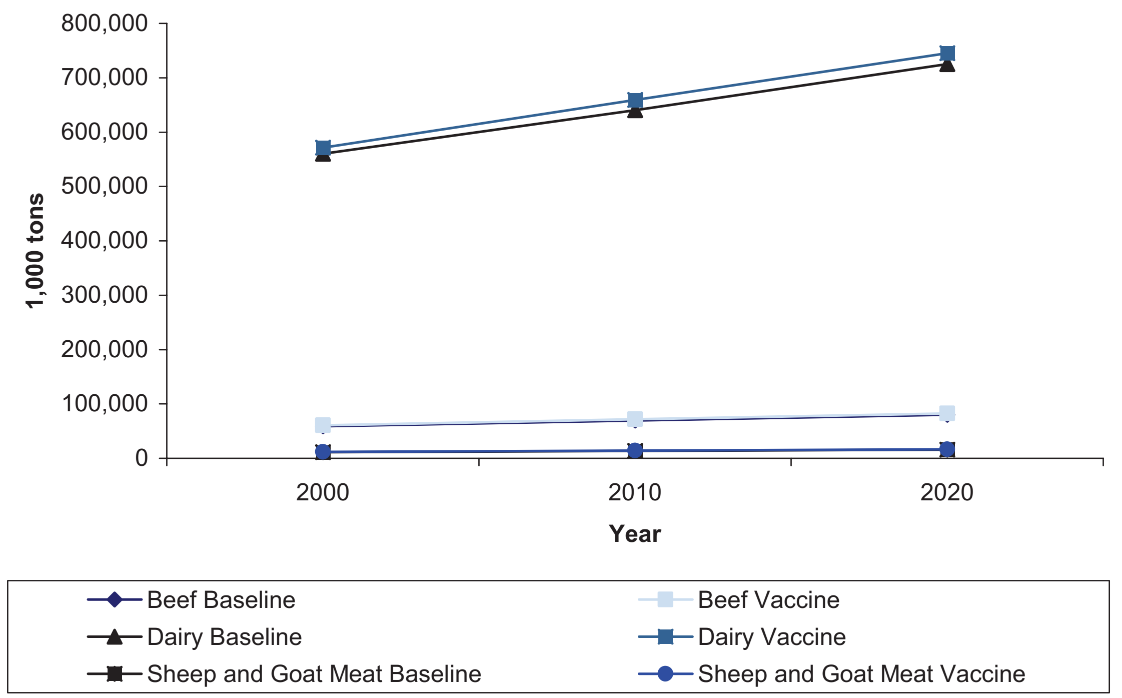
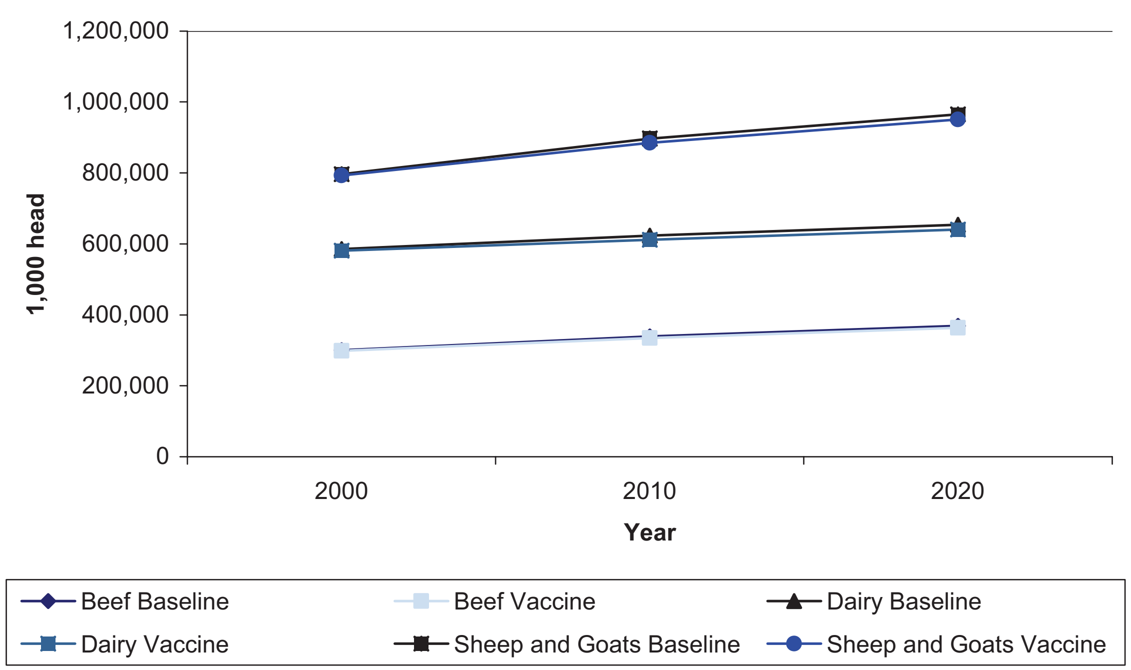


Figure 1-30: Effect of Global Adoption of the Antimethanogen Vaccine Mitigation Option on Global Number of Animals Using the IMPACT Model



The second example simulates the effects of global adoption of the shallow flooding mitigation option on rice markets relative to baseline values. The shallow flooding option is expected to result in both reduced emissions and higher productivity. As shown in Figure 1-31, the global price of rice is reduced, with reductions ranging from about 3 percent to 10 percent. Figure 1-32 presents the effects on global rice production, where production increases by 1 percent to 2.5 percent. In Figure 1-33, the impact on global rice area is shown, with the IMPACT model estimating acreage reductions between 0.3 to 1 percent. Similar to the antimethanogen vaccine option examined above, this option results in an increase in productivity, which results in more production from less area. The positive supply shift leads to a decrease in equilibrium market price.

These market-level changes in area, production, and price are then incorporated into the MAC to examine the sensitivity of the MACs to inclusion of market effects. These effects are potentially very important because many options will have an effect on equilibrium prices and quantities if widely adopted, which will affect the cost of mitigation, as well as total mitigation achieved. However, the engineering approach used in this report is unable to capture feedbacks from changing market conditions. For comparison purposes, the MAC curves without market adjustments are recalculated with full adoption of a single option being analyzed to be consistent with the MACs calculated using IMPACT model results.

Figure 1-34 compares net GHG abatement under global adoption of the antimethanogen vaccine calculated three different ways: 1) with the number of animals held constant, 2) with production of the relevant commodities held constant, and 3) allowing both number of animals and production to vary, as well as reflecting other market adjustments simulated using the IMPACT model. Mitigation with production held constant is much greater than with the number of animals held constant because this is an option that increases productivity. Thus, the same production level can be achieved with fewer animals, which provides additional emissions reductions on top of the reduction in emissions per animal associated with the option. Incorporating market adjustments results in a price decrease, which leads to reduced incentives for investment and production in the livestock sector than if price were constant. Thus, the increase in production is smaller than for the constant number of animals case. Because there is an increase in production under the market adjustments scenario, the reduction in number of animals is smaller than for the constant production case. In addition, there are shifts in production regions and trade patterns, though the changes are relatively small for this particular option.

Similarly, Figure 1-35 compares net GHG abatement under global adoption of the shallow flooding mitigation option: 1) with rice area held constant, 2) with rice production held constant, and 3) allowing both area and production to vary, as well as reflecting other market adjustments simulated by the IMPACT model. Mitigation is similar with area held constant and production held constant for this option because the yield changes are relatively small, causing less differentiation between calculation method. The global curve with market adjustments is similar to the area constant and production constant curves other than at very low and very high prices. However, there are differences in the regions estimated to provide mitigation at different price levels depending on the abatement cost calculation method. Because there are larger differences in estimated yield changes between regions, there are more substantial shifts in production regions and trade patterns than for the antimethanogen vaccine option considered above.

Figure 1-31: Effect of Global Adoption of the Shallow Flooding Mitigation Option on World Prices Using the IMPACT Model

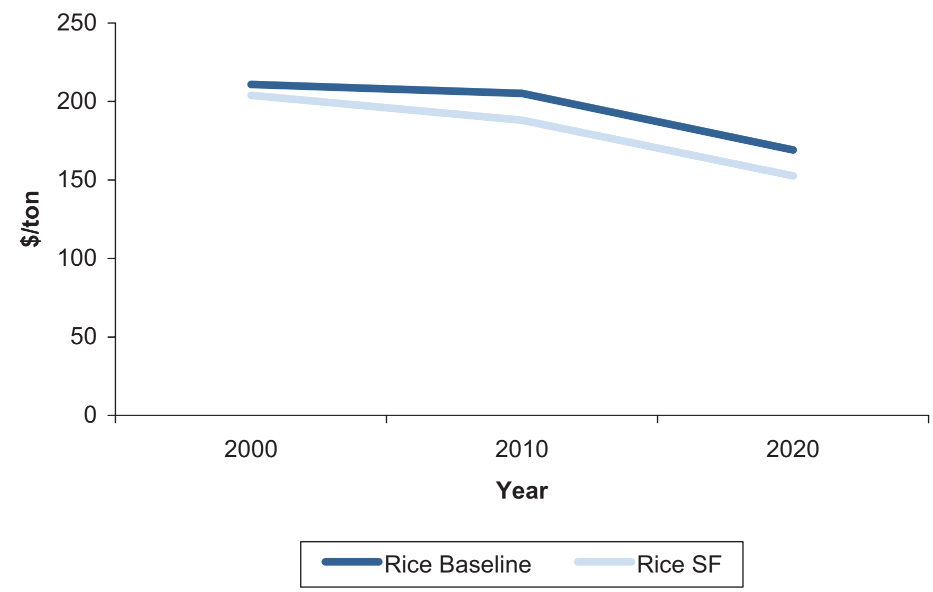


Figure 1-32: Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Production Using the IMPACT Model

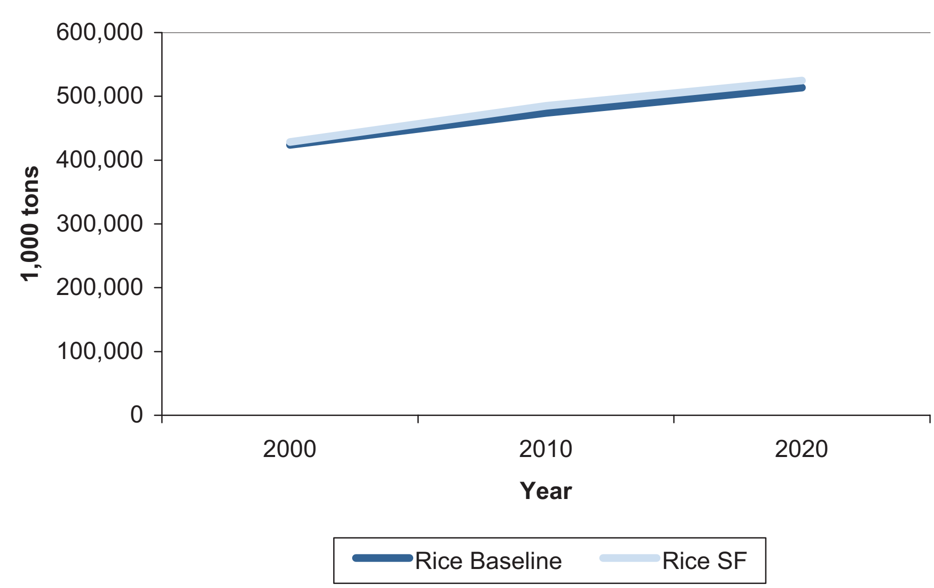


Figure 1-33: Effect of Global Adoption of the Shallow Flooding Mitigation Option on Global Rice Area Using the IMPACT Model

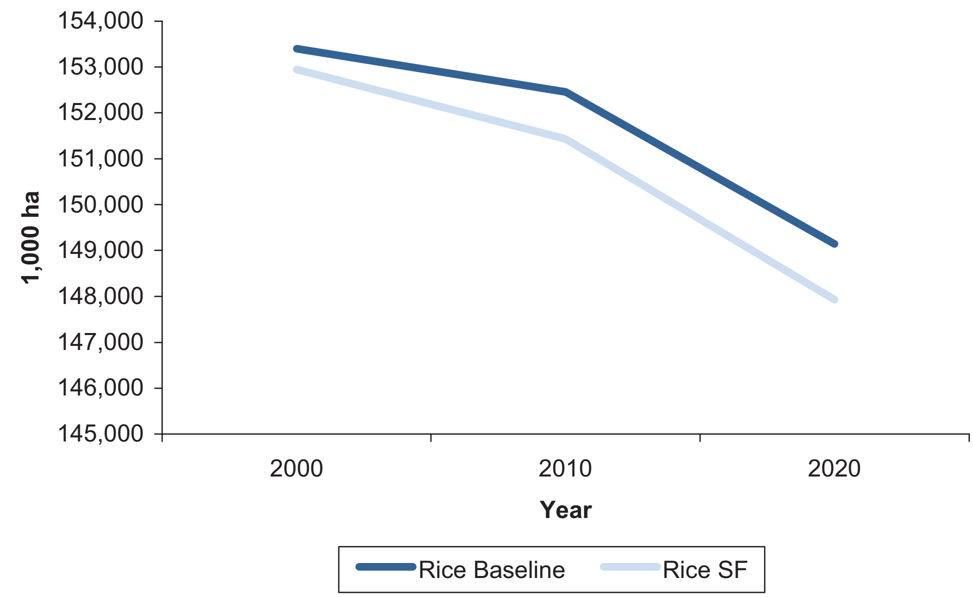


Figure 1-34: Net GHG Abatement under Global Adoption of the Antimethanogen Vaccine Option with Number of Cattle Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010

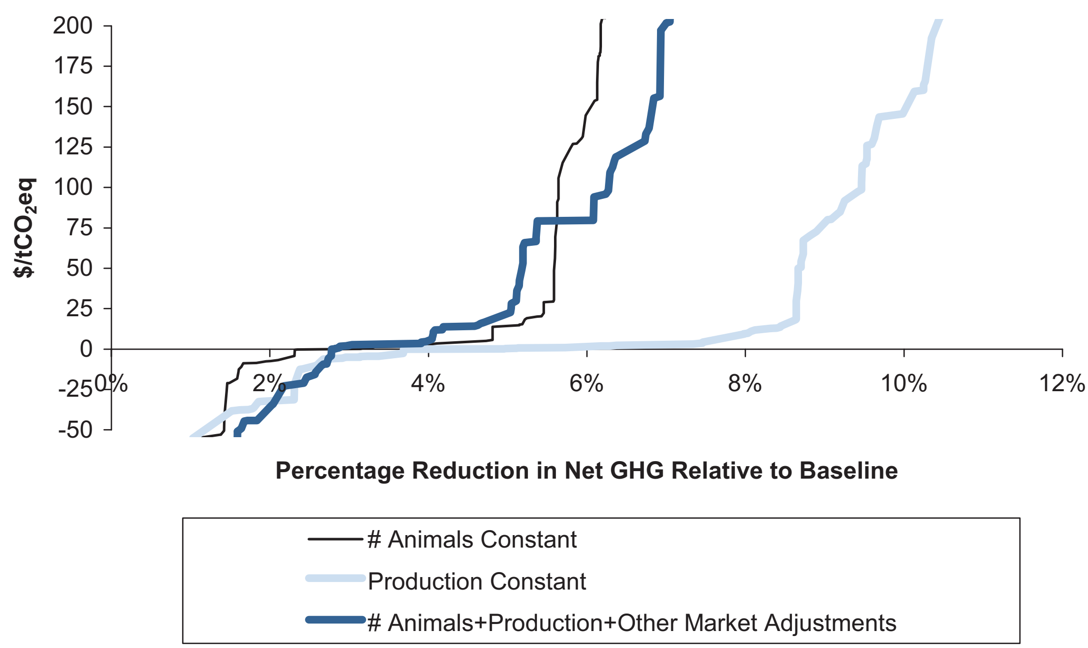
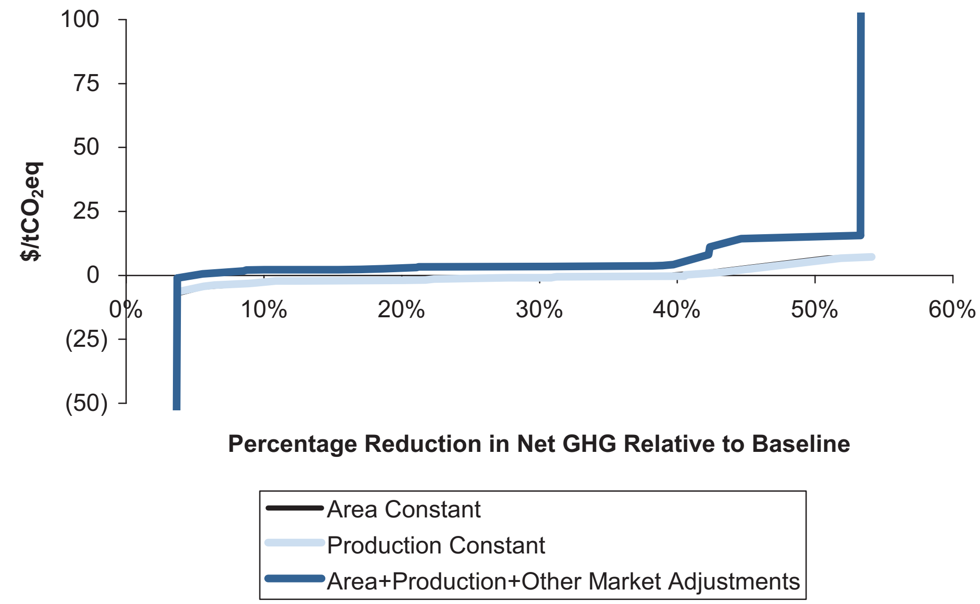


Figure 1-35: Comparison of Net GHG Abatement from Rice Cultivation under Global Adoption of the Shallow Flooding Mitigation Option with Area Constant, Production Constant, and Market Adjustments Using the IMPACT Model, 2010



V.4 Conclusions

The agricultural sector generates the largest share of global non-CO_2 greenhouse gas emissions and a significant share of total global greenhouse gas emissions. Emissions in this sector are projected to increase significantly over the foreseeable future, especially in developing countries. Mitigation options to abate agricultural non-CO_2 emissions have been identified in the literature for most significant sources. This report uses a number of data sources, analytic tools, and modeling approaches to compile and estimate baseline emissions of the most significant world agricultural non-CO_2 sources and to estimate the costs of the technical mitigation potential for key regions and world totals. This report makes no explicit assumption about the policy mechanisms that might be required for adopting the mitigation options in different regions.

Cost estimates are feasible for most greenhouse gas mitigation options in the agricultural sector. This report uses an engineering bottom-up approach to estimate the \$/tCO_2eq of each mitigation option in different regions, over different time periods, by including most key elements that affect cost: net greenhouse gas effects, changes in crop yield or livestock productivity, regionally specific agricultural commodity prices, capital and input costs required to implement the mitigation option, and changes in labor requirements. The quality of data and tools used for these input parameters varies by region and by agricultural emissions category.

At the globally aggregated scale (including all regions and all non-CO_2 sources), the technical potential to mitigate non-CO_2 greenhouse gases from agriculture appears significant but not overwhelming in percentage terms. At roughly zero costs (where the benefits of implementing the mitigation options compensate for the costs of doing so), approximately 10 percent of global agricultural non-CO_2 emissions can be mitigated. At very high costs around \$150/tCO_2eq, the technical mitigation potential at the global scale approaches 20 percent of baseline emissions. These estimated percentage reductions are larger than the previous analysis supported by the USEPA and carried out for EMF-21, but these two studies are very different; this report uses more recent baseline scenarios for livestock emissions and uses completely different approaches to estimate the baseline and mitigation scenarios from croplands and rice cultivation.

For individual emissions categories, the magnitude of net greenhouse gas mitigation potential appears significant to modest depending on region and time frame. For global cropland N_2O and soil carbon emissions, approximately 15 percent of baseline emissions can be mitigated at zero costs. At costs above \$50/tCO_2eq, the percentage reduction approaches 25 percent. Nitrification inhibitors and no-till appear the most viable mitigation options, according to the simulations with the DAYCENT model, with regard to net emissions reduction potential and yield effects. The options where baseline nitrogen fertilizers are simply reduced result in net emissions similar to baseline levels.

For Asian rice systems (representing about 90 percent of world rice emissions), close to 15 percent of net baseline emissions (CH_4, N_2O and soil carbon) can be mitigated at zero costs in years 2010 and 2020. As costs approach \$100/tCO_2eq, over 25 percent of net baseline emissions can be mitigated. Shallow flooding, ammonium sulfate, and full conversion to midseason drainage appear the most viable mitigation options, according to the simulations with the DNDC model, with regard to net emissions mitigation potential and yield effects. Upland rice almost eliminates emissions but has adverse yield effects. Shallow flooding has the additional benefit of water conservation, though water as an unpriced commodity in this context does not factor into the cost estimates.

For global livestock emissions, approximately 7 percent can be mitigated at zero costs assuming a constant number of animals, whereas roughly 9 percent can be mitigated assuming a constant level of production. As costs approach \$125/tCO_2eq, the technical mitigation potential reaches 16 and 18 percent of baseline emissions, when, respectively, constant number of animals and constant production are assumed. There are somewhat surprisingly few large differences among the mitigation options in terms of their non-CO_2 mitigation potential at the global scale relative to baseline levels.

Many mitigation options have negative costs and it is difficult to assess whether important costs have been omitted or if barriers to adoption exist that are not accounted for. High-cost options tend to be those that are either not very effective at reducing net greenhouse gases or that have adverse yield and productivity effects. Adoption barriers have not been explicitly addressed (all mitigation options considered technically feasible in a given region are assumed to be adopted in data year 2000). Accounting for adoption barriers to gain a more complete picture of greenhouse gas mitigation potential is an important area for future research.

Consideration of net greenhouse gas effects (CH_4, N_2O, and soil carbon) is particularly important in the agricultural sector to evaluate the effectiveness of different mitigation options. This is especially true for croplands and rice cultivation. In croplands, options considered *a priori* to be good candidates for reducing soil N_2O emissions (e.g., reducing baseline nitrogen application rates) led to no significant net greenhouse gas emissions reductions relative to the baseline because of offsetting soil carbon effects. Likewise with rice cultivation, some options are good CH_4-reducing strategies but increase N_2O (e.g., midseason drainage), while others have little effect on CH_4 but are good N_2O-reducing strategies (e.g., use of ammonium sulfate under certain conditions). The inclusion of fossil fuel CO_2 emissions associated with either on-farm practices or off-farm production processes, such as fertilizer production, is an additional net greenhouse gas consideration that was not included here.

The long-lasting benefits of N_2O and CH_4 reductions relative to the potentially reversible benefits of soil carbon sequestration deserve attention. In this report, there is no reversal of soil carbon sequestration due to, say, adoption of no till, because this practice is assumed to be adopted immediately and continuously through to 2020.

Estimating mitigation potential of agricultural non-CO_2 emissions is challenging at the international scale given the high degree of heterogeneity in management and biophysical conditions. Use of process models like DAYCENT (for cropland emissions) and DNDC (for rice cultivation emissions) in this report can help capture this variability and improve confidence in net greenhouse gas and yield estimates. Use of these models at such large scales is intended to show the general trends between baseline and mitigation scenarios, while adequately capturing heterogeneous effects. These models are not intended to match small-scale (e.g., farm scale) conditions over the entire regions to which they are being applied.

Livestock baseline emissions are taken from USEPA (2006), which for many regions relies on IPCC Tier I default methodologies. Mitigation studies found in the literature are applied to those baselines. This approach raises two key issues that need to be addressed in future work: 1) the identification of more detailed baseline management activities so that there is more certainty about the implications of adopting the mitigation options and 2) the suitability of applying mitigation options to regions outside of an original case study area.

Adoption of the mitigation options in this report would lead to agricultural commodity effects and therefore would affect baseline commodity prices, crop area, production levels of crops, and livestock populations and livestock products. These changes in turn change greenhouse gas levels and thus the effectiveness of the mitigation options. The agricultural market sensitivity experiments with the IMPACT model show this to be the case. The core mitigation estimates in this report use a static, engineering approach that is unable to capture these market dynamics. For this reason, cost estimates and marginal abatement curves are shown using either constant area (livestock population) or constant crop (livestock) production. For the livestock sector, where many mitigation options actually increase emissions per animal, it is particularly important to show the implications of both approaches; using constant livestock production, as expected, leads to greater emissions reduction estimates. Fuller representation of these market feedbacks for future global agricultural mitigation analyses will be important.

Additional research is also necessary to identify which mitigation options are best suited for different regions and subregions and what kind of adoption barriers different mitigation options may face. This report excludes some options from being applied in certain regions, but further refinement is required.

Finally, anthropogenic climate change is not considered in this report for the 2000 to 2020 period but could affect future agricultural baseline emissions and thus mitigation potential. Anthropogenic climate change will become a more important issue for analyses that look beyond 2020.

V.5 References

AEA Technology Environment. 1998. *Options to Reduce Nitrous Oxide Emissions*. Report prepared for the European Commission.

Babu, Y.J., C. Li, S. Frolking, D.R. Nayak, A. Datta, and T.K. Adhya. 2005. "Modelling of Methane Emissions from Rice-Based Productions Systems in India with the Denitrification and Decomposition Model: Filed Validation and Sensitivity Analysis." *Current Science* 89 11, 1–6.

Bates, J. 2001. *Economic Evaluation of Emissions Reductions of Nitrous Oxides and Methane in Agriculture in the EU: Bottom-Up Analysis*. Contribution to a Study for DG Environment, European Commission by Ecofys Energy and Environment, AEA Technology Environment and National Technical University of Athens.

Belward, A.S. 1996. *The IGBP-DIS Global 1 Km Land Cover Dataset (Discover) Proposal and Implementation Plans: IGBP-DIS Working Paper No. 13.* Toulouse, France.

Belward, A.S., J.E. Estes, and K.D. Kline. 1999. "The IGBP-DIS 1-Km Land-Cover Data Set DISCover: A Project Overview." *Photogrammetric Engineering and Remote Sensing* 65 9, 1013–1020.

Bouwman, A.F., G. van Drecht, and K.W. van der Hoek. 2005. "Global and Regional Surface Nitrogen Balances in Intensive Agricultural Production Systems for the Periode 1970–2030." *Pedosphere* 15 2, 137–55.

Cai, Z., S. Sawamoto, C. Li, G. Kang, J. Boonjawat, A. Mosier, and R. Wassmann. 2003. "Field Validation of the DNDC Model for Greenhouse Gas Emissions in East Asian Cropping Systems." *Global Biogeochemical Cycles* 17 4, doi:10.1029/2003GB002046.

Cai, Z.C., G.X. Xing, G.Y. Shen, H. Xu, X.Y. Yan, and H. Tsuruta. 1999. "Measurements of CH_4 and N_2O Emissions from Rice Paddies in Fengqiu, China." *Soil Science Plant Nutrition* 45, 1–13.

Cramer, W., D.W. Kicklighter, A. Bondeau, B. Moore, G. Churkina, B. Nemry, A. Ruimy, and A.L. Schloss. 1999. "Intercomparison, the Participants of the Potsdam NPP Model. Comparing Global Models of Terrestrial Net Primary Productivity (NPP): Overview and Key Results." *Global Change Biology* Supplement 1, 5 4, 1–15.

Conservation Technology Information Center (CTIC). 1994. *1994 National Crop Residue Management Survey*. West Lafayette, IN: Conservation Technology Information Center.

DeAngelo, B.J., F. de la Chesnaye, R.H. Beach, A. Sommer and B.C. Murray. In press. "Methane and Nitrous Oxide Mitigation in Agriculture." *Energy Journal*.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.D. Hartman, L. Brenner, D.S. Ojima, and D.S. Schimel. 2001. Simulated Interaction of Carbon Dynamics and Nitrogen Trace Gas Fluxes Using the DAYCENT Model. In M. Schaffer, et al. (Eds.), *Modeling Carbon and Nitrogen Dynamics for Soil Management*, p. 303–332. Boca Raton, FL: CRC Press.

Del Grosso, S.J., A.R. Mosier, W.J. Parton, and D.S. Ojima. 2005. "DAYCENT Model Analysis of Past and Contemporary Soil N_2O and Net Greenhouse Gas Flux for Major Crops in the USA." *Soil Tillage and Research* 83, 9–24.

Ehhalt, D., M. Prather, et al. 2001. Atmospheric Chemistry and Greenhouse Gases. In J.T. Houghton et al. (eds.) *Climate Change 2001: The Scientific Basis*, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Food and Agriculture Organization (FAO). 2000. *Fertilizer Requirements for 2015 and 2030*. Rome, Italy: UN Food and Agriculture Organization.

Food and Agriculture Organization (FAO). 2002. World Agriculture: Towards 2015/2030. Rome, Italy: UN Food and Agriculture Organization.

Food and Agriculture Organization/United Nations Educational, Scientific, and Cultural Organization (FAO/UNESCO). 1996. *Digital Soil Map of the World and Derived Soil Properties; Derived from the FAO/UNESCO Soil Map of the World, Original Scale 1:5,000,000*. Rome, Italy: UN Food and Agriculture Organization.

FAOSTAT. 2004a. FAO Production Yearbook 2003, v. 57. In: *FAO Statistics Series* (FAO). No. 177. Rome, Italy: UN Food and Agriculture Organization.

FAOSTAT. 2004b. FAO Fertilizer Yearbook 2003, v. 53 In: *FAO Statistics Series* (FAO). No. 183. Rome, Italy: UN Food and Agriculture Organization.

Frolking, S., J. Qiu, S. Boles, X. Xiao, J. Liu, Y. Zhuang, C. Li, and X. Qin. 2002. "Combining Remote Sensing and Ground Census Data to Develop New Maps of the Distribution of Rice Agriculture in China." *Global Biogeochemical Cycles* 16 4, doi:10.1029/2001GB001425.

Gerbens, S. 1998. *Cost-Effectiveness of Methane Emissions Reduction from Enteric Fermentation of Cattle and Buffalo*. Draft Report.

Global Soil Data Task Group. 2000. *Global Gridded Surfaces of Selected Soil Characteristics, International Geosphere-Biosphere Programme—Data and Information System Data Set*. Oak Ridge National Laboratory Distributed Active Archive Center. Available at <http://www.daac.ornl.gov>.

Global Trade Analysis Project (GTAP). 2005. GTAP6 Data Base. Available at <https://www.gtap.agecon.purdue.edu/>.

Groffman, P.M., R. Brumme, K. Butterbach-Bahl, K.E. Dobbie, A.R. Mosier, D. Ojima, H. Papen, W.J. Parton, K.A. Smith, and C. Wagner-Riddle. 2000. "Evaluating Annual Nitrous Oxide Fluxes at the Ecosystem Scale." *Global Biogeochemcial Cycles* 14 4, 1061–1070.

Holzapfel-Pschorn, A., R. Conrad, and W. Seiler. 1985. "Production, Oxidation, and Emissions of Methane in Rice Paddies." *FEMS Microbiology Ecology* 31, 149–158.

International Fertilizer Industry Association (IFA). 2002. *Fertilizer Use by Crop*, 5th edition. Available at <http://www.fertilizer.org/ifa/statistics/crops/fubc5ed.pdf>.

Johnson, D., H.W. Phetteplace, A.F. Seidl, U.A. Schneider, and B.A. McCarl. 2003a. Selected Variations in Management of U.S. Dairy Production Systems: Implications for Whole Farm Greenhouse Gas Emissions and Economic Returns. In *Proceedings of the 3rd International Methane and Nitrous Oxide Mitigation Conference*, November 17-21, Beijing, China.

Johnson, D., H.W. Phetteplace, A.F. Seidl, U.A. Schneider, and B.A. McCarl. 2003b. Management Variations for U.S. Beef Production Systems: Effects on Greenhouse Gas Emissions and Profitability. In *Proceedings of the 3rd International Methane and Nitrous Oxide Mitigation Conference*, November 17-21, Beijing, China.

Kistler, R., E. Kalnay, W. Collins, S. Saha, G. White, J. Woolen, M. Chelliah, W. Ebisuzaki, M. Kanamitsu, V. Kousky, H. van den Dool, R. Jenne, and M. Fiorino. 2001. "The NCEP-NCAR 50-Year Reanalysis: Monthly Means CD-ROM and Documentation." *Bulletin of the American Meteorological Society* 82, 247–267.

Kroeze, C., and A. Mosier. 1999. New Estimates for Emissions of Nitrous Oxides. In *Second International Symposium on Non-CO_2 Greenhouse Gases*. J. van Ham, A.P.M. Baede, L.A. Meyer, and R. Ybema (eds.). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Krüger, M., G. Eller, R. Conrad, and P. Frenzel. 2001. "Seasonal Variation in Pathways of CH_4 Production and in CH_4 Oxidation in Rice Fields Determined by Stable Carbon Isotopes and Specific Inhibitors." *Global Change Biology* 8 3, 265–280.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. 1998. *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Boca Raton, FL: Lewis Publishers.

Leff, B., N. Ramankutty, and J.A. Foley. 2004. "Geographic Distribution of Major Crops across the World." *Global Biogeochemical Cycles* 18 1, GB1009 10.1029/2003GB002108.

Li, C., and W. Salas. 2005. *Update Results for DNDC Dynamics Modeling Runs of Net GWP from Rice Cultivation in China from 2000 to 2020 and Site Level Results for India and Thailand*. Memorandum to Benjamin DeAngelo, USEPA. April 26.

Li, C., A. Mosier, R. Wassmann, Z. Cai, X. Zheng, Y. Huang, H. Tsuruta, J. Boonjawat, and R. Lantin. 2004. "Modeling Greenhouse Gas Emissions from Rice-Based Production Systems: Sensitivity and Upscaling." *Global Biogeochemical Cycles* 18, GB1043, doi:10.1019/2003GB002045.

Li, C., W. Salas, B. DeAngelo, and S. Rose. In press. "Assessing Alternatives for Mitigating Net Greenhouse Gas Emissions and Increasing Yields from Rice Production in China Over the Next 20 Years." *Journal of Environmental Quality*.

Li, C., J. Qiu, S. Frolking, X. Xiao, W. Salas, B. Moore III, S. Boles, Y. Huang, and R. Sass. 2002. "Reduced Methane Emissions from Large-Scale Changes in Water Management in China's Rice Paddies During 1980–2000." *Geophysical Research Letter* 29 20, doi:10.1029/2002GL015370.

Li, Q.K. 1992. Water Management of Paddy Soils. In Q. Li (ed.), *Paddy Soils of China*. Beijing, China: Science Press, pp. 1–545 (in Chinese).

Melillo, J.M., A.D. McGuire, D.W. Kicklighter, B. Moore III, C.J. Vorosmarty, and A.L. Schloss. 1993. "Global Climate Change and Terrestrial Net Primary Productivity Production." *Nature* 363, 234–240.

Moomaw, W.R., J.R. Moreira, K. Blok, et al. 2001. Technological and Economic Potential of Greenhouse Gas Emissions Reduction. In *Climate Change 2001: Mitigation, Intergovernmental Panel on Climate Change, Working Group III*. Cambridge University Press.

Moser, C.M., and C.B. Barrett. 2002. *The System of Rice Intensification in Practice: Explaining Low Farmer Adoption and High Disadoption in Madagascar*. Cornell University Working Paper. Ithaca, NY: Cornell University.

Mosier, A., C. Kroeze, C. Nevison, O. Oenema, S. Seitzinger, and O. van Cleemput. 1998. "Closing the Global N_2O Budget: Nitrous Oxide Emissions through the Agricultural Nitrogen Cycle—OECD/IPCC/IEA Phase II Development of IPCC Guidelines for National Greenhouse Gas Inventory Methodology." *Nutrient Cycling in Agroecosystems* 52, 225–248.

Mosier, A.R., J.W. Doran, and J.R. Freney. 2002. "Managing Soil Denitrification." *Journal of Water and Soil Conservation* 57 6, 505–513.

Parton, W.J., M.D. Hartman, D.S. Ojima, and D.S. Schimel. 1998. "DAYCENT: Its Land Surface Submodel: Description and Testing." *Global and Planetary Change* 19, 35–48.

Pathak, H., C. Li, and R. Wassmann. 2005. "Greenhouse Gas Emissions from Indian Rice Fields: Calibration and Upscaling Using the DNDC Model." *Biogeosciences* 2, 113–123.

Peterson, G.A., A.D. Halvorson, J.L. Havlin, O.R. Jones, D.J. Lyon, and D.L. Tanaka. 1998. "Reduced Tillage and Increasing Cropping Intensity in the Great Plains Conserves Soil C." *Soil & Tillage Research* 47 3, 207–218.

Prentice, I.C., G.A. Farquhar, M.J.R. Fasham, et al. 2001. The Carbon Cycle and Atmospheric Carbon Dioxide. In *Climate Change 2001: The Scientific Basis, Intergovernmental Panel on Climate Change, Working Group I*. Cambridge University Press.

Riemer, P., and P. Freund. 1999. *Technologies for Reducing Methane Emissions*. IEA Greenhouse Gas Programme.

Robertson, G.P. 2004. Abatement of Nitrous Oxide, Methane, and the Other Non-CO_2 Greenhouse Gases: The Need for a Systems Approach. In C.B. Field and M.R. Raupach (eds.), pp. 493–506, *The Global Carbon Cycle*. Washington, DC: Island Press.

Roos. Personal communication. 2005.

Sass, R.L., F.M. Fisher, P.A. Harcombe, and F.T. Turner. 1990. "Methane Production and Emissions in a Texas Rice Field." *Global Biogeochemical Cycles* 4, 47–68.

Scharf, P., L. Mueller, and J. Medeiros. 2005. *Making Urea Work in No-Till*. Grant progress report, Missouri Agricultural Experiment Station. Available at <http://aes.missouri.edu/pfcs/research/ prop604a.pdf>.

Scheehle, E., and D. Kruger. In press. "Global Anthropogenic Methane and Nitrous Oxide Emissions." *Energy Journal*.

Shen, Z.R., X.L. Yang, and Y.S. Pei. 1998. Enhancing Researches on Elevating Efficiency of Water Use in Chinese Agriculture. In Z.R. Shen and R.Q. Su (eds.), *Strategies Against Water Crisis in Chinese Agriculture*. Beijing, China: Chinese Agricultural Science and Technology Press, pp. 1–267. (in Chinese).

Siebert et al. Personal communication.

Smith, K.A., and F. Conen. 2004. "Impacts of Land Management on Fluxes of Trace Greenhouse Gases." *Soil Use and Management* 20, 255–263.

Stehfest et al. Personal communication.

U.S. Energy Information Administration (USEIA). 2003. *Electricity Prices for Industry*. Available at <www.eia.doe.gov/emeu/international/elecprii.html>.

U.S. Environmental Protection Agency (USEPA). 2003. *Current Status of Farm-Scale Digesters*. Ag STAR Digest, EPA-430-F-02-028. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). 2005a. *Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture*. EPA 430-R-05-006. Washington, DC: USEPA. Available at <www.epa.gov/sequestration>.

U.S. Environmental Protection Agency (USEPA). 2005b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003*. *EPA* 430-R-05-003. Washington, DC: USEPA.

U.S. Environmental Protection Agency (USEPA). 2006. *Global Anthropogenic Non-*CO_2 *Greenhouse Gas Emissions: 1990–2020*. Washington, DC: USEPA.

Van der Gon, H.A.D., P.M. Van Bodegom, R. Wassmann, R.S. Lantin, and T.M. Metra-Corton. 2001. "Sulfate-Containing Amendments to Reduce Methane Emissions from Rice Fields: Mechanisms, Effectiveness and Costs." *Mitigation and Adaptation Strategies for Global Change* 6, 71–89.

Van Vuuren, D., J. Weyant, and F. de la Chesnaye. In press. "Multigas Scenarios to Stabilise Radiative Forcing." *Energy Journal*.

Wassmann, R., R.S. Lantin, H.U. Neue, L.V. Buendia, T.M. Corton, and Y. Lu. 2000. "Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs." *Nutrient Cycling in Agroecosystems* 58, 23–36.

Webb, R.W., C.E. Rosenzweig, and E.R. Levine. 2000. *Global Soil Texture and Derived Water-Holding Capacities Data Set*. Oak Ridge National Laboratory Distributed Active Archive Center. Available at <http://www.daac.ornl.gov>.

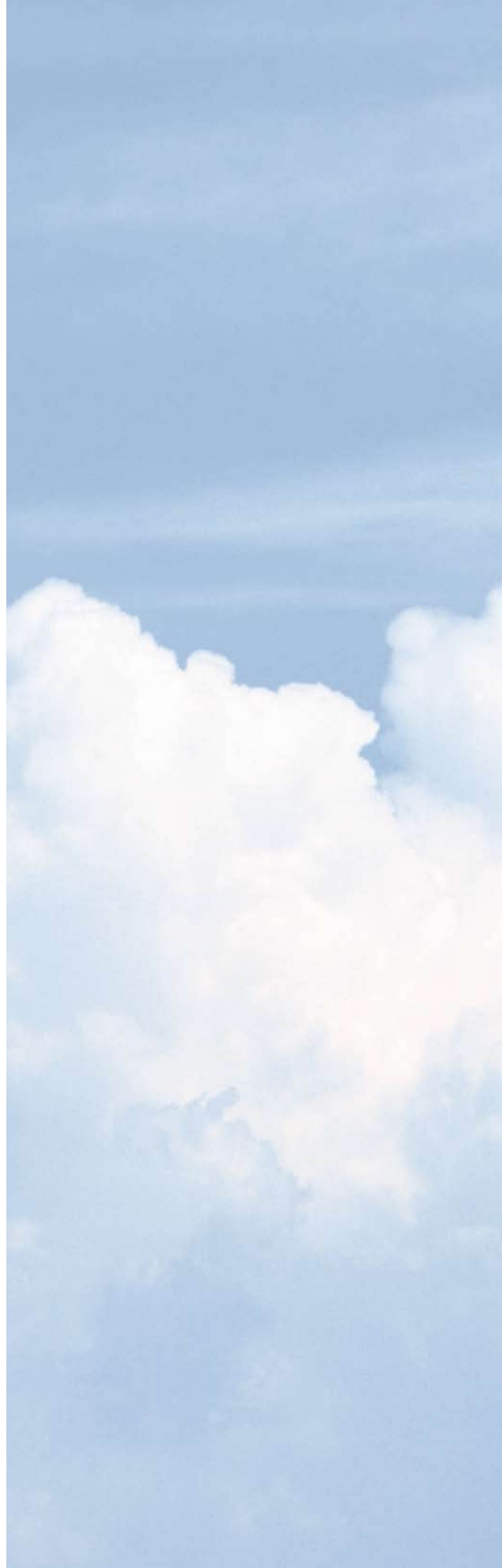
Zhang, Y., C. Li, C.C. Trettin, H. Li, and G. Sun. 2002. "An Integrated Model of Soil, Hydrology and Vegetation for Carbon Dynamics in Wetland Ecosystems." *Global Biogeochemical Cycles* 10.1029/2001GB001838.

Zheng X., M. Wang, Y. Wang, R. Shen, J. Gou, J. Li, J. Jin, and L. Li. 2000. "Impacts of Soil Moisture on Nitrous Oxide Emissions from Croplands: A Case Study on the Rice-Based Agro-Ecosystem in Southeast China." *Chemosphere-Global Change Science* 2, 207–224.

Zheng, X.H., M.X. Wang, Y.S. Wang, R.X. Shen, X.J. Shangguan, J. Heyer, M. Kögge, H. Papen, J.S. Jin, and L.T. Li. 1997. "CH_4 and N_2O Emissions from Rice Paddies in Southeast China." *Chinese Journal of Atmosphere Science* 21, 167–174.

Section V: Agriculture Sector Appendixes

Appendixes for this section are available for download from the USEPA's Web site at http://www.epa.gov/nonco2/econ-inv/international.html.



Global Mitigation of Non-CO_2 Greenhouse Gases

United States Environmental Protection Agency
Office of Atmospheric Programs (6207J)
1200 Pennsylvania Ave., NW
Washington, DC 20460