# V. Agriculture Sector

# V.1. Non-Rice Croplands

## V.1.1 Sector Summary

Land management in croplands influences soil $N_2O$ emissions, $CH_4$ fluxes, and soil organic carbon (C) stocks (and associated $CO_2$ fluxes to the atmosphere). Soil $N_2O$ emissions are influenced by human activity, including synthetic nitrogen fertilization practices, application of organic fertilizers such as manure, drainage of organic soils, cultivation of N-fixing crops, and enhancement of N mineralization in soils through practices such as cultivation/management of native grasslands and forests (Mosier et al., 1998; Smith et al., 2007). Globally, $N_2O$ emissions from agricultural soils increased by about 19% between 1990 and 2010 While $N_2O$ emissions from all sources grew only 4%. In 2010, soil $N_2O$ emissions account for approximately 56% of the global $N_2O$ emissions, up from 51% in 1990.[1] In contrast to soil $N_2O$, where there are sizable annual fluxes that depend on human activity, soil organic C stocks are assumed to be approximately in equilibrium.[2]

The marginal abatement cost curves presented in this chapter consider mitigation strategies that apply to only a fraction of the total emissions from agriculture. Specifically, the following categories are included:

- Direct and indirect emissions from mineral-based cropland soils processes
  - Synthetic and organic fertilization
  - Residue N
  - Mineralization and asymbiotic fixation, based on temperature and moisture, etc.
- Major crops supplemented by selected similar minor crops
  - Barley (plus rye)
  - Maize (plus green corn)
  - Sorghum
  - Soybeans (plus lentils, other beans)
  - Wheat (plus oats)

In addition, compared to the estimates typically developed for GHG inventories, the emissions presented in this chapter will be lower because the following types of emissions are excluded due to data and resource limitations:

- Drainage of organic soils.
- Grassland soils
- Other crops not mentioned above (e.g. vegetables)
- Restoration of degraded lands
- Burning of residues or biofuel

The focus is on emissions from major crops, which is consistent with our evaluation of mitigation options that can be applied to mitigate emissions from these major crops in this chapter.

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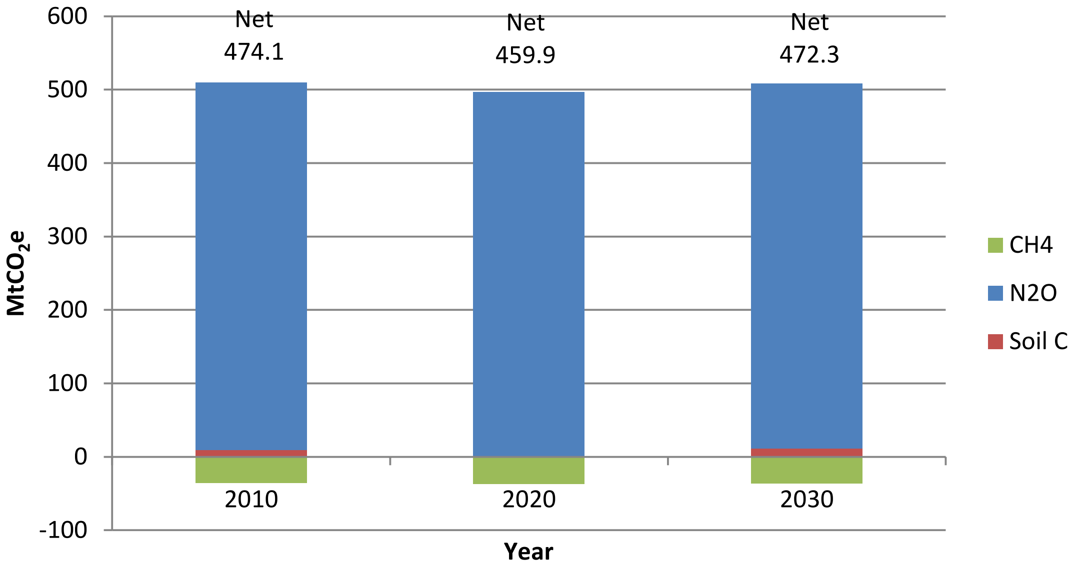
[1] Global total $N_2O$ emissions were 3240.7 $MtCO_2e$ in 1990 and 3,519.6 $MtCO_2e$ in 2010. Agricultural soils total $N_2O$ emissions were 1,658.1 $MtCO_2e$ in 1990 and 1,969.0 MtCO2e in 2010 (USEPA, 2012).

[2] Major changes in soil C occurred when land was first cultivated, but changes associated with agricultural soil management are approximately balanced at a global scale based on current management and land use change trends (Smith et al., 2007).

For the period 2010—2030 a business-as-usual forecast was constructed using projected growth rates in acreage, output, prices, yields, population, and GDP by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Nelson et al., 2010). The IFPRI IMPACT model projections provide a set of prices consistent with population and productivity assumptions for the MAC analysis.[3,4]

Figure 1-1 presents projected baseline $N_2O$ and $CH_4$ emissions and changes in soil organic carbon from non-rice cropland soils; As shown in Figure 20-1, $N_2O$ emissions from global non-rice cropland soils are projected to be 506, 500 and 504 million metric tons of $CO_2$ equivalent ($MtCO_2e$) in 2010, 2020 and 2030, respectively.[5] Non-rice cropland soils are a net sink for methane, sequestering approximately 38 $MtCO_2e$ of $CH_4$ per year. The estimated net changes in soil organic carbon suggest that the carbon stock changes are roughly balanced at the global scale.

Figure 1-1: Global Baseline Emissions from Non-Rice Croplands by GHG: 2010-2030



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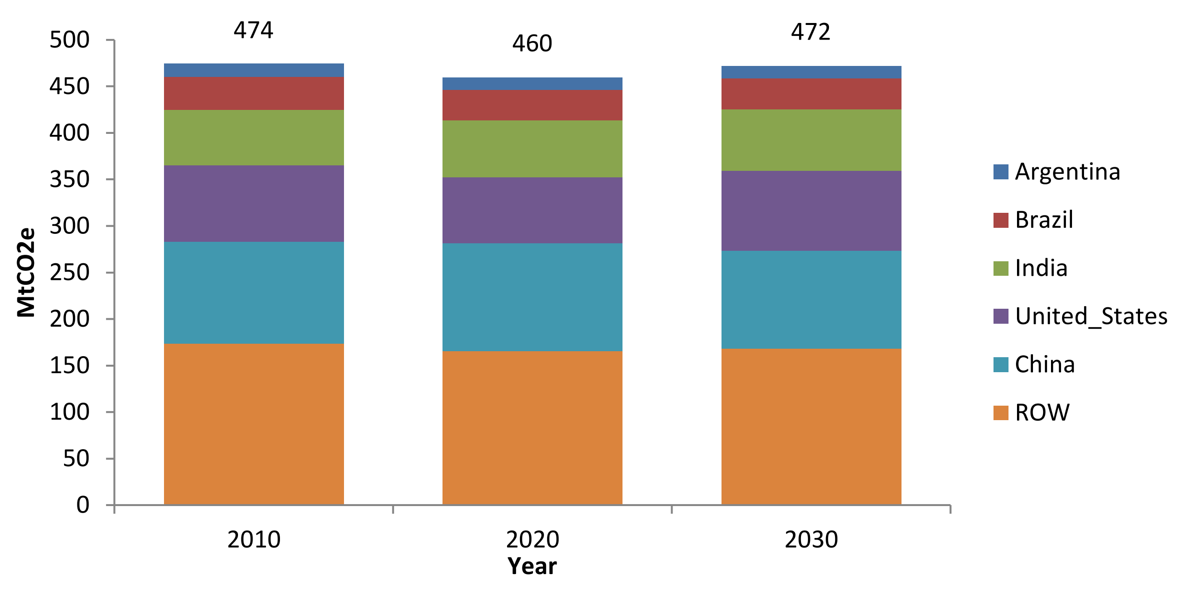
[3] The IMPACT outputs separated the world into 116 regions, with larger countries defined individually and smaller countries combined into regions. A mapping was created between IMPACT regions and the 195 countries in this analysis, using shares of country-level Non-Rice Croplands population in 2010 based on USEPA (2012) to disaggregate regional projections from the IMPACT model to individual countries within each region.

[4] The business as usual forecast excludes such potential drivers as deforestation, biofuels expansion and changes in consumer preferences for meat.

[5] The relative constant GHG emissions projected in the baseline are mainly driven by the DAYCENT modeling that assumes the same management practices are applied throughout the study period as well as relatively small changes in demand in the IMPACT model projections.

Figure 1-2 presents the projected net GHG emissions ($N_2O$ and $CH_4$) from the top-five emitting countries. The top 5 countries of China, India, the United States, Brazil and Argentina represent about 63% of global net emissions from cropland in 2010.

Figure 1-2: Baseline Net GHG Emissions from Non-Rice Croplands, Top Five Emitting Countries



Note: ROW indicates Rest of the World

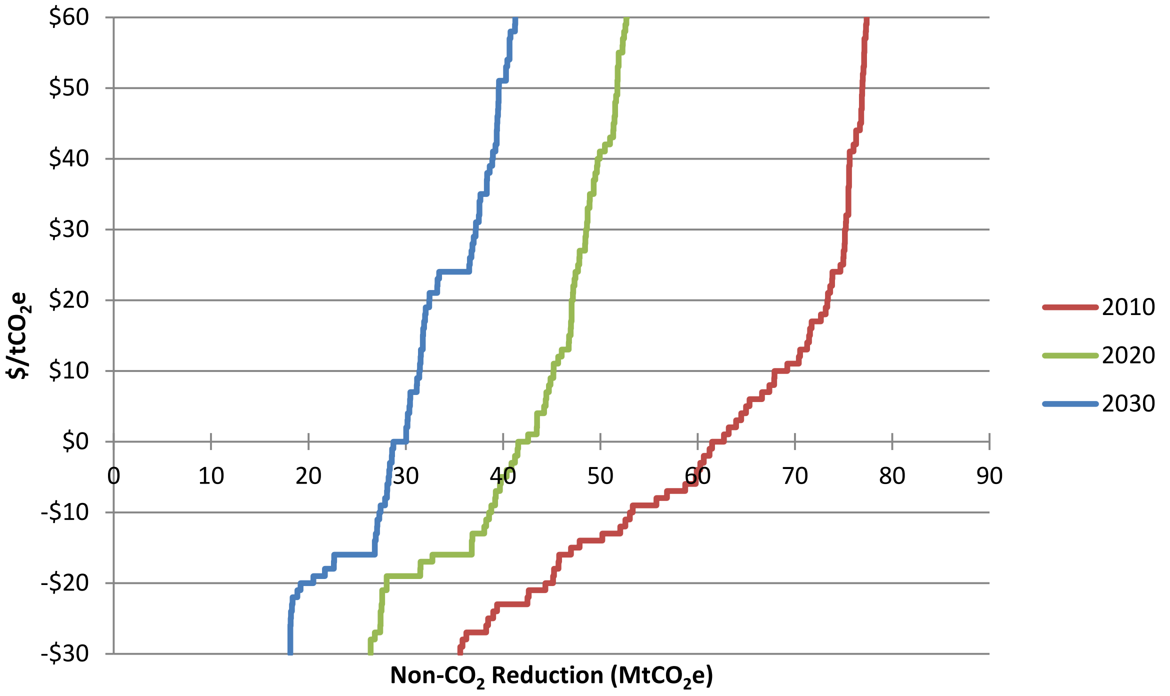
## Table 1-1: Projected Net GHG Baseline Emissions from Non-Rice Croplands by Country: 2010–2030 ($MtCO_2e$)

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| Top 5 Emitting Countries | | | | | | |
| China | 109 | 123 | 116 | 115 | 105 | -0.2% |
| U.S.A | 82 | 80 | 71 | 84 | 86 | 0.2% |
| India | 60 | 58 | 61 | 61 | 66 | 0.5% |
| Brazil | 35 | 32 | 33 | 33 | 34 | -0.2% |
| Argentina | 14 | 16 | 14 | 16 | 13 | -0.2% |
| Rest of Regions | | | | | | |
| Asia | 31 | 26 | 27 | 27 | 27 | -0.8% |
| Africa | 31 | 26 | 30 | 28 | 29 | -0.3% |
| Europe | 62 | 56 | 59 | 63 | 60 | -0.2% |
| Middle East | 4 | 9 | 7 | 9 | 10 | 4.2% |
| Central & South America | 13 | 14 | 15 | 15 | 15 | 0.8% |
| Eurasia | 18 | 14 | 15 | 15 | 13 | -1.4% |
| North America | 15 | 15 | 14 | 16 | 14 | -0.2% |
| World Totals | 474 | 470 | 460 | 482 | 472 | 0.0% |

Figure 1-3 presents the MAC curves for the global non-rice croplands, in 2010, 2020 and 2030. The non-rice croplands MAC curves presented in this chapter are distinctive because they show less abatement potential in 2030 than in 2010 – the 2030 curve is to the left or "inside" the 2020 and 2010 curves. This is due to the effect of soils becoming "saturated" with C and reaching a new equilibrium within a few years of a management change. In other words, the 2020 mitigation estimate is the change from the baseline emissions in 2020, *for a management change started in 2010*.

MAC analysis of the mitigation options described above suggests that at a relatively low carbon price of $5 per ton of $CO_2$ equivalent ($/t$CO_2$e), net GHG abatement potential for global non-rice cropland soils is approximately 65 Mt$CO_2$e, or about 13% of its baseline net emissions of 476 Mt$CO_2$e in 2010. Mitigation potential at $5/ t$CO_2$e reduces to 10% of the sector's baseline emissions in 2020 and 6% in 2030.

Figure 1-3: Global MAC Curve for Net GHG Reductions from Non-Rice Cropland Soils



The following section offers a brief description of the model used. Section IV.20.3 presents selected abatement technologies, their technical specifications, costs and potential benefits. Section IV.20.4 discusses the MAC analysis and estimated abatement potential and at global and regional levels. The final section discusses uncertainties and limitations.

## V.1.2 Emissions from Non-Rice Croplands

### V.1.2.1 Methodology

The DAYCENT ecosystem model was used to estimate crop yields, $N_2O$ and $CH_4$ emissions, and soil C stocks in this analysis. DAYCENT is a process-based model (Parton et al., 1998; Del Grosso et al., 2001) that simulates biogeochemical C and N fluxes between the atmosphere, vegetation, and soil by representing the influence of environmental conditions on these fluxes including soil characteristics and weather patterns, crop and forage qualities, and management practices. DAYCENT utilizes the soil C modeling framework developed in the Century model (Parton et al. 1987, 1988, 1994; Metherell et al. 1993), with refinement to simulate C dynamics at a daily time-step. Key processes simulated by DAYCENT include crop production, organic matter formation and decomposition, soil water and temperature regimes by layer, in addition to nitrification and denitrification processes. DAYCENT has been evaluated in several studies (e.g., Del Grosso et al. 2002, 2005, 2009) and has also been recently adopted by EPA to develop the soil C and soil estimates for the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks (EPA, 2013) submitted to the UNFCCC.

Crop yields, direct $N_2O$ and $CH_4$ emissions, and soil organic C stock changes were simulated by DAYCENT at a 0.5°grid resolution. Indirect $N_2O$ emissions[6] were estimated simulated amounts of nitrate leaching, N runoff in overland water flow, and $NO_x$ emissions from a site according to the DAYCENT model[7] combined with the IPCC default factors for indirect $N_2O$ emissions (De Klein et al., 2006). In order to represent the longer term effect of cultivation on soil C, simulations started in 1700 after a simulation of 3000 years of native vegetation, which is a similar procedure to the methods applied in the US Greenhouse Gas Inventory for agricultural soil C and $N_2O$ (USEPA, 2013).

For this study, a number of data sources were used to establish the business-as-usual baseline conditions and simulate alternative management options for the global non-rice croplands. Weather data were based on a dataset generated by the North American Carbon Program at a 0.5°resolution with daily minimum and maximum temperatures and daily precipitation.[8] The soils data were based on the FAO Digitized Soil Map of the World (FAO 1996). Major cropland areas of the world were simulated according to a global cropland map developed by Ramankutty et al. (2008), with grid cells with less than 5% cropland area excluded in the analysis.

Native vegetation data are described in Cramer and Field (1999) and Melillo et al. (1993). Natural vegetation was converted to cropland in the DAYCENT simulations at an approximate first year of cultivation, based on historical records compiled by Ramankutty and Foley (1998) and Ramankutty et al., (2008).

Due to lack of global data availability, low input crop production with intensive tillage practices were assumed prior to 1950, consistent with typical practices in that time period. From 1950 to 2010, management was based on data including tillage and residue management, weeding practices, mineral N fertilization, manure N amendments to soils, and irrigation. Crop planting and harvest dates were based on Sacks et al. (2008). Crops were assumed to grow in monoculture due to insufficient data for determining typical crop rotation practices from the global datasets. Maize and sorghum were double-cropped in some regions based on Sacks et al. (2008). Model performance was evaluated by comparing simulated crop yields to observed crop yields (Monfreda et al. 2008), and minor adjustments were made to parameters in order to be reasonably consistent with the observed yields. More detail on the input data and simulation framework is provided in Appendix O.

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[6] $N_2O$ emissions occurring with transport of N from one site to another where $N_2O$ emissions occur with N addition.

[7] The same method as used in the US National Greenhouse Gas Inventory (USEPA, 2013).

[8] The Multi-Scale Synthesis and Terrestrial Model Intercomparison Project (MsTMIP) developed consistent weather data in order to "isolate, interpret, and address differences in process parameterizations among [terrestrial biospheric models]" Source: http://nacp.ornl.gov/MsTMIP.shtml.

Global DAYCENT modeling was carried out for irrigated and non-irrigated production systems for maize, wheat, barley, soybean and sorghum. Crop yields and GHG fluxes were simulated at the 0.5°resolution for periods 2000-2010 and 2011-2030 with five-year increments. A baseline scenario is established for each crop production system assuming business-as-usual management practices described above. Seven mitigation scenarios were then analyzed (see Section 3.4 below).

Emissions estimated by the DAYCENT model for major crop types (maize, wheat, barley, sorghum, soybean and millet) were based on emissions per unit (m2) of physical area in each in each 0.5° x 0.5° grid cell, and so were multiplied by an estimate of cropland area in each grid cell to compute total GHG emissions. We approximated crop-specific areas using harvested area data. First, crop-specific harvested areas for each 0.5° x 0.5° grid cell were estimated from Monfreda et al. (2008). For each grid cell where we simulated double-cropping for maize or sorghum, we reduced maize or sorghum harvested area by 50%. Next, harvested areas for analogous crops were added to areas of the major crop types (i.e., oats with wheat, rye with barley, green corn with maize, and lentil, green bean, string bean, broad bean, cow pea, chickpea and dry bean with soybeans) to increase the coverage of cropland area. The sums of harvested areas fractions computed in this manner were less than total cropland areas (Ramankutty et al. 2008) for all but 1.6% of grid cells. In the last step, total harvested area was scaled to match at the country scale data on harvested areas reported in FAOSTAT. By including analogous crops and matching FAOSTAT harvested areas, the cropland area simulated by DAYCENT was about 61% of the global non-rice cropland areas reported by FAOSTAT.

Projected baseline emissions and crop production were then established for both irrigated and rainfed production systems using simulated yields and GHG emissions rates from DAYCENT model and adjusting with projected growth rates of these production systems by IFPRI's International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. In DAYCENT, crop production areas were held constant at the 2010 level to obtain the biophysical effects of management practice changes on crop yields and GHG fluxes. Projected acreage changes from IMPACT model reflect socio-economic drivers such as population growth and technological changes to meet global food demand (Nelson et al., 2010).

## V.1.3 Abatement Measures and Engineering Cost Analysis

### V.1.3.1 Mitigation Technologies

The mitigation options evaluated in this analysis were based on review of the literature to identify the most promising options, while also taking data availability and potential for modeling within DAYCENT into consideration. The mitigation options represent alternative management practices that would alter crop yields and the associated GHG emissions, including adoption of no-till management, split N fertilization applications, application of nitrification inhibitors, increased N fertilization (20% increase over business-as-usual), decreased N fertilization (20% reduction from business-as-usual), and 100% crop residue incorporation.

The N management practices (split N fertilization, nitrification inhibitors, increased and decreased N fertilization) influence $N_2O$ emissions in addition to soil organic C stocks due to reduced or enhanced C inputs associated with the level of crop production. Smith et al. (2007) estimated that 89% of the overall technical potential for mitigation of agricultural greenhouse gas emissions is associated with carbon sequestration in soils. Although soil organic C stock fluxes are negligible in the baseline, there is considerable opportunity to modify stocks in the future. Levels of soil organic matter and in particular soil carbon both influence, and are influenced by cropland productivity. Other things being equal, higher crop yields may increase soil C wherever more crop residue can be incorporated into the soil. Similarly, reducing crop residue removal would impact soil organic C stocks by changing the amount of C input to the soil. Practices such as adoption of conservation tillage, restoration of degraded lands, improved water and nutrient management, and cropping intensification can increase soil carbon by enhancing C inputs to soils from greater crop production or decrease the losses of C from soils with lower decomposition rates (Paustian et al. 1997; Six et al., 2000).

### No-Till Adoption

All cultivation and field preparation events were removed except for seeding, which occurred directly into the residue.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: There are reductions in labor costs associated with the reduction in field preparation that are based on data from U.S. Department of Agriculture (USDA) Agricultural Resource Management Survey (ARMS) data, which provides labor estimates for conventional and conservation tillage on both irrigated and rain-fed land by major crop. Conversion to no-till would require purchasing equipment for direct planting. However, if this equipment is purchased in place of equipment used for traditional tillage, there may be little incremental capital cost 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 lead to reduced equipment depreciation. Thus, no incremental capital costs were assumed for no-till adoption.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

### Reduced Fertilization

This option reduced baseline fertilizer application levels by 20%.

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option reduces operation costs by the value of fertilizer withheld.
- Additional Factors: In cases where yields decrease as a result, the reduction in production is valued at the market price. No tax or other benefits are included in this option.

### Increased Fertilization

This option increased baseline fertilizer application levels by 20%.

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option increases operation costs by the value of additional fertilizer used.
- Additional Factors: In cases where yields increase as a result, production is valued at the market price. No tax or other benefits are included in this option.

### Split N Fertilization

Under this option, the baseline N application amount was applied in three separate and equal amounts (planting day, 16 days after planting day, and 47 days after planting day) instead of once on planting day.[9]

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: This option was assumed to require 14% more labor to account for additional passes over the fields to apply fertilizer multiple times rather than only once.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

### Nitrification Inhibitors

The baseline N application amount was applied once annually on date of planting. Nitrification inhibitors were applied at time of fertilization, and reduced nitrification by 50% for 8 weeks[10].

- Applicability: This option is available in all regions and all time periods with nonzero baseline fertilizer application levels.
- Economic Applicability and Cost: The costs of this option include the cost of the nitrification inhibitor, assumed to be $20 per hectare for the United States (Scharf et al., 2005) and scaled to other regions.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

### 100% Residue Incorporation

In this option, all crop residue was assumed to remain after harvest. This option serves to evaluate how reducing removals would impact soil organic C stocks.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: No cost is associated with this option.
- Additional Factors: In cases where yields change as a result, production is valued at the market price. No tax or other benefits are included in this option.

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[9] Following Del Grosso et al. (2009).

[10] Following Del Grosso et al. (2009) and Branson et al. (1992).

Table 1-2: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric tons of Grain per Hectare)

| | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| **Maize** | | | | | |
| Base Yield | 3.64 | 3.64 | 3.64 | 3.59 | 3.6 |
| No-Till | 0 | -0.25 | -0.17 | -0.12 | -0.07 |
| Optimal N fertilization* | 0 | 2.9 | 3.05 | 3.1 | 3.08 |
| Split N Fertilization | 0 | 0.16 | 0.17 | 0.19 | 0.18 |
| 100% Residue Inc. | 0.22 | 0.23 | 0.24 | 0.24 | 0.24 |
| Nitrification Inhibitors | 0 | -0.01 | -0.01 | -0.01 | -0.01 |
| Reduced Fertilization | -0.05 | -0.36 | -0.39 | -0.4 | -0.4 |
| Increased Fertilization | 0.04 | 0.28 | 0.29 | 0.31 | 0.31 |
| **Millet** | | | | | |
| Base Yield | 1.16 | 1.17 | 1.14 | 1.11 | 1.12 |
| No-Till | 0 | -0.09 | -0.07 | -0.05 | -0.03 |
| Optimal N fertilization* | 0 | 2.38 | 2.59 | 2.55 | 2.61 |
| Split N Fertilization | 0 | 0.09 | 0.09 | 0.09 | 0.08 |
| 100% Residue Inc. | 0.09 | 0.08 | 0.09 | 0.09 | 0.08 |
| Nitrification Inhibitors | 0 | 0.02 | 0.03 | 0.03 | 0.03 |
| Reduced Fertilization | -0.01 | -0.08 | -0.09 | -0.1 | -0.1 |
| Increased Fertilization | 0.01 | 0.08 | 0.09 | 0.09 | 0.09 |
| **Sorghum** | | | | | |
| Base Yield | 2.34 | 2.34 | 2.35 | 2.33 | 2.32 |
| No-Till | 0 | -0.18 | -0.13 | -0.1 | -0.06 |
| Optimal N fertilization* | 0 | 3.07 | 3.27 | 3.19 | 3.25 |
| Split N Fertilization | 0 | 0.14 | 0.14 | 0.13 | 0.14 |
| 100% Residue Inc. | 0.15 | 0.15 | 0.17 | 0.16 | 0.17 |
| Nitrification Inhibitors | 0 | -0.02 | -0.03 | -0.02 | -0.02 |
| Reduced Fertilization | -0.03 | -0.22 | -0.25 | -0.26 | -0.27 |
| Increased Fertilization | 0.03 | 0.19 | 0.22 | 0.22 | 0.23 |
| **Winter Wheat** | | | | | |
| Base Yield | 2.94 | 2.92 | 2.89 | 2.8 | 2.87 |
| No-Till | 0 | -0.13 | -0.11 | -0.07 | -0.05 |
| Optimal N fertilization* | 0 | 1.55 | 1.82 | 1.87 | 1.78 |
| Split N Fertilization | 0 | 0.09 | 0.1 | 0.11 | 0.11 |
| 100% Residue Inc. | 0.1 | 0.11 | 0.12 | 0.13 | 0.12 |
| Nitrification Inhibitors | 0 | 0.03 | 0.04 | 0.04 | 0.05 |
| Reduced Fertilization | -0.01 | -0.22 | -0.26 | -0.25 | -0.27 |
| Increased Fertilization | 0 | 0.19 | 0.2 | 0.2 | 0.21 |

(continued)

Table 1-2: DAYCENT Base Mean Yields, and Differences from Mean Yield for Mitigation Strategies, by Year (Metric tons of Grain per Hectare) (continued)

| | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Spring Wheat | | | | | |
| Base Yield | 2.85 | 2.94 | 2.92 | 2.85 | 2.83 |
| No-Till | 0 | -0.16 | -0.13 | -0.1 | -0.08 |
| Optimal N fertilization* | 0 | 1.49 | 1.46 | 1.4 | 1.36 |
| Split N Fertilization | 0 | 0.07 | 0.08 | 0.08 | 0.08 |
| 100% Residue Inc. | 0.1 | 0.11 | 0.11 | 0.11 | 0.11 |
| Nitrification Inhibitors | 0 | 0.02 | 0.03 | 0.03 | 0.03 |
| Reduced Fertilization | -0.03 | -0.2 | -0.22 | -0.21 | -0.21 |
| Increased Fertilization | 0.02 | 0.14 | 0.15 | 0.14 | 0.14 |
| Winter Barley | | | | | |
| Base Yield | 3.55 | 3.59 | 3.58 | 3.5 | 3.57 |
| No-Till | 0 | -0.2 | -0.21 | -0.15 | -0.1 |
| Optimal N fertilization | 0 | 2.64 | 3.11 | 3.07 | 3 |
| Split N Fertilization | 0 | 0.04 | 0.06 | 0.06 | 0.05 |
| 100% Residue Inc. | 0.35 | 0.37 | 0.39 | 0.39 | 0.39 |
| Nitrification Inhibitors | 0 | 0.01 | 0.03 | 0.03 | 0.03 |
| Reduced Fertilization | 0 | -0.34 | -0.39 | -0.41 | -0.43 |
| Increased Fertilization | 0 | 0.31 | 0.35 | 0.36 | 0.38 |
| Spring Barley | | | | | |
| Base Yield | 2.76 | 2.83 | 2.79 | 2.77 | 2.77 |
| No-Till | 0 | -0.29 | -0.24 | -0.2 | -0.17 |
| Optimal N fertilization* | 0 | 1.8 | 1.8 | 1.67 | 1.63 |
| Split N Fertilization | 0 | 0.08 | 0.09 | 0.09 | 0.08 |
| 100% Residue Inc. | 0.19 | 0.21 | 0.22 | 0.21 | 0.21 |
| Nitrification Inhibitors | 0 | 0.01 | 0.02 | 0.02 | 0.02 |
| Reduced Fertilization | -0.04 | -0.28 | -0.31 | -0.31 | -0.32 |
| Increased Fertilization | 0.04 | 0.24 | 0.26 | 0.25 | 0.25 |
| Soybeans | | | | | |
| Base Yield | 2.9 | 2.95 | 2.94 | 2.92 | 2.92 |
| No-Till | 0 | -0.02 | -0.02 | -0.01 | -0.01 |
| Optimal N fertilization* | 0 | 0.06 | 0.07 | 0.07 | 0.07 |
| Split N Fertilization | 0 | 0 | 0 | 0 | 0 |
| 100% Residue Inc. | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Nitrification Inhibitors | 0 | 0 | 0.01 | 0.01 | 0.01 |
| Reduced Fertilization | 0 | -0.01 | -0.01 | -0.01 | -0.01 |
| Increased Fertilization | 0 | 0.01 | 0.01 | 0.01 | 0.01 |

*Note: Optimal N Fertilization, discussed below, is excluded from the main MAC analysis and presented for information only

## V.1.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-$CO_2$ sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

This section describes the general modeling approach applied in this sector, which serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

### V.1.4.1 Estimate Abatement Measure Costs and Benefits

As a general framework of the MAC analysis, the break-even price for each mitigation option is calculated by setting total benefits (i.e., higher yields ) equal to total costs of a given mitigation option. This framework, also referred to as the International Marginal Abatement Cost (IMAC) model, is documented in USEPA (2006) and Beach et al. (2008).

### V.1.4.2 MAC Analysis Results

Global abatement potential in the Non-Rice Croplands sector equates to approximately 6 to 13% of its total annual emissions between 2010 and 2030 at a relatively low carbon price of $5 per ton of $CO_2$ equivalent ($/t$CO_2$e). Table 1-3 presents mitigation potential at selected break-even prices for 2030. GHG mitigation and its cost-effectiveness vary significantly by country or region. Figure 1-4 displays the MAC curve of the top-five emitting countries in 2010 and 2030.

Table 1-3: Abatement Potential at Selected Break-Even Prices in 2030 (No "Optimal Fertilization "Scenario)

| | Break-Even Price ($/t$CO_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | –10 | –5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| Top 5 Emitting Countries | | | | | | | | | | | |
| China | 11.2 | 11.2 | 11.2 | 11.2 | 11.3 | 11.3 | 11.3 | 12.1 | 12.1 | 12.1 | 12.8 |
| U.S.A | 5.4 | 5.4 | 5.5 | 5.5 | 5.5 | 5.5 | 5.5 | 8.7 | 8.7 | 8.8 | 10.9 |
| India | 2.5 | 2.9 | 3.1 | 3.1 | 3.6 | 3.6 | 3.6 | 3.6 | 4.0 | 4.0 | 5.3 |
| Brazil | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 2.1 |
| Argentina | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 1.0 |
| Rest of Region | | | | | | | | | | | |
| Africa | 1.7 | 1.9 | 2.1 | 2.2 | 2.2 | 2.2 | 2.2 | 2.3 | 2.3 | 2.8 | 3.9 |
| Asia | 1.5 | 1.6 | 1.8 | 1.9 | 1.9 | 2.0 | 2.0 | 2.0 | 2.3 | 2.5 | 3.0 |
| Central & South America | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 | 0.8 | 0.8 | 0.8 | 0.9 | 1.1 | 1.8 |
| Eurasia | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 1.7 | 2.3 | 2.7 |
| Europe | 3.0 | 3.0 | 3.4 | 3.5 | 3.6 | 3.6 | 3.8 | 4.1 | 4.3 | 6.0 | 8.7 |
| Middle East | 0.2 | 0.3 | 0.8 | 0.8 | 0.8 | 0.8 | 1.3 | 1.3 | 1.4 | 1.4 | 1.7 |
| North America | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 0.8 | 0.8 | 0.9 | 0.9 | 1.0 | 1.9 |
| World Total | 27.4 | 28.3 | 30.0 | 30.4 | 31.5 | 31.8 | 32.4 | 37.2 | 39.6 | 43.0 | 55.8 |

Figure 1-4: Marginal Abatement Cost Curve for Top-Five Emitting Countries in 2010 and 2030

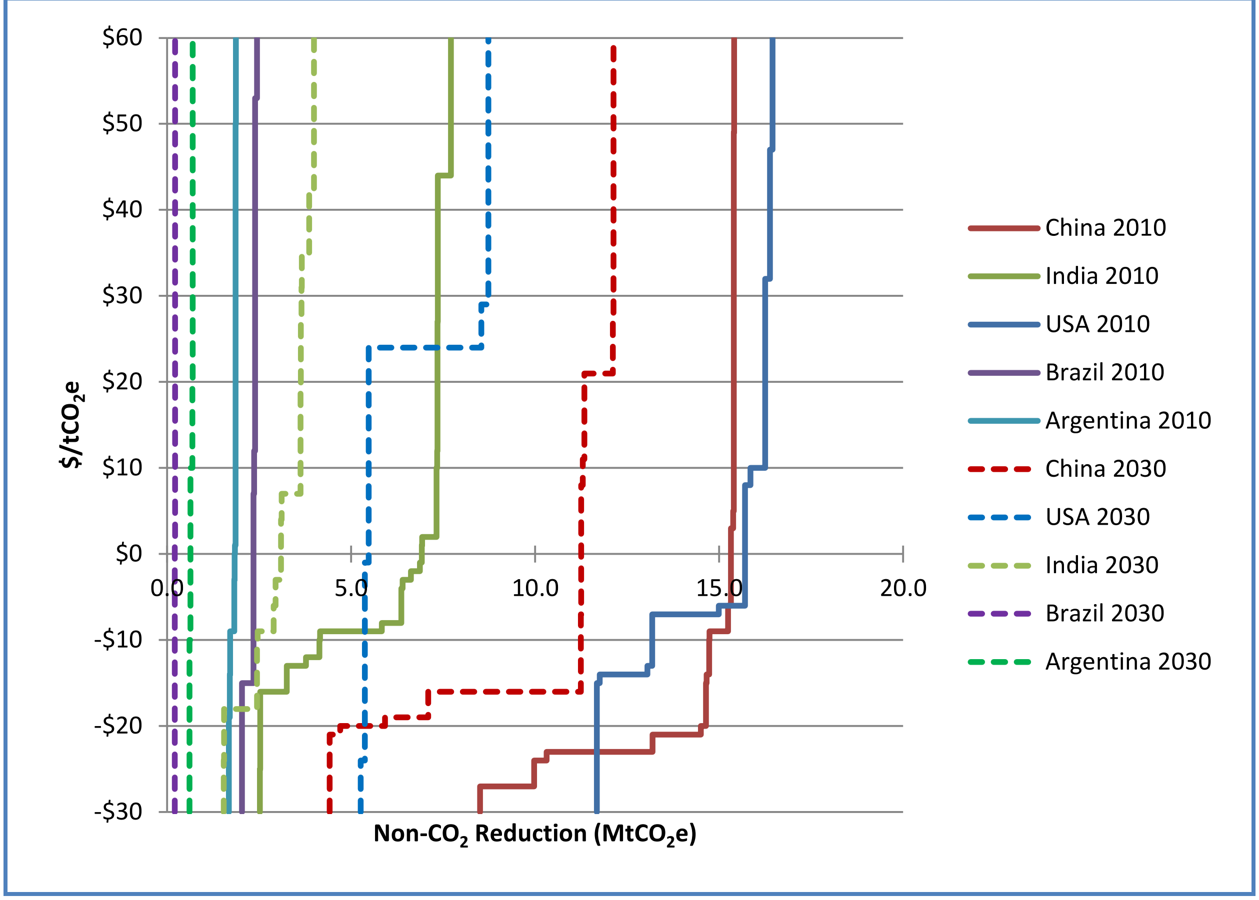

Table 1-4 below presents a summary of estimated global total mitigation potential by mitigation option. Overall the MAC analysis results suggest that No-till is the most effective strategy for GHG mitigation in cropland soil management.[11] This option accounts for approximately 70% of the total global mitigation potential in 2010 and 43.7% in 2030. The second most significant mitigation option is reduced fertilization, accounting for about 16% of the global total mitigation potential in 2010 and 40% in 2030. Adoption of nitrification inhibitors and split fertilization may also make significant contributions to net GHG reductions from cropland soil management.

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[11] As discussed above, mitigation potential from adoption of no-till practice is likely over-estimated with 100% conventional tillage assumed in the business-as-usual baseline.

Table 1-4: Global Total Abatement Potential from Cropland Soils by Measure ($MtCO_2e$) ("Optimal N Fertilization" Strategy excluded)

| | GHG Mitigation by Option (total all prices) | | | | | |
|---|---|---|---|---|---|---|
| | 2010 | | 2020 | | 2030 | |
| Reduced Fertilization | 14.05 | 16% | 18.09 | 26% | 22.39 | 40.1% |
| Increased Fertilization | 0.30 | 0% | 0.03 | 0% | 0.00 | 0.0% |
| 100% Residue Incorporation | 0.33 | 0% | 0.18 | 0% | 0.04 | 0.1% |
| Nitrification Inhibitors | 7.08 | 8% | 6.46 | 9% | 6.66 | 11.9% |
| Split N Fertilization | 4.38 | 5% | 3.14 | 4% | 2.36 | 4.2% |
| No-Till Adoption | 60.82 | 70% | 42.47 | 60% | 24.40 | 43.7% |
| Optimal N Fertilization | 0.00 | 0% | 0.00 | 0% | 0.00 | 0.0% |
| TOTAL | 86.94 | 100% | 70.37 | 100% | 55.85 | 100.0% |

The relative mitigation potentials of no-till and reduced fertilization illustrate the difference between dynamics of soil C and $N_2O$ and are worth a closer look. No-till dominates the mitigation potentials in the early years, owing to its large effect on soil C. However, this dominance disappears over time as soils become "saturated" with C. By 2030, the mitigation potential (limited to $N_2O$) of reduced fertilization nearly equals that of no-till. Over an even longer time scales, only the $N_2O$ flux remains as soils reach a new equilibrium level of Soil C.

## V.1.5 Sensitivity Analysis

We tested the sensitivity of the results by adding an additional "Optimal N Fertilization" option, which has substantial effects on global yields and emissions.

### *Optimal N fertilization*

This option allows the model to maximize soil carbon through optimization of fertilizer inputs, giving a "best case" result of the application of existing technology and crop patterns. Of course, baseline levels vary widely from this optimum with some regions over-applying N and many under-applying N relative to crop needs. This case shows what could be achieved if nutrient stress is removed at each time step.

- Applicability: This option is available in all regions and all time periods
- Economic Applicability and Cost: Due to the large number of ways this option might be put in practice, costs are limited to the change in N used.
- Additional factors: In cases where yields increase as a result, production is valued at the market price. No tax or other benefits are included in this option.

This analysis resulted in the global MAC curve shown in Figure 1-5, and summarized in Table 1-5. With Optimal N Fertilization included in the analysis, global mitigation increases from a maximum of 86 Mt to 129 Mt in 2010. Global mitigation in 2030 increases from a maximum of 56 Mt to about 86 Mt.

Overall the MAC analysis results suggest that optimal fertilization to achieve maximum crop yields is potentially the single most significant source of GHG mitigation in cropland soil management. This option accounts for approximately 44% of the total global mitigation potential in 2010 and 2030. The second most significant mitigation option is no-till practice, accounting for about 39% of the global total mitigation potential.[12] Reduction in N fertilizer application and adoption of nitrification inhibitors would also make substantial contributions to net GHG reductions from cropland soil management.

Figure 1-5: Global Abatement Potential in Non-rice Croplands Management: 2010, 2020, and 2030 (Includes "Optimal N Fertilization" Strategy)

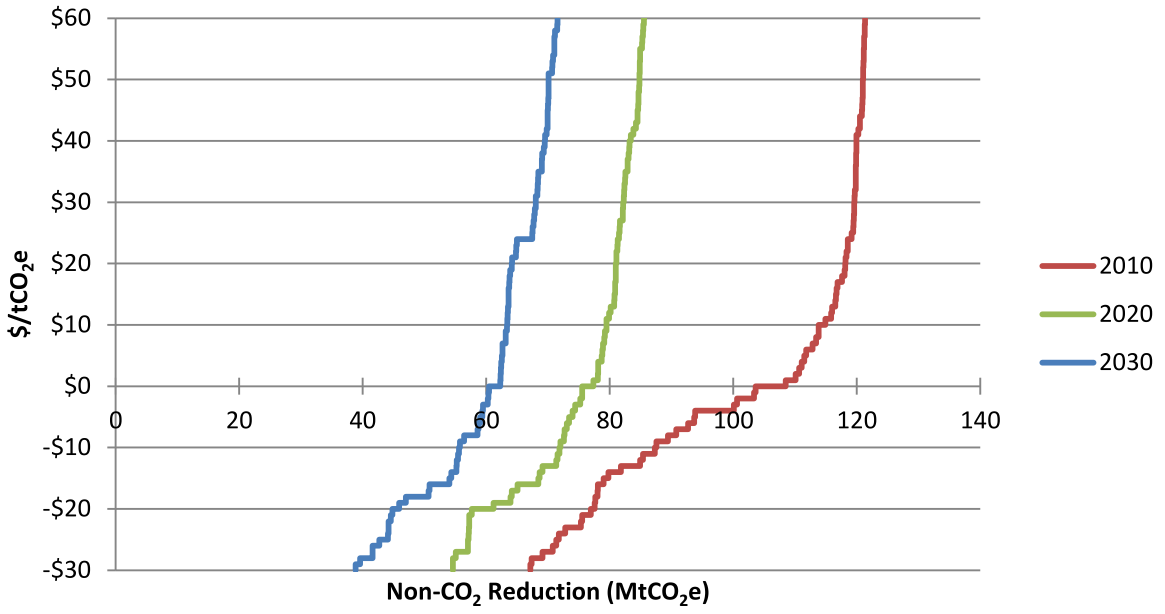

Table 1-5: Global Total Abatement Potential from Cropland Soils by Measure ($MtCO_2e$) (Includes "Optimal N Fertilization" Strategy)

| | GHG Mitigation by Option (total all prices) | | | | | |
|---|---|---|---|---|---|---|
| | 2010 | | 2020 | | 2030 | |
| Reduced Fertilization | 11.1 | 9% | 0.0 | 14% | 17.7 | 21% |
| Increased Fertilization | 0.2 | 0% | 0.0 | 0% | 0.0 | 0% |
| 100% Residue Incorporation | 0.3 | 0% | 0.1 | 0% | 0.0 | 0% |
| Nitrification Inhibitors | 6.0 | 5% | 5.6 | 6% | 6.1 | 7% |
| Split N Fertilization | 3.6 | 3% | 2.7 | 3% | 2.2 | 3% |
| No-Till Adoption | 50.8 | 39% | 35.4 | 35% | 20.9 | 25% |
| Optimal N Fertilization | 57.3 | 44% | 42.2 | 42% | 37.7 | 45% |
| TOTAL | 129.4 | 100% | 86.1 | 100% | 84.7 | 100% |

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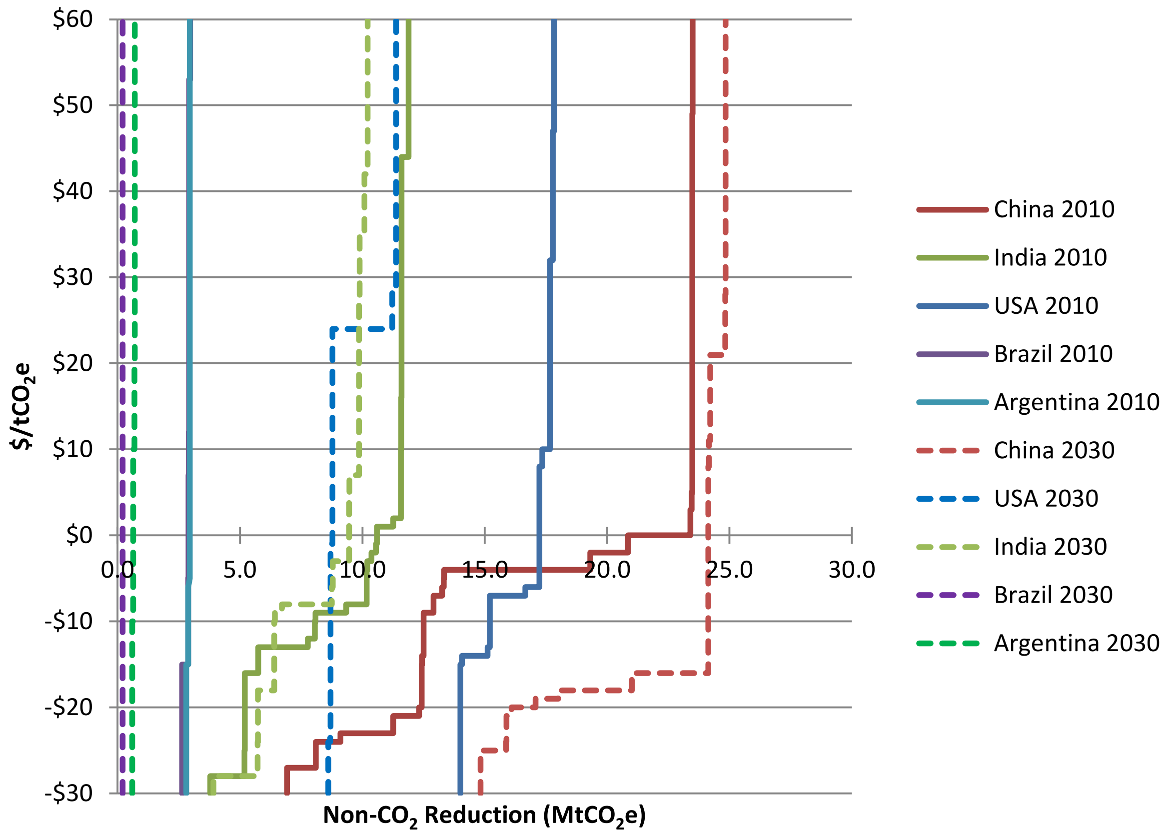
[12] As discussed above, mitigation potential from adoption of no-till practice is likely over-estimated with 100% conventional tillage assumed in the business-as-usual baseline.

Figure 1-6 shows the effect on the top-5 countries. With "Optimal N Fertilization" included as a strategy, China has the largest mitigation potential of any country and is also among the few countries that have mitigation potential that increases over the 2010-2030 period. This appears to be related to fertilizer use that is much higher than optimal.[13] This suggests that $N_2O$ emissions may be reduced without a yield, or soil C, penalty.

Figure 1-6: Marginal Abatement Cost Curve for Top 5 Emitters in 2010, 2030 (Includes "Optimal N Fertilization" Strategy)



## V.1.5 Uncertainties and Limitations

Given the complexities of the global crop production sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Optimistic assumptions on technology adoption.*** Mitigation technologies represent technical potentials. The analysis assumes that if mitigation technology is considered feasible in a country

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[13] In the DAYCENT optimal fertilization scenario, where the model determined the optimal fertilizer rates, fertilizer use typically decreased in China between 30 and 50% for major crops as compared to baseline levels. $N_2O$ emissions also declined.

or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially slow the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.

- ***Availability and quality of data to represent the highly complex and heterogeneous crop production systems of the world.*** Compared to the previous EPA marginal abatement cost curve analysis (USEPA, 2006), there are major improvements in the datasets used to represent the global crop production systems and the business-as-usual baseline conditions. However, data in some areas, such as management practices which have significant influence on the GHG fluxes, are not always available for all countries or regions. Approximations had to be made based on limited literature or expert judgment. Moreover, collecting and developing regionally specific cost estimates of emerging and/or not widely adopted management practices or mitigation measures has been a challenge and in some cases global datasets had to be used.
- ***Biophysical modeling uncertainties.*** The evaluation of simulated crop yields against observed yields suggests that DAYCENT modeling performance varies by crop[14], leading to potential biases in estimated GHG emissions. Model structure is found to be the largest contributor to uncertainty in simulation results using DAYCENT, typically more than 75% of overall uncertainty in estimates (Ogle et al. 2010, Del Grosso et al. 2010). Further model evaluation will be carried out to understand potential model bias and prediction error using empirical based procedure discussed in Ogle et al. (2007). In addition, soil carbon, which has a significant impact on the net GHG emissions and mitigation potential from the sector, is particularly challenging to simulate given the lack of monitoring data at the global scale. Sensitivity tests would be useful to assess how alternative modeling approaches and assumptions may influence modeling results.
- ***Potential interactions of multiple mitigation measures are not fully addressed in this analysis.*** In this analysis, mitigation options are applied to independent segments of the crop production systems to avoid double counting. In reality, multiple mitigation options can be applied, and their order of adoption and potential interactions may affect the aggregate GHG mitigation. Alternative approach should be investigated to provide more realistic representation of economic applicability of potential mitigation measures.

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[14] Overall, simulated yields for maize agree reasonably well with observed yields; simulated average yields for wheat, barley and sorghum are lower than observed yields; simulated average yields for soybean are above observed yields.

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# V.2. Rice Cultivation

## V.2.1 Sector Summary

Rice cultivation is an important global source of methane ($CH_4$) and nitrous oxide ($N_2O$) emissions. There are also changes in soil organic carbon (C) stocks and associated $CO_2$ fluxes. When paddy fields are flooded, decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions in the soil. Anaerobic decomposition of soil organic matter by methanogenic bacteria generates $CH_4$. Some of this $CH_4$ is dissolved in the floodwater, but the remainder is released to the atmosphere, primarily through the rice plants themselves. Minor amounts of $CH_4$ also escape from the soil via diffusion and bubbling through the floodwaters. In addition, as with other crops, human activities influence soil $N_2O$ emissions through addition of synthetic and organic nitrogen fertilizers and other practices and soil C stocks through residue management as well as any practices that effect crop yields.

In 2010, the net global GHG emissions from rice cultivation were approximately 561 $MTCO_2e$. The top 5 emitting countries – India, Indonesia, Bangladesh, Vietnam, and China –accounted for 77% of the global total net emissions. Figure 2-1 displays the baseline net global GHG emissions for the rice sector. Net GHG emissions from rice cultivation are projected to grow by 33% to 750 $MTCO_2e$ between 2010 and 2030. There is a small amount of growth in emissions occurring in developing regions to meet the demand for rice products from growing populations and higher incomes, but the biggest contributor to the increase in net GHG emissions simulated between 2010 and 2030 is a reduction in the soil C sink over time. In the Denitrification-Decomposition (DNDC) model, there are fairly large increases in soil C in the initial periods in many countries as they have recently changed practices to incorporate more residues into the soil. However, as soil C moves to a new equilibrium, the incremental changes in future years become much smaller and offset a smaller portion of the non-$CO_2$ emissions.

**Figure 2-1: Net GHG Emissions Projections for Rice Cultivation: 2000–2030**

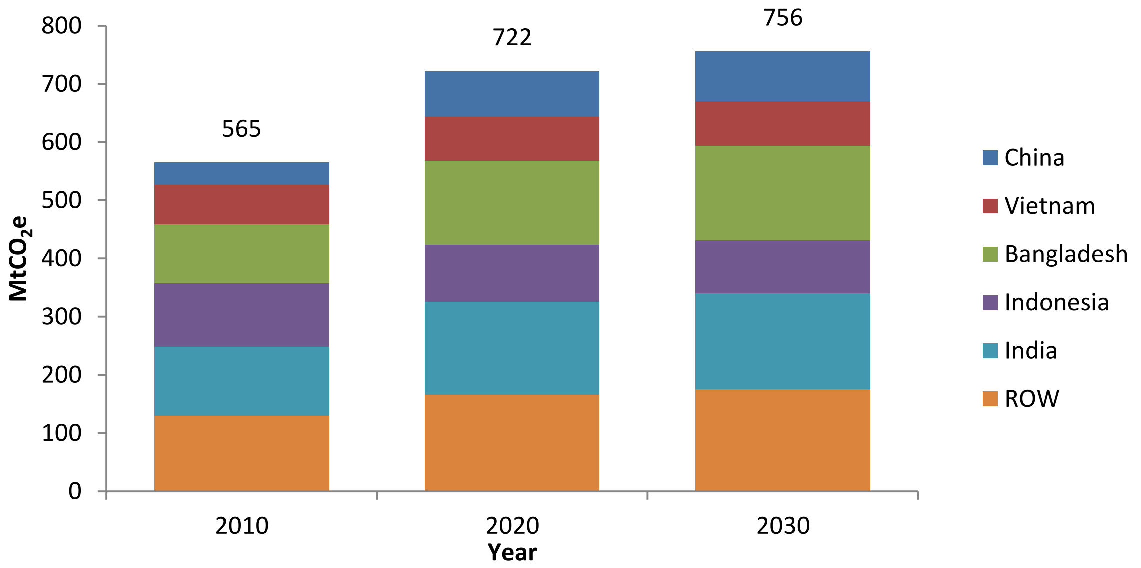


Table 2-1 shows the baseline $CH_4$, $N_2O$ and soil carbon estimates for rice cropland by region. Rice cultivation results in emissions of $CH_4$ and $N_2O$, and these are offset by storage of carbon in the soil. In 2010, GHG emissions from rice cultivation include 484.1 $MTCO_2e$ $CH_4$ and 260.0 $MTCO_2e$ $N_2O$, offset by 179.2 $MTCO_2e$ of c stored in the soil, for net non-$CO_2$ emissions of 564.9.1 $MTCO_2e$, or about 5.8 percent of global non-$CO_2$ emissions (EPA, 2012).

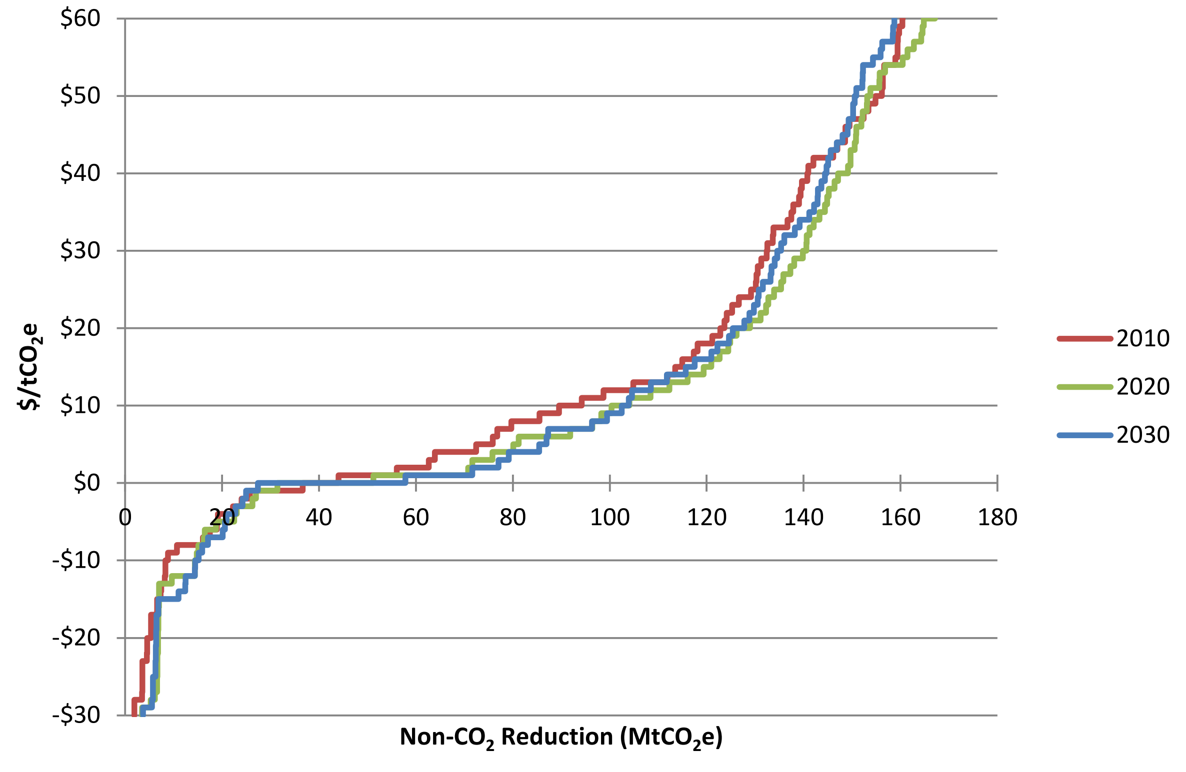
**Table 2-1: Baseline $CH_4$, $N_2O$, and Soil Carbon Estimates for Rice Cropland for 2010, 2020 and 2030 by Region**

| | 2010 | | | 2020 | | | 2030 | | |
|---|---|---|---|---|---|---|---|---|---|
| Country/Region | $CH_4$ | $N_2O$ | Soil C | $CH_4$ | $N_2O$ | Soil C | $CH_4$ | $N_2O$ | Soil C |
| **Top 5 Emitting Countries** | | | | | | | | | |
| India | 91.2 | 76.7 | -50 | 94 | 93.2 | -27.5 | 89 | 94.1 | -18.6 |
| Indonesia | 81.7 | 25.5 | 2.2 | 75.4 | 23.4 | -0.5 | 70.7 | 22.1 | -1.3 |
| China | 72.9 | 34.6 | -69.4 | 72.8 | 36.7 | -31.3 | 66.5 | 35.9 | -16.9 |
| Vietnam | 47 | 25.7 | -4.8 | 45.4 | 33.1 | -2.8 | 44 | 34.5 | -1.8 |
| Bangladesh | 54.4 | 63 | -16 | 54.3 | 98.6 | -8.5 | 54.5 | 112.4 | -5 |
| **Rest of Region** | | | | | | | | | |
| Africa | 11.6 | 4.5 | -3.8 | 12.6 | 6.2 | -2.7 | 13.4 | 7 | -2.1 |
| Asia | 79.8 | 22.8 | -26.6 | 85.9 | 25.3 | -13.2 | 85.9 | 25.9 | -8.5 |
| Central & South America | 32.3 | 4.5 | -5.1 | 33.5 | 5.3 | -3.2 | 33.4 | 5.6 | -2.2 |
| Eurasia | 1 | 0.1 | -0.1 | 1.2 | 0.1 | 0.1 | 1.3 | 0.1 | 0 |
| Europe | 1.8 | 0.1 | -1.4 | 2.2 | 0.1 | -0.6 | 2.3 | 0.1 | -0.4 |
| Middle East | 2.8 | 0.1 | -1.4 | 3.6 | 0.1 | -0.6 | 3.9 | 0.1 | -0.4 |
| North America | 7.5 | 2.3 | -2.8 | 8.3 | 2.4 | -0.6 | 8.1 | 2.6 | -0.4 |
| **World Total** | **484.1** | **260** | **-179.2** | **489.2** | **324.5** | **-91.6** | **472.9** | **340.5** | **-57.4** |

Global abatement potential in paddy rice cultivation systems equates to approximately 27% - 35% of total annual net emissions. Marginal abatement cost (MAC) curve results are presented in Figure 2-2 for 2010, 2020, and 2030, assuming that production remains equal to baseline levels under the mitigation scenarios. Maximum abatement potential in the rice sector is 199 $MtCO_2e$ in 2010, 203 $MtCO_2e$ in 2020 and 200 $MtCO_2e$ in 2030.

Figure 2-2 also shows the finding that significant reductions are feasible even at a low values per ton of carbon. For example, there are approximately 76 $MtCO_2e$ of net GHG emission reductions that are cost-effective in 2010 at a price of $5/ton, (13.5 % of the baseline estimate). In 2030, approximately 87 $MtCO_2$ of reductions are feasible at a price of $5 per ton (11.5 % of the baseline estimate). These results suggest that there are significant opportunities for net GHG reductions in the rice cultivation sector.

**Figure 2-2: Global Abatement Potential in Rice Cultivation with Production Equal to Baseline Levels: 2010, 2020, and 2030**



The following section offers a brief description of $CH_4$ and $N_2O$ emissions as well as changes in soil carbon stock from rice cultivation, and a discussion of projected trends in global baseline emissions. The subsequent section presents possible abatement technologies, their technical specifications, costs and potential benefits. The final section discusses the estimated abatement potential and MAC analysis at a regional level.

## V.2.2 $CH_4$ and $N_2O$ Emissions and Changes in Soil Carbon from Rice Cultivation

Rice production is a major source of GHG emissions. Global, Tier-I datasets such as EPA's Global Anthropogenic Non-$CO_2$ GHG Emissions Report (EPA, 2012) show that agriculture is the biggest source of $CH_4$ emissions, and within agriculture, rice cultivation is the second largest source, behind enteric fermentation.[1] Rice cultivation accounted for 7% of global $CH_4$ emissions in 2005 (USEPA, 2012). Rice cultivation is also a significant source of $N_2O$ emissions but these are not included in most global datasets.

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[1] Global $CH_4$ emissions from agriculture were estimated at 3,035.4 $MtCO_2e$ (2005), about 45% of the global total of 6815.8 $MtCO_2e$. Rice produced 500.9 $MtCO_2e$ and enteric fermentation produced 1,894.3 $MtCO_2e$ (USEPA, 2012, Table 6).

In this section, we describe baseline emissions of $CH_4$,, $N_2O$, and soil carbon from rice cultivation as well as crop production data and assumptions that support the analysis of mitigation potential.

Rice production systems can be classified as wetland rice (irrigated, rain-fed and deepwater) or upland rice (Neue, 1993). Wetland rice is the largest category, and is responsible for large net $CH_4$ emissions.[2] Aerobic decomposition of organic matter gradually depletes the oxygen present in the soil and water, resulting in anaerobic conditions in the rice paddies. Methanogenic bacteria decompose soil organic matter under anaerobic conditions in rice paddies, generating $CH_4$. Significant amounts of $CH_4$ are oxidized by aerobic methanotrophic bacteria into $CO_2$ in the soil. The remaining unoxidized $CH_4$ is released to the atmosphere through diffusion and ebullition and through roots and stems of rice plants. Thus, unlike the non-paddy rice agricultural soils which are typically $CH_4$ sinks, paddy rice cultivation is a major source of $CH_4$ emissions.

$N_2O$ is another significant component of net GHG emissions from rice cultivation. $N_2O$ is produced through nitrification and denitrification from microbial activities under the anoxic condition. $N_2O$ emissions occur directly from soils, and indirectly through volatilization of compounds such as $NH_3$ and $NO_x$ and subsequent deposition as well as through leaching and runoff. Table 2-1 shows that in 2010, while $CH_4$ accounted for the largest share of emissions with 484.1 $MtCO_2e$ (65% of non-$CO_2$ emissions from rice cultivation), $N_2O$ contributed substantially, with 260.0 $MtCO_2e$ (35%). Both dry and irrigated rice are a source of $N_2O$ emissions.

Soil carbon stocks are not a non-$CO_2$ GHG but also have important implications for net GHG emissions and are affected by non-$CO_2$ mitigation options so we estimate total emissions net of their effect on soil C stocks in this report.

### V.2.2.1 Activity Data or Important Sectoral or Regional Trends and Related Assumptions

#### *DNDC Modeling of GHG Fluxes and Crop Yields*

The Denitrification-Decomposition (DNDC) model was used to simulate production, crop yields and greenhouse gas fluxes of global paddy rice under “business-as-usual” (BAU) condition and various mitigation strategies. DNDC is a soil biogeochemical model that simulates the processes determining the interactions among ecological drivers, soil environmental factors, and relevant biochemical or geochemical reactions, which collectively determine the rates of trace gas production and consumption in agricultural ecosystems (Li, 2001). Details of management (e.g., crop rotation, tillage, fertilization, manure amendment, irrigation, weeding, and grazing) have been parameterized and linked to the various biogeochemical processes (e.g., crop growth, litter production, soil water infiltration, decomposition, nitrification, denitrification, fermentation) embedded in DNDC (e.g., Li et al., 2004; Li et al., 2006; Li, 2011; Abdalla et al., 2011; Giltrap et al., 2011; Dai et al., 2012).[3]

DNDC predicts daily $CH_4$, $N_2O$ and soil carbon fluxes from rice paddies through the growing and fallow seasons as fields remain flooded or move between flooded and drained conditions during the season.

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[2] Globally, about 2 percent of rice is grown in dry conditions and this production system is a net sink for $CH_4$ (source: DNDC estimates discussed below).

[3] The paddy-rice version of DNDC has been validated for a number of countries and world regions and is used for national trace gas inventory studies in North America, Europe, and Asia (e.g., Smith et al., 2002; Follador et al., 2011; Leip et al., 2011; Li et al., 2002; Cai et al., 2003; Li et al., 2005).

For this study, a modified version of the DNDC 9.5 Globe database was used to simulate crop yields and GHG fluxes from global paddy rice cultivation systems. The DNDC 9.5 global database contains information on soil characteristics, crop planted area, and management conditions (fertilization, irrigation, season, and tillage) on a 0.5 by 0.5 degree grid cell of the world. The database is used to establish the initial conditions in the model in 2000. The model considers all paddy rice production systems, including irrigated and rainfed rice, and single, double and mixed rice as well as deepwater and upland cropping systems. For this study, baseline and mitigation scenario modeling is carried out for all rice-producing countries in the world that produce a substantial quantity of rice.

The Food and Agriculture Organization (FAO) country-level statistics (FAOSTAT 2010) were used to establish harvested area for rice. The total area was calculated for each country in the Globe database for each type, and evenly distributed across all grid cells within a country in the absence of sub-national information. Figure 2-3 shows the distribution of rice across major systems for the five largest producers and an aggregate of the rest of the world.

**Figure 2-3: DNDC Rice Cropland Area Sown, Top 5 countries, by Type and Water Management**

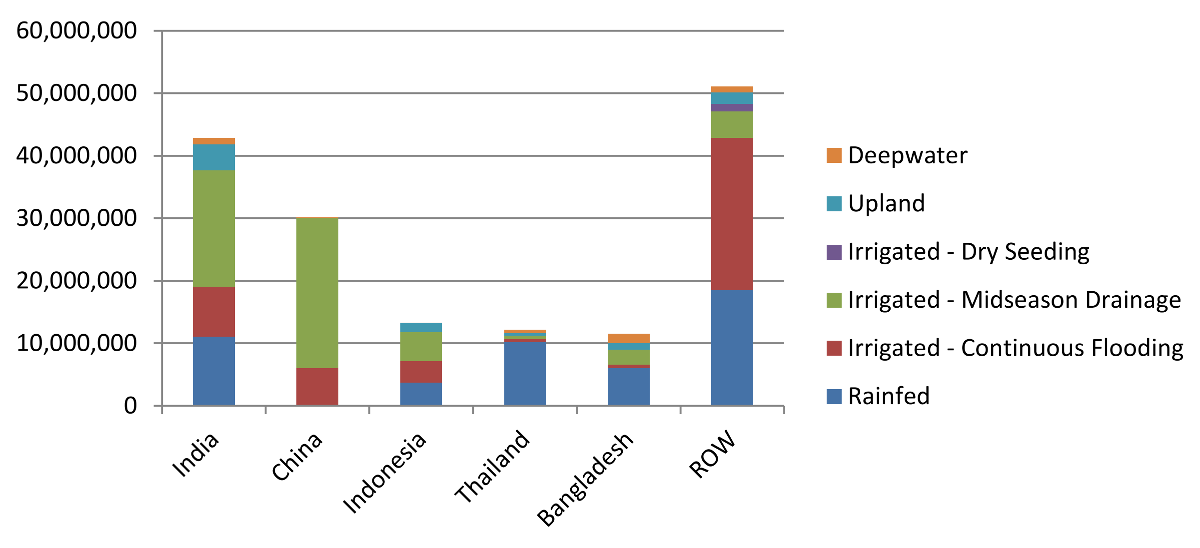

**Table 2-2: Baseline yields for 2010, 2020 and 2030 for selected countries (kg/ha)**

| | 2010 | | | | 2020 | | | | 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/Region | Irrigated | Rainfed | Deepwater | Upland | Irrigated | Rainfed | Deepwater | Upland | Irrigated | Rainfed | Deepwater | Upland |
| **Top 5 Countries by Production** | | | | | | | | | | | | |
| China | 6,158.2 | 4,002.9 | 622.5 | 2,280.5 | 6,522.0 | 4,193.0 | 702.5 | 2,560.9 | 7,161.0 | 4,583.2 | 814.9 | 2,920.1 |
| India | 4,832.6 | 1,681.5 | 685.3 | 1,114.1 | 5,271.8 | 1,745.2 | 846.7 | 1,266.8 | 5,722.5 | 1,849.3 | 993.5 | 1,409.6 |
| Indonesia | 5,546.1 | 4,758.1 | 1,233.3 | 2,142.8 | 5,625.0 | 4,756.5 | 1,167.0 | 2,010.9 | 5,833.2 | 4,859.4 | 1,171.8 | 1,961.6 |
| Bangladesh | 7,322.9 | 4,823.1 | 1,257.6 | 2,501.9 | 7,447.9 | 4,732.3 | 1,592.3 | 2,927.3 | 7,642.4 | 4,766.4 | 1,857.9 | 3,196.2 |
| Vietnam | 7,388.0 | 5,208.4 | 963.2 | 2,240.9 | 7,503.2 | 5,156.1 | 940.4 | 2,386.4 | 7,647.7 | 5,222.3 | 960.5 | 2,513.0 |

**Table 2-3: Baseline production for 2010, 2020 and 2030 for selected countries (metric tonnes)**

| | 2010 | | | | 2020 | | | | 2030 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Country/ Region | Irrigated | Rainfed | Deepwater | Upland | Irrigated | Rainfed | Deepwater | Upland | Irrigated | Rainfed | Deepwater | Upland |
| **Top 5 Countries by Production** | | | | | | | | | | | | |
| China | 185,106,646 | 136,866 | 532 | 72,470 | 187,171,179 | 136,879 | 573 | 77,697 | 187,849,985 | 136,761 | 607 | 80,982 |
| India | 128,759,438 | 18,667,823 | 701,074 | 4,544,661 | 137,564,781 | 18,975,458 | 848,345 | 5,061,283 | 141,353,559 | 19,034,013 | 942,360 | 5,330,762 |
| Indonesia | 44,515,927 | 17,723,001 | 3,144 | 3,230,419 | 45,020,613 | 17,666,403 | 2,966 | 3,022,817 | 45,509,275 | 17,593,406 | 2,903 | 2,874,405 |
| Bangladesh | 22,123,824 | 29,082,198 | 1,870,274 | 2,471,779 | 22,891,662 | 29,029,646 | 2,409,109 | 2,942,311 | 23,309,923 | 29,015,593 | 2,789,425 | 3,187,968 |
| Vietnam | 27,265,526 | 15,725,436 | 260,980 | 1,121,298 | 27,967,786 | 15,723,459 | 257,362 | 1,206,084 | 28,142,533 | 15,722,150 | 259,495 | 1,253,843 |

The global meteorological data from the National Oceanic and Atmospheric Administration's National Centers for Environmental Prediction climate reanalysis product were used to establish climate data for 2010 in the model. The 2010 climate data were used for all model years. Planting and harvest dates were matched approximately to local growing season. Tillage and flooding and drainage dates for irrigated rice were established based on the planting dates.

Nitrogen fertilizer application rates were based on DNDC fertilizer use data, which is derived from global data sources. Table 2-4 summarizes the assumed fertilizer use per hectare for rice by country. Assumptions on the distribution of irrigated rice across water management regimes for each country were developed based on Yan et al. (2009) (see Table 2-5).

**Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type**

| | | Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha) | | | |
|---|---|---|---|---|---|
| Country | Planted Area | Irrigated | Rainfed | Upland | Deepwater |
| Afghanistan | 208,030 | 40 | 40 | — | — |
| Angola | 2,465 | 1 | 1 | — | — |
| Argentina | 211,148 | 90 | 90 | 9 | — |
| Australia | 175,085 | 180 | 180 | 15 | — |
| Azerbaijan | 5,720 | 20 | 20 | 1 | — |
| Bangladesh | 11,526,108 | 107 | 107 | 30 | — |
| Belize | 5,303 | 50 | 50 | 11 | — |
| Benin | 24,138 | 50 | 50 | 2 | — |
| Bhutan | 30,472 | 40 | 40 | — | — |
| Bolivia | 232,626 | 30 | 30 | 1 | — |
| Brazil | 2,696,270 | 50 | 50 | 15 | — |
| Brunei | 613 | 5 | 5 | — | — |
| Bulgaria | 24,732 | 60 | 60 | 24 | — |
| Burkina-Faso | 133,240 | 25 | 25 | 1 | — |
| Burundi | 18,582 | 40 | 40 | — | — |
| Cambodia | 2,730,963 | 30 | 30 | — | — |
| Cameroon | 32,568 | 35 | 35 | 1 | — |
| Central-African-Republic | 13,560 | 30 | 30 | — | — |
| Chad | 118,190 | 10 | 10 | 2 | — |
| Chile | 49,282 | 50 | 50 | 30 | — |
| China | 30,125,402 | 164 | 164 | 23 | — |
| Colombia | 435,924 | 108 | 108 | 18 | — |
| Congo | 520,829 | 2 | 2 | — | — |
| Costa-Rica | 87,372 | 50 | 50 | 18 | — |
| Cote-dIvoire | 493,322 | 7 | 7 | 2 | — |
| Cuba | 196,891 | 28 | 28 | 6 | — |

(continued)

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

| | | Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha) | | | |
|---|---|---|---|---|---|
| Country | Planted Area | Irrigated | Rainfed | Upland | Deepwater |
| Dominican-Republic | 208,865 | 35 | 35 | 10 | — |
| Ecuador | 454,982 | 55 | 55 | 6 | — |
| Egypt | 402,249 | 203 | 203 | 34 | — |
| El-Salvador | 8,674 | 88 | 88 | 19 | — |
| Ethiopia | 40 | 25 | 25 | 3 | — |
| France | 18,919 | 127 | 127 | 28 | — |
| French-Guiana | 10,920 | 20 | 20 | 8 | — |
| Gabon | 202 | 35 | 35 | — | — |
| Ghana | 105,678 | 30 | 30 | — | — |
| Greece | 42,021 | 94 | 94 | 20 | — |
| Guatemala | 25,578 | 40 | 40 | 15 | — |
| Guinea | 818,010 | 1 | 1 | — | — |
| Guinea-Bissau | 162,054 | 30 | 30 | 1 | — |
| Guyana | 187,731 | 5 | 5 | 11 | — |
| Haiti | 82,387 | 10 | 10 | 2 | — |
| Honduras | 10,531 | 40 | 40 | 26 | — |
| Hungary | 53,797 | 35 | 35 | 15 | — |
| India | 42,848,326 | 69 | 69 | 20 | — |
| Indonesia | 13,261,499 | 82 | 82 | 16 | — |
| Iran | 563,918 | 79 | 79 | 17 | — |
| Iraq | 47,978 | 40 | 40 | 56 | — |
| Italy | 220,850 | 99 | 99 | 22 | — |
| Japan | 1,627,707 | 80 | 80 | 24 | — |
| Kazakhstan | 97,643 | 30 | 30 | — | — |
| Kenya | 7,358 | 50 | 50 | 8 | — |
| Korea-North | 582,246 | 70 | 70 | 15 | — |
| Korea-South | 902,339 | 189 | 189 | 34 | — |
| Kyrgyzstan | 14,724 | 39 | 39 | 5 | — |
| Laos | 848,955 | 45 | 45 | 2 | — |
| Liberia | 79,879 | 10 | 10 | — | — |
| Madagascar | 1,703,119 | — | — | 1 | — |
| Malawi | 28,106 | 20 | 20 | 9 | — |
| Malaysia | 677,984 | 65 | 65 | 16 | — |
| Mali | 646,334 | 40 | 40 | 2 | — |

(continued)

### Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

| Country | Planted Area | Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha) | | | |
|---|---|---|---|---|---|
| | | Irrigated | Rainfed | Upland | Deepwater |
| Mauritania | 28,607 | 85 | 85 | — | — |
| Mexico | 162,208 | 85 | 85 | 18 | — |
| Morocco | 12,110 | 120 | 120 | 13 | — |
| Mozambique | 64,834 | 5 | 5 | 1 | — |
| Myanmar | 8,013,037 | 50 | 50 | 8 | — |
| Nepal | 1,455,906 | 22 | 22 | 5 | — |
| Nicaragua | 136,469 | 85 | 85 | 5 | — |
| Niger | 41,083 | 10 | 10 | — | — |
| Nigeria | 2,415,653 | 20 | 20 | 3 | — |
| Pakistan | 2,366,291 | 40 | 40 | 20 | — |
| Panama | 110,696 | 10 | 10 | 9 | — |
| Paraguay | 44,291 | 85 | 85 | 2 | — |
| Peru | 383,322 | 170 | 170 | 17 | — |
| Philippines | 4,355,767 | 60 | 60 | 19 | — |
| Portugal | 88,342 | 90 | 90 | 10 | — |
| Romania | 13,191 | 85 | 85 | 6 | — |
| Russia | 200,099 | 85 | 85 | 3 | — |
| Rwanda | 3,790 | 85 | 85 | — | — |
| Senegal | 75,558 | 85 | 85 | 4 | — |
| Sierra-Leone | 500,905 | 25 | 25 | — | — |
| Spain | 122,793 | 76 | 76 | 17 | — |
| Sri-Lanka | 1,062,007 | 60 | 60 | 16 | — |
| Sudan | 303 | 45 | 45 | 1 | — |
| Suriname | 39,758 | 50 | 50 | 27 | — |
| Switzerland | 2,320 | 40 | 40 | 27 | — |
| Tajikistan | 31,808 | 85 | 85 | 2 | — |
| Tanzania | 1,058,671 | 30 | 30 | 1 | — |
| Thailand | 12,116,749 | 30 | 30 | 20 | — |
| The-Gambia | 12,677 | 10 | 10 | — | — |
| Togo | 39,899 | 8 | 8 | 3 | — |
| Trinidad-Tobago | 2,838 | 35 | 35 | 21 | — |
| Turkey | 99,015 | 127 | 127 | 20 | — |
| Turkmenistan | 60,042 | 30 | 30 | 11 | — |
| Uganda | 54,966 | 30 | 30 | — | — |

(continued)

Table 2-4: DNDC Average N Fertilizer Application Rate by Country and Rice Production Type (continued)

| Country | Planted Area | Planted Area-Weighted Mean Fertilizer N Rate (kgN/ha) | | | |
|---|---|---|---|---|---|
| | | Irrigated | Rainfed | Upland | Deepwater |
| Ukraine | 29,078 | 85 | 85 | 3 | — |
| United-States | 1,444,924 | 139 | 139 | 19 | — |
| Uruguay | 174,987 | 151 | 151 | 11 | — |
| Uzbekistan | 36,221 | 90 | 90 | 30 | — |
| Venezuela | 295,441 | 85 | 85 | 16 | — |
| Vietnam | 7,481,119 | 120 | 120 | 29 | — |
| Zambia | 13,872 | 12 | 12 | 4 | — |
| Zimbabwe | 176 | 15 | 15 | 8 | — |

Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%)

| Region | Continuous Flooding | Midseason Drainage | Dry Seeding |
|---|---|---|---|
| Afghanistan | 100% | 0% | 0% |
| Algeria | 100% | 0% | 0% |
| Angola | 100% | 0% | 0% |
| Argentina | 100% | 0% | 0% |
| Australia | 100% | 0% | 0% |
| Azerbaijan | 100% | 0% | 0% |
| Bangladesh | 20% | 80% | 0% |
| Belize | 100% | 0% | 0% |
| Benin | 100% | 0% | 0% |
| Bhutan | 100% | 0% | 0% |
| Bolivia | 100% | 0% | 0% |
| Brazil | 100% | 0% | 0% |
| Brunei | 100% | 0% | 0% |
| Bulgaria | 100% | 0% | 0% |
| Burkina-Faso | 100% | 0% | 0% |
| Burundi | 100% | 0% | 0% |
| Cameroon | 100% | 0% | 0% |
| Central-African-Republic | 100% | 0% | 0% |
| Chad | 100% | 0% | 0% |
| Chile | 100% | 0% | 0% |
| China | 20% | 80% | 0% |
| Colombia | 100% | 0% | 0% |
| Comoros | 100% | 0% | 0% |

**Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)**

| Region | Continuous Flooding | Midseason Drainage | Dry Seeding |
|---|---|---|---|
| Congo | 100% | 0% | 0% |
| Costa-Rica | 100% | 0% | 0% |
| Cote-dIvoire | 100% | 0% | 0% |
| Cuba | 100% | 0% | 0% |
| Dominican-Republic | 100% | 0% | 0% |
| Ecuador | 100% | 0% | 0% |
| Egypt | 100% | 0% | 0% |
| El-Salvador | 100% | 0% | 0% |
| Ethiopia | 100% | 0% | 0% |
| Fiji | 100% | 0% | 0% |
| France | 100% | 0% | 0% |
| French-Guiana | 100% | 0% | 0% |
| Gabon | 100% | 0% | 0% |
| Ghana | 100% | 0% | 0% |
| Greece | 100% | 0% | 0% |
| Guatemala | 100% | 0% | 0% |
| Guinea | 100% | 0% | 0% |
| Guinea-Bissau | 100% | 0% | 0% |
| Guyana | 100% | 0% | 0% |
| Haiti | 100% | 0% | 0% |
| Honduras | 100% | 0% | 0% |
| Hungary | 100% | 0% | 0% |
| India | 30% | 70% | 0% |
| Indonesia | 43% | 57% | 0% |
| Iran | 100% | 0% | 0% |
| Iraq | 100% | 0% | 0% |
| Italy | 100% | 0% | 0% |
| Jamaica | 100% | 0% | 0% |
| Japan | 20% | 80% | 0% |
| Kazakhstan | 100% | 0% | 0% |
| Kenya | 100% | 0% | 0% |
| Korea-North | 100% | 0% | 0% |
| Korea-South | 100% | 0% | 0% |
| Kyrgyzstan | 100% | 0% | 0% |
| Liberia | 100% | 0% | 0% |
| Macedonia | 100% | 0% | 0% |

(continued)

**Table 2-5: Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)**

| Region | Continuous Flooding | Midseason Drainage | Dry Seeding |
|---|---|---|---|
| Madagascar | 100% | 0% | 0% |
| Malawi | 100% | 0% | 0% |
| Malaysia | 100% | 0% | 0% |
| Mali | 100% | 0% | 0% |
| Mauritania | 100% | 0% | 0% |
| Mexico | 100% | 0% | 0% |
| Micronesia | 100% | 0% | 0% |
| monsoon Asia | 43% | 57% | 0% |
| Morocco | 100% | 0% | 0% |
| Mozambique | 100% | 0% | 0% |
| Nepal | 100% | 0% | 0% |
| Nicaragua | 100% | 0% | 0% |
| Niger | 100% | 0% | 0% |
| Nigeria | 100% | 0% | 0% |
| Pakistan | 100% | 0% | 0% |
| Panama | 100% | 0% | 0% |
| Papua-New-Guinea | 100% | 0% | 0% |
| Paraguay | 100% | 0% | 0% |
| Peru | 100% | 0% | 0% |
| Philippines | 100% | 0% | 0% |
| Portugal | 100% | 0% | 0% |
| Reunion | 100% | 0% | 0% |
| Romania | 100% | 0% | 0% |
| Russia | 100% | 0% | 0% |
| Rwanda | 100% | 0% | 0% |
| Senegal | 100% | 0% | 0% |
| Sierra-Leone | 100% | 0% | 0% |
| Solomon-Is | 100% | 0% | 0% |
| Somalia | 100% | 0% | 0% |
| South-Africa | 100% | 0% | 0% |
| Spain | 100% | 0% | 0% |
| Sri-Lanka | 100% | 0% | 0% |
| Sudan | 100% | 0% | 0% |
| Suriname | 100% | 0% | 0% |
| Swaziland | 100% | 0% | 0% |
| Tajikistan | 100% | 0% | 0% |

Table 2-5: **Distribution of Baseline Water Management for Irrigated Rice by Country (%) (continued)**

| Region | Continuous Flooding | Midseason Drainage | Dry Seeding |
|---|---|---|---|
| Tanzania | 100% | 0% | 0% |
| The-Gambia | 100% | 0% | 0% |
| Timor-Leste | 100% | 0% | 0% |
| Togo | 100% | 0% | 0% |
| Trinidad-Tobago | 100% | 0% | 0% |
| Turkey | 100% | 0% | 0% |
| Turkmenistan | 100% | 0% | 0% |
| Uganda | 100% | 0% | 0% |
| Ukraine | 100% | 0% | 0% |
| United-States-California | 100% | 0% | 0% |
| United-States-Mid_South | 0% | 0% | 100% |
| Uruguay | 100% | 0% | 0% |
| Uzbekistan | 100% | 0% | 0% |
| Venezuela | 100% | 0% | 0% |
| Vietnam | 100% | 0% | 0% |
| Zambia | 100% | 0% | 0% |
| Zimbabwe | 100% | 0% | 0% |

Source: Yan et al. (2009).

A baseline scenario is established for each country using DNDC 9.5, reflecting assumptions on water management, fertilizer application, residue management and tillage practices described above. Rice yields and GHG fluxes ($CH_4$, direct and indirect $N_2O$ and changes in soil organic carbon) were simulated in DNDC model for each grid cell and results were aggregated at the country level for irrigated, rainfed, deep water, and upland production systems for each scenario, in both mean annual rates per hectare and mean annual national totals.[4] Results were reported for 2010 and by 5-year increments through 2030.

Finally, results from DNDC were adjusted with projected acreage of these production systems by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model. In DNDC, rice production areas were held constant at the 2010 level to obtain the biophysical effects of management practice changes on crop yields and GHG fluxes. Projected acreage changes from IMPACT model reflect socio-economic drivers (such as population growth) and technological changes to meet the global food demand (Nelson et al., 2010). The IMPACT modeling projects that while global rice production would increase by 11 percent between 2010 and 2030, the total area dedicated to rice cultivation would decrease by 5 percent during the same period due to productivity improvements.

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[4] The mean values were calculated using weighted averages; rice yields represent total annual yields of rice from all production systems.

### V.2.2.2 Emissions Estimates and Related Assumptions

This section briefly discusses the historical and projected emission trends from global paddy rice cultivation and presents simulated baseline emissions projections.

#### *Historical Emissions Estimates*

According to the EPA Global Emissions Report (GER) (USEPA, 2012), total methane emissions from global rice cultivation increased by 4.4% between 1990 and 2005, from 480 $MtCO_2e$ to 501 $MtCO_2e$. Asia, the predominant rice-producing region, accounted for over 80% of the total $CH_4$ emissions in 2005. Africa contributed another 10%, and the remaining methane emissions in this sector came from Central and South America and other regions. The GER did not report historic $N_2O$ emissions and soil carbon stock changes from the rice cultivation sector.

#### *Projected Emissions Estimates*

Worldwide $CH_4$ and $N_2O$ emissions from rice cultivation are projected to have only modest increases between 2010 and 2030. This is mainly because demand for rice products will remain relatively constant while global food demand shifts towards more livestock and other more expensive food products with higher incomes. The estimated total $CH_4$ emissions from rice cultivation are 484.1 $MtCO_2e$ in 2010, 482.2 $MtCO_2e$ in 2020 and 472.9 $MtCO_2e$ in 2030. The total estimated $N_2O$ emissions are 260.0 $MtCO_2e$ in 2010, 324.5 $MtCO_2e$ in 2020 and 340.5 $MtCO_2e$ in 2030.

## V.2.3 Abatement Measures and Engineering Cost Analysis

The mitigation options included in the analysis were based on review of the literature to identify the most promising options, while also taking data availability and potential for modeling within DNDC into consideration. For the purposes of developing MAC curves for this study, mitigation options that increase net emissions of non-$CO_2$ GHG were excluded from the analysis.

Twenty-six mitigation scenarios were then analyzed using DNDC 9.5[5]. The scenarios addressed management techniques in various combinations hypothesized to reduce GHG emissions from rice systems: water management regime (continuous flooding, mid-season drainage, dry seeding, alternate wetting and drying, and switching to dryland rice production system), residue management (partial or total residue incorporation), tillage, and various fertilizer management alternatives (ammonium sulfate in place of urea, urea with nitrification inhibitor, slow release urea, 10% reduced fertilizer, 20% reduced fertilizer, and 30% reduced fertilizer).

The water management system under which rice is produced is one of the most important factors influencing $CH_4$ emissions. Specifically, switching from continuous flooding of rice paddy fields to draining flooded fields periodically during the growing season – a water conservation practice that is increasingly adopted in the baseline to reduce water use – would significantly reduce $CH_4$ emissions. Other practices (e.g., fertilizer applications, tillage practices and residue management) also alter the soil conditions and hence affect crop yields and the soil carbon- and nitrogen-driving processes such as

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[5] Note that 38 different scenario names are reported in the outputs. Because water management practices are assumed not to affect non-irrigated rice emissions, the simulation results for options combine d with continuous flooding or midseason drainage are the same for non-irrigated rice. The analogous options that alter fertilizer and other management practices but do not affect water management were identified as beginning with "base" rather than "cf" or "md".

decomposition, nitrification and denitrification (Neue and Sass, 1994; Li et al., 2006). Due to the complex interactions, changes in management practices would trigger changes in multiple GHG fluxes. For instance, while drainage of rice fields during the growing season would significantly reduce $CH_4$ emissions, emissions of $N_2O$ actually increase (Zheng et al., 1997, 2000; Cai et al., 1999; Zou et al. 2007).

### *Rice mitigation options*

The mitigation options included for rice water management system under which rice is produced is one of the most important factors influencing $CH_4$ emissions. Specifically, switching from continuous flooding of rice paddy fields to draining flooded fields periodically during the growing season – a water conservation practice that is increasingly adopted in the baseline to reduce water use – would significantly reduce $CH_4$ emissions. Other practices (e.g., fertilizer applications, tillage practices and residue management) also alter the soil conditions and hence affect crop yields and soil carbon- and nitrogen-driving processes.

There were 26 scenarios that were run using DNDC 9.5 (see Table 2-6). The scenarios addressed management techniques in various combinations hypothesized to reduce GHG emissions from rice systems: flood regime (continuous flooding [CF], mid-season drainage [MD], dry seeding [DS], alternate wetting and drying [AWD], and switching to dryland (upland) rice), residue management (partial removal or 100% incorporation), conventional tillage or no till, and various fertilizer alternatives (conventional / urea, ammonium sulfate in place of urea, urea with nitrification inhibitor, slow release urea, 10% reduced fertilizer, 20% reduced fertilizer, 30% reduced fertilizer, and DNDC optimization of fertilizer application to maximize yields). Further definition of these assumptions is provided in Table 2-7.

**Table 2-6: Alternative Rice Management Scenarios Simulated using DNDC**

| Abbreviation | Scenario | Flooding | Residue Incorporation | Alternative Management | Fertilization |
|---|---|---|---|---|---|
| cf_r50 | Continuous Flooding | CF | 50% | — | conventional |
| cf_r100 | Continuous Flooding, 100% Residue Incorporation | CF | 100% | — | conventional |
| cf_r50_amsu | Continuous Flooding, Ammonium Sulphate Fertilizer | CF | 50% | — | ammonium sulfate |
| cf_r50_ninhib | Continuous Flooding, Nitrification Inhibitor Fertilizer | CF | 50% | — | nitrification inhibitor |
| cf_r50_slowrel | Continuous Flooding, Slow Release Fertilizer | CF | 50% | — | slow release |
| cf_r50_notill | Continuous Flooding, No Till | CF | 50% | no till | conventional |
| cf_r50_f70 | Continuous Flooding, 30% Reduced Fertilizer | CF | 50% | — | 30% reduced |
| cf_r50_f90 | Continuous Flooding, 10% Reduced Fertilizer | CF | 50% | — | 10% reduced |
| cf_r50_auto | Continuous Flooding, Auto-fertilization to maximize yields | CF | 50% | — | Automatically adjusted by DNDC to maximize yields |
| md_r50 | Mid-season Drainage | MD | 50% | — | conventional |

(continued)

**Table 2-6: Alternative Rice Management Scenarios Simulated using DNDC (continued)**

| Abbreviation | Scenario | Flooding | Residue Incorporation | Alternative Management | Fertilization |
|---|---|---|---|---|---|
| md_r100 | Mid-season Drainage w/100% Residue Incorporation | MD | 100% | — | conventional |
| md_r50_amsu | Mid-season Drainage, Ammonium Sulphate Fertilizer | MD | 50% | — | ammonium sulfate |
| md_r50_ninhib | Mid-season Drainage, Nitrification Inhibitor Fertilizer | MD | 50% | — | nitrification inhibitor |
| md_r50_slowrel | Mid-season Drainage, Slow Release Fertilizer | MD | 50% | — | slow release |
| md_r50_notill | Mid-season Drainage, No Till | MD | 50% | no till | conventional |
| md_r50_f70 | Mid-season Drainage, 30% Reduced Fertilizer | MD | 50% | — | 30% reduced |
| md_r50_f90 | Mid-season Drainage, 10% Reduced Fertilizer | MD | 50% | — | 10% reduced |
| md_r50_ds | Mid-season Drainage, Dry Seeding | MD w/DS | 50% | — | conventional |
| md_r50_auto | Mid-season Drainage, Auto-fertilization to maximize yields | MD | 50% | — | Automatically adjusted by DNDC to maximize yields |
| awd_r50 | Alternate Wetting & Drying (AWD) | AWD | 50% | — | conventional |
| awd_r50_ninhib | AWD w/Nitrification Inhibitor | AWD | 50% | — | nitrification inhibitor |
| awd_r50_slowrel | AWD w/Slow Release | AWD | 50% | — | slow release |
| base_r50_ds | Dry Seeding | DS | 50% | — | conventional |
| base_r50_f80_ds | Dry Seeding, 20% Reduced Fertilizer | DS | 50% | — | 20% reduced |
| dry_r50 | Dryland Rice | dryland rice | 50% | — | conventional |
| dry_r50_f80 | Dryland Rice, 20% Reduced Fertilizer | dryland rice | 50% | — | 20% reduced |

For non-irrigated rice, there is no difference between scenarios with alternative water management. Thus, we refer to those scenarios for the non-irrigated rice with "base_" in front rather than "cf" or "md".

Table 2-7: Rice Management Techniques

| Management Technique | Description |
|---|---|
| **Rice flooding** | |
| Continuous Flooding (CF) | rice paddy is flooded on planting date and drained 10 days prior to harvest date - applies to both irrigated and rainfed rice |
| Mid-season drainage (MD) | rice paddy is drained twice during growing season for 8 days - final drainage is 10 days prior to harvest date - applies only to irrigated rice |
| Alternate wetting and drying (AWD) | rice paddy is initially flooded to 10 cm – water level is reduced at rate of -0.5 cm/day till to -5cm and then reflooded at rate of 0.5 cm/day till to 10 cm - applies only to irrigated rice |
| Dryland rice | all irrigated and rainfed rice are swapped for dryland rice - no flooding occurs |
| **Rice seeding** | |
| Direct seeding (DS) | rice paddy is flooded 40 days after planting date and drained 10 days prior to harvest date - applies to both irrigated and rainfed rice |
| **Residue incorporation** | |
| 50% | 50% of above-ground crop residue is removed - remaining residue is incorporated at next tillage |
| 100% | all residue remains in place and is incorporated at next tillage |
| **Tillage** | |
| Conventional | prior to first crop in rotation tillage to 20cm depth; subsequent tillages (following each crop in rotation) to 10cm depth |
| No-till | tillage only mulches residue |
| **Fertilizer** | |
| Conventional | fertilizer N applied as urea on plant date using a crop-specific rate |
| Ammonium sulfate | fertilizer N applied as ammonium sulfate on plant date using a crop-specific rate |
| Nitrification inhibitor | nitrification inhibitor is used with urea; reduced conversion of NH4 to NO3 is simulated with 60% efficiency over 120 days |
| Slow-release | slow-release urea applied on planting date – N is released over 90 days at a linear rate |
| 10% reduced | Crop-specified baseline fertilizer N rate is reduced by 10% (applied as urea) |
| 20% reduced | Crop-specified baseline fertilizer N rate is reduced by 20% (applied as urea) |
| 30% reduced | Crop-specified baseline fertilizer N rate is reduced by 30% (applied as urea) |
| auto fertilization | Fertilizer N is applied at the rate that maximizes crop yield |

Most of the major rice producing countries have some mix of flood regimes in DNDC (see Table 2-5). To determine baseline emissions for each country, simulation results were combined based on the fraction of rice area in each rice category (deepwater, upland, rainfed, and irrigated) and flood regime for irrigated rice. For instance, baseline emissions for Bangladesh were determined by averaging the results of the CF and MD scenarios with 50% residue removal (cf_r50 * 0.2 + md_r50 * 0.8).

However, for the purposes of calculating emissions reductions, mitigation options were compared to the portions of the baseline to which they could potentially be applied rather than to the national weighted average. For instance, application of the mitigation option of switching to ammonium sulphate fertilizer (cf_r50_amsu) was compared to baseline emissions from continuously flooded rice with conventional fertilizer (cf_r50) and to baseline emissions from rice managed using mid-season drainage with conventional fertilizer (md_r50) rather than being compared to the baseline weighted average emissions per ha. This is done to better represent the mitigation potential from adopting each mitigation option on each baseline subcategory. As an example, an option such as cf_r50_amsu may result in emissions reductions relative to cf_r50 but increases in emissions relative to md_r50 (and possibly the weighted baseline emissions as well) in many countries. This is resulting from the change in water management regime in moving from mid-season drainage to continuous flooding, whereas we are trying to isolate the effects of changing fertilizer for a given baseline water management strategy in that example.

- **Capital Cost:** None of the options were assumed to have any capital cost.
- **Annual Operation and Maintenance (O&M) Cost:** Changes in labor, fertilizer, and other inputs associated with each option.
- **Annual Benefits:** Calculated based on changes in production associated with changes in yield, valued at market prices.
- **Applicability:** All options applicable for a given cropping pattern were assumed available to all acres in all countries. However, water management options (e.g., shifting from continuous flooding to midseason drainage, etc.) are only applicable to irrigated systems. No water management options are available for rainfed, deepwater, or upland rice
- **Technical Efficiency:** Determined by the DNDC Model for each country, production type, and water management combination for each mitigation option.
- **Technical Lifetime:** Indefinite; there are no capital costs being included for which a lifetime must be defined.

## V.2.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-$CO_2$ sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

### V.2.4.1 MAC Analysis Results

The MAC analysis of the mitigation options described above suggests that net GHG abatement potential for global paddy rice cultivation equates to approximately 6 percent of its total annual emissions between 2010 and 2030 at a carbon price of $5 per ton of $CO_2$ equivalent ($/t$CO_2$e). In 2030, total abatement potential in the sector is 21 Mt$CO_2$e at no carbon price, 57 Mt$CO_2$e at a carbon price of $5/t$CO_2$e, and 124 Mt$CO_2$e at a carbon price of $20/t$CO_2$e, representing 2%, 6% and 12% of the net GHG emissions in the year, respectively. Figure 2-4 presents the MAC curves for the global rice cultivation, in 2010, 2020 and 2030. The estimated net GHG mitigation potential at various break-even prices for the top-emitting countries and aggregate regions comprising the rest of the globe are presented in Table 2-8.

Table 2-8: Abatement Potential by Region at Selected Break-Even Prices in 2030 ($MtCO_2e$)

| Country/ Region | Break-Even Price ($/tCO$_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | –10 | –5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| India | 2.4 | 2.4 | 5.5 | 14.5 | 15.1 | 16.8 | 16.8 | 16.8 | 20.4 | 28.8 | 34.5 |
| Indonesia | 6.0 | 9.1 | 12.8 | 14.4 | 16.3 | 19.1 | 19.1 | 19.1 | 21.8 | 24.8 | 25.6 |
| Bangladesh | 2.8 | 3.4 | 19.5 | 30.4 | 30.4 | 30.5 | 30.5 | 31.9 | 33.1 | 35.6 | 35.9 |
| Vietnam | 0.0 | 0.0 | 6.9 | 9.0 | 9.8 | 13.2 | 16.0 | 16.0 | 16.0 | 17.6 | 21.6 |
| China | 0.6 | 1.6 | 3.2 | 3.5 | 9.5 | 10.0 | 10.6 | 10.6 | 12.6 | 19.1 | 23.7 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | 0.1 | 0.3 | 0.8 | 1.2 | 1.6 | 2.7 | 3.6 | 4.1 | 5.1 | 5.4 | 5.7 |
| Asia | 2.1 | 2.7 | 6.9 | 9.2 | 14.7 | 16.6 | 21.1 | 25.5 | 28.2 | 31.3 | 34.9 |
| Central & South America | 0.4 | 0.6 | 1.4 | 3.5 | 4.5 | 6.3 | 7.3 | 8.1 | 9.5 | 10.9 | 12.1 |
| Eurasia | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 |
| Europe | 0.0 | 0.0 | 0.1 | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.4 | 0.7 | 1.0 |
| Middle East | 0.0 | 0.1 | 0.1 | 0.1 | 0.3 | 0.3 | 0.4 | 0.5 | 0.8 | 1.1 | 1.2 |
| North America | 0.7 | 0.7 | 0.8 | 1.0 | 1.5 | 1.7 | 1.9 | 2.2 | 2.8 | 3.4 | 3.7 |
| **World Total** | **15.2** | **20.9** | **57.8** | **87.0** | **103.9** | **117.5** | **127.8** | **135.4** | **150.9** | **178.9** | **200.3** |

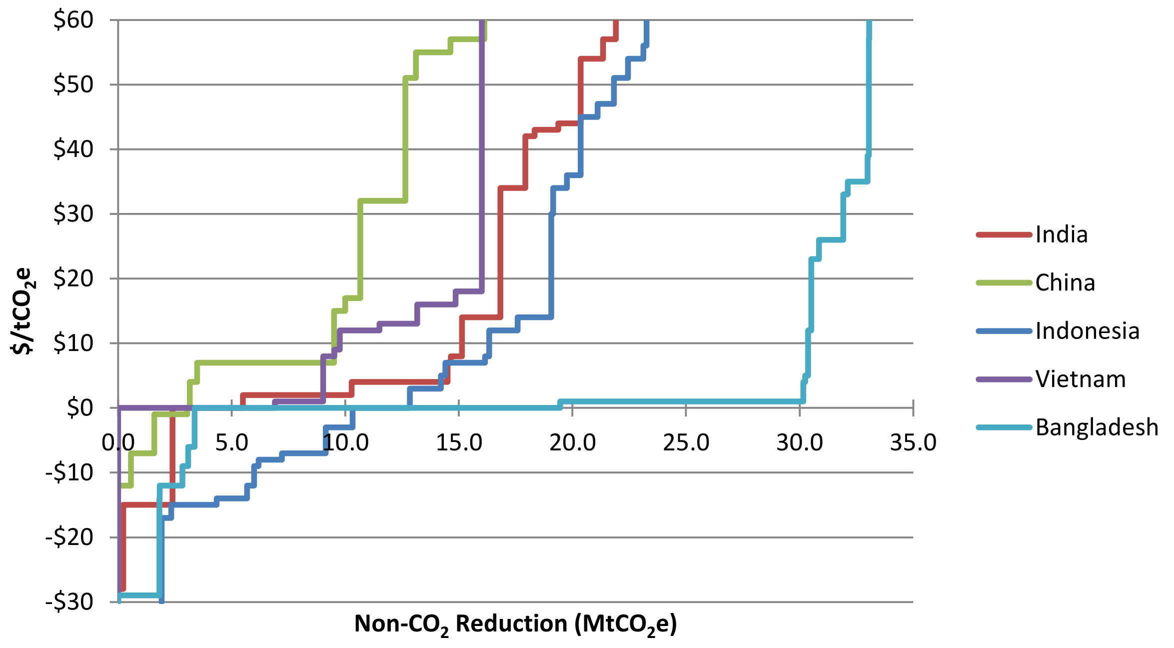
Mitigation potential and its cost-effectiveness vary significantly by country or region. At the regional level, Asia (in particular South and Southeast Asia), Africa, Central and South America and the European Union show the most significant potential for reducing GHG emissions from rice cultivation. For instance, in 2030 mitigation potential in Asia is estimated to be 27 $MtCO_2e$ with no carbon price and 34 $MtCO_2e$ at a carbon price of $20/tCO$_2$e. Central and South America can achieve mitigation potential of 12 $MtCO_2e$ in 2030 at no carbon price, and mitigation potential can increase to 22 $MtCO_2e$ at a carbon price of $20/tCO$_2$e. Figure 2-4 shows the MAC curves for the top-five emitting countries in 2030.

There are a large number of mitigation options included for rice cultivation and almost all provide net GHG reductions. The overall distribution of GHG mitigation across mitigation options included in this analysis is presented in Table 2-9. The options providing the largest quantify of GHG reductions are the two that involve switching to dryland production, which significantly reduces or eliminates $CH_4$ emissions. Those options do result in major reductions in yields, however. Other options that account for large reductions include nitrification inhibitors in combination with midseason drainage or alternate wetting and drying, along with switching to no-till, fertilizer reductions, and optimal fertilization options on non-irrigated lands. The relative share of mitigation provided by different options varies across years due to the dynamics of GHG emissions, especially for changes in soil C.

**Table 2-9: Distribution of Net GHG Reductions across Mitigation Options, Baseline Production Case**

| | 2010 | 2020 | 2030 |
|---|---|---|---|
| base_r100 | 1.74 | 0.35 | 0.36 |
| base_r50_amsu | 2.23 | 1.86 | 1.57 |
| base_r50_ninhib | 4.86 | 4.38 | 4.64 |
| base_r50_slowrel | 1.37 | 0.36 | 0.27 |
| base_r50_notill | 4.42 | 15.39 | 17.84 |
| base_r50_f70 | 6.59 | 12.77 | 13.12 |
| base_r50_f80 | 4.49 | 8.81 | 8.96 |
| base_r50_f90 | 2.30 | 4.52 | 4.57 |
| base_r50_auto | 5.89 | 10.55 | 11.46 |
| base_r50_ds | 0.95 | 0.61 | 0.57 |
| base_r50_f80_ds | 1.01 | 0.66 | 0.62 |
| cf_r100 | 0.11 | 0.00 | 0.00 |
| cf_r50_amsu | 1.26 | 1.50 | 1.51 |
| cf_r50_ninhib | 2.22 | 2.57 | 2.61 |
| cf_r50_slowrel | 2.24 | 1.96 | 1.87 |
| cf_r50_notill | 0.04 | 0.01 | 0.01 |
| cf_r50_f70 | 0.46 | 0.47 | 0.46 |
| cf_r50_f80 | 0.34 | 0.35 | 0.35 |
| cf_r50_f90 | 0.19 | 0.19 | 0.19 |
| cf_r50_auto | 0.40 | 0.23 | 0.18 |
| md_r50 | 5.08 | 5.52 | 5.59 |
| md_r100 | 6.36 | 3.76 | 3.75 |
| md_r50_amsu | 6.47 | 6.97 | 6.92 |
| md_r50_ninhib | 18.32 | 20.02 | 20.40 |
| md_r50_slowrel | 7.93 | 7.43 | 7.48 |
| md_r50_notill | 3.12 | 3.10 | 2.93 |
| md_r50_f70 | 6.14 | 6.66 | 7.07 |
| md_r50_f80 | 5.98 | 6.49 | 6.80 |
| md_r50_f90 | 5.61 | 6.10 | 6.30 |
| md_r50_auto | 4.80 | 5.13 | 5.33 |
| md_r50_ds | 1.34 | 1.01 | 1.01 |
| awd_r50 | 5.27 | 4.85 | 4.31 |
| awd_r50_ninhib | 19.70 | 19.11 | 17.95 |
| awd_r50_slowrel | 8.41 | 7.53 | 7.08 |
| dry_r50 | 25.35 | 15.00 | 13.23 |
| dry_r50_f80 | 25.74 | 17.00 | 13.00 |
| **TOTAL** | **198.73** | **203.23** | **200.33** |

**Figure 2-4: Marginal Abatement Cost Curve for Top 5 Emitters in 2030, Baseline Production Case**



## V.2.5 Sensitivity Analyses

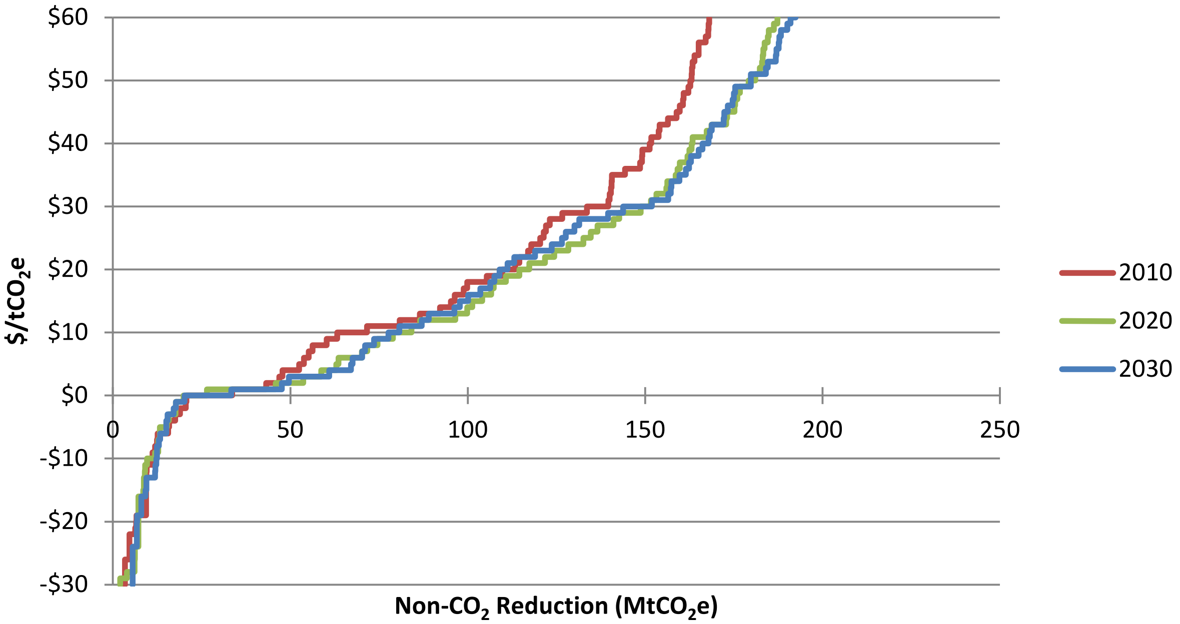
In this section, we explore sensitivity analyses to examine the potential effects of alternative assumptions on estimated mitigation potential. Because many of the mitigation options simulated impact rice yields, the assumption of constant production implies a change in the area devoted to rice production. There are options that increase productivity, but also many that decrease productivity. Thus, land requirements may increase or decrease to maintain production at baseline levels, but overall the package of mitigation options being considered tends to reduce yields. In this sensitivity analysis, we hold the area of cultivated rice at the baseline area and recalculate the MACs.

### *Baseline Acreage*

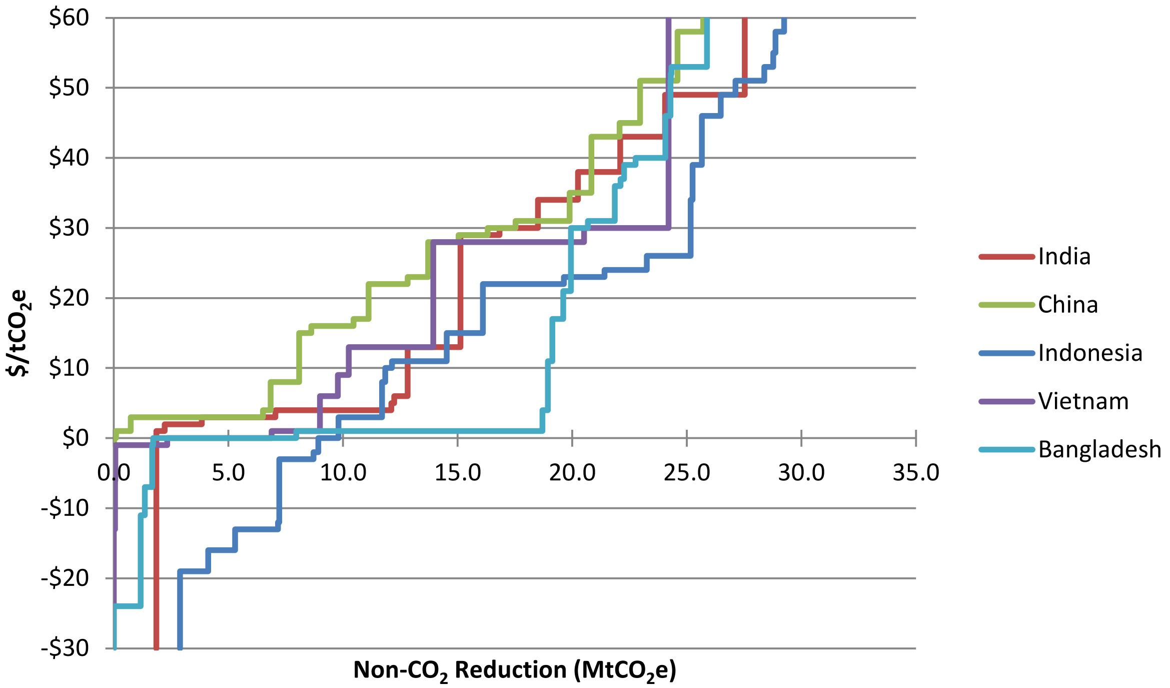
This section explores this relationship further by presenting an alternative scenario built around a constraint on the number of acres, keeping the harvested area the same as estimated in the baseline.

As before, the MAC model only includes options that result in lower emissions. The result for area held fixed at projected baseline area is shown in Figure 2-5. Generally speaking, emissions and emission reduction potential are slightly higher although the effects vary by country. Overall, global maximum potential mitigation is 320 MtCO2e, 60% higher than the global maximum potential mitigation of 200MtCO2e in the constant production case. Figure 2-6 shows the MAC for the top 5 rice producing countries under the constant area case. China's MAC shows relatively little change under the assumption of constant area, but the other countries show increased emissions mitigation potential to varying degrees.

## Figure 2-5: Marginal Abatement Cost Curve, Baseline Area Case



## Figure 2-6: Marginal Abatement Cost Curve for Top 5 Emitters in 2030, Baseline Area Case



### V.2.5. Uncertainties and Limitations

Given the complexities of the global rice sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Availability and quality of data to represent the highly complex and heterogeneous rice production systems of the world.*** Although there are major improvements in representing the global rice production systems and the business-as-usual baseline conditions compared to the previous EPA report (USEPA, 2006), data in some areas, such as management practices, are not always available for all countries or regions and approximations must be made based on limited literature or expert judgment. Moreover, collecting and developing consistent cost estimates of emerging and/or not widely adopted mitigation measures is challenging.
- ***Biophysical modeling uncertainties, in particular with respect to soil organic carbon simulations.*** The DNDC modeling of the business-as-usual baseline conditions and mitigation scenarios was performed using a set of inputs and assumptions developed based on various sources. The quality of input data ultimately affects the simulated results. Soil organic carbon, which has a significant impact on the net GHG emissions from the sector, is particularly challenging to simulate given the lack of monitoring data at the global scale. Sensitivity tests would be useful to assess how alternative modeling approaches and assumptions may influence modeling results.
- ***Optimistic assumptions on technology adoption.*** The analysis assumes that if mitigation technology is considered feasible in a country or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially slow the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.
- ***Potential interactions of multiple mitigation measures are not fully addressed in this analysis.*** In this analysis, mitigation options are applied to independent segments of the rice production systems to avoid double counting. In reality, multiple mitigation options can be applied, and their order of adoption and potential interactions may affect the aggregate GHG mitigation

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# V.3. Livestock

## V.3.1 Sector Summary

Livestock operations generate methane ($CH_4$) and nitrous oxide ($N_2O$) emissions. The greenhouse gas (GHG) emissions mainly come from two sources, enteric fermentation and manure management. Methane is produced as a by-product of the digestive process in animals through a microbial fermentation process. The quantity of enteric fermentation $CH_4$ emissions is determined by the animal's digestive system, diet and management practices. Livestock manure management can produce both $CH_4$ and $N_2O$ emissions. Methane is produced when manure decomposes under anaerobic conditions. The quantity of manure $CH_4$ emissions is determined by the type of treatment or storage facility, the ambient climate, and the composition of the manure. Manure $N_2O$ emissions result from nitrification and denitrification of the nitrogen that is excreted in manure and urine.

In 2010, the global non-$CO_2$ GHG emissions from livestock operations were approximately 2,286 $MtCO_2e$. Figure 3-1 presents projected total emissions for the top 5 emitting countries and the total for the rest of the world.

Methane emissions predominate with 2,152 $MtCO_2e$ emitted in 2010. Globally, livestock is the largest source of $CH_4$ emissions, contributing approximately 29% of total global $CH_4$ emissions in 2010. As shown in Figure 3-2, the top 5 emitting countries – India, China, Brazil, the United States, and Pakistan – accounted for 44% of the sector's total $CH_4$ emissions. Growth in $CH_4$ emissions is expected to be about 20% between 2010 and 2030.

**Figure 3-1: Total Net GHG Emissions and Projections for the Livestock Sector: 2000-2030**

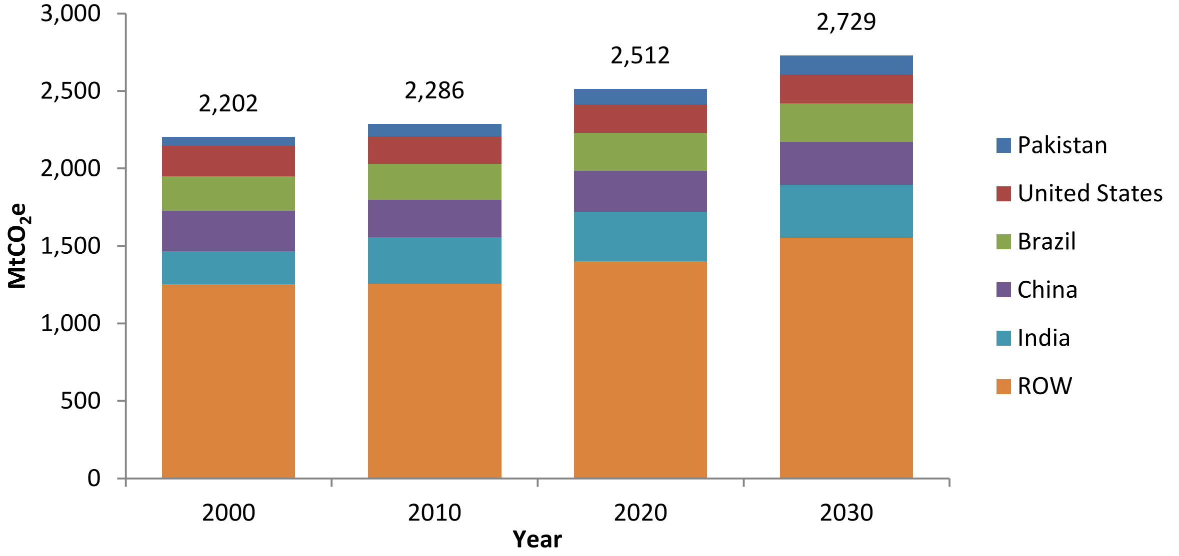
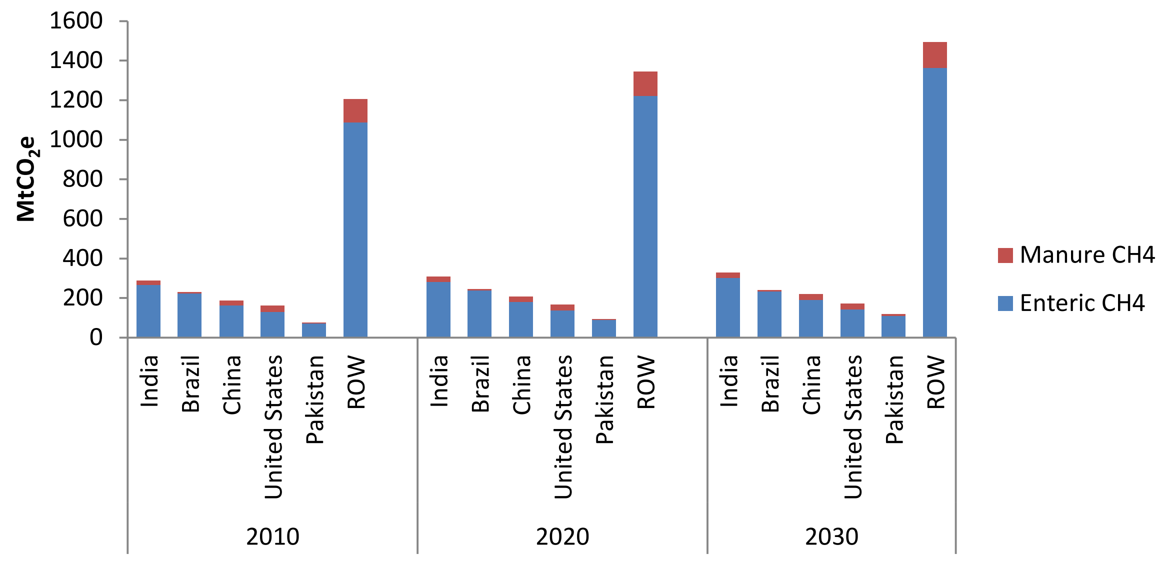
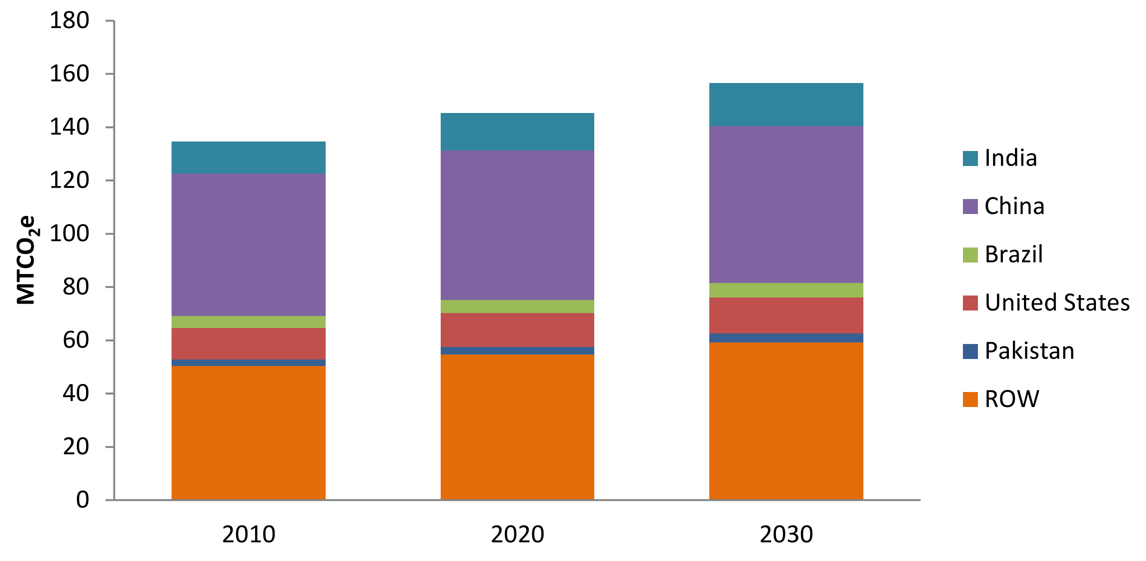


**Figure 3-2: CH4 Emissions Projections for the Livestock Sector: 2010–2030**



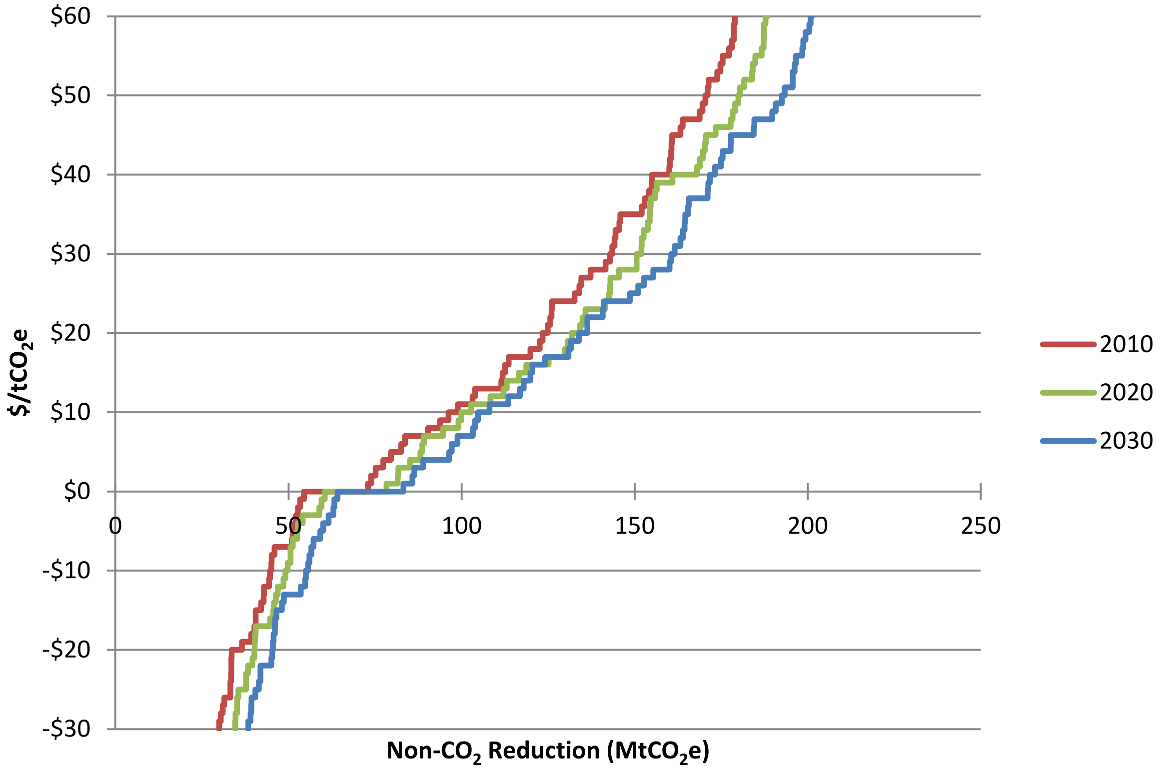
Nitrous oxide emissions from manure management are a second significant source of GHG emissions within the livestock sector, contributing an additional 135 $MtCO_2e$. Livestock contributed approximately 4% of total global $N_2O$ emissions in 2010. As presented in Figure 3-3, China, India, the United States, Brazil, and Pakistan together account for 63% of global $N_2O$ emissions from livestock operations in 2010. $N_20$ emissions are expected to grow about 16% between 2010 and 2030 to about 156 $MtCO_2e$, slightly lower than the projected growth in $CH_4$ emissions over the same time period.

**Figure 3-3: $N_20$ Emissions Projections from the Livestock Sector: 2010–2030**



Marginal abatement cost (MAC) curve results assuming the production of livestock products remains constant at projected baseline levels are presented in Figure 3-4. Maximum abatement potential in the livestock sector is 268 $MtCO_2e$ in 2030, or about 9.8% of total GHG emissions in that year.[1] These results suggest that there are significant opportunities for GHG reductions in the livestock sector. Approximately 86 $MtCO_2e$ can be reduced in 2030 at no or low carbon prices below $5 per ton of $CO_2$ equivalent.

**Figure 3-4: Global Abatement Potential in Livestock Management: 2010, 2020, and 2030**



The following section offers a brief description of $CH_4$ and $N_2O$ emissions from livestock operations, and a discussion of projected trends in global baseline emissions. The subsequent section presents possible abatement technologies, their technical specifications, costs and potential benefits. The final section discusses the MAC analysis and estimated abatement potential at global and regional levels.

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[1] This analysis only assesses abatement measures that are designed to reduce $CH_4$ emissions. Mitigation options that focus on potential reductions in $N_2O$ emissions are not included due to relatively small potential abatement potential and limited information on abatement measures and costs. However, $N_2O$ emissions are affected by changes in livestock productivity under our primary scenario with production held constant because the number of animals required to produce a given quantity of livestock products, and their associated emissions, changes with productivity.

## V.3.2 $CH_4$ and $N_2O$ Emissions from Livestock Management

This section discusses how $CH_4$ and $N_2O$ emissions are produced in livestock operations and the current projections of baseline emissions between 2010 and 2030.

### V.3.2.1 CH4 Emissions from Enteric Fermentation

Enteric fermentation produced about 1945 $MtCO_2e$ of $CH_4$ in 2010 and accounts for about 90% of the total $CH_4$ emissions from livestock. Methane is produced as a by-product of the digestive process in animals. This microbial fermentation process produces $CH_4$ that can be exhaled or excreted by the animal. The quantity of $CH_4$ produced through enteric fermentation depends largely on the animal's digestive system, diet and management practices. Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major sources of enteric $CH_4$ emissions; nonruminant animals (e.g., swine, horses, mules) also produce enteric $CH_4$ emissions but at much lower rates compared to ruminant animals.

The quantity, quality and digestibility of feed significantly affect enteric $CH_4$ emissions. The main constituents of the diet - sugars, starch, fiber, protein and lipid - appear to have varying impacts on methane emissions. In general, increased intake of starch and soluble sugars decreases rumen pH, which suppresses methanogens, thus resulting in lower $CH_4$ emissions. Lower feed quality such as higher content of insoluble fiber leads to higher $CH_4$ emissions. Provision of feed supplements, such as dietary oils, is found to have an inhibitory effect on $CH_4$ production in the rumen (Hristov et al., 2013). Management practices that improve animal productivity, such as the usage of antibiotics and bovine somatotropin (bST), often reduce $CH_4$ emissions per unit of meat or milk even though these activities can increase $CH_4$ emissions per animal.

### V.3.2.2 $CH_4$ and $N_2O$ Emissions from Manure Management

#### *Manure Management $CH_4$ Emissions*

Manure management produced about 206 $MtCO_2e$ of $CH_4$ in 2010, smaller than enteric fermentation but still a significant global source of $CH_4$ at about 3% of global total methane production.[2] In livestock waste management systems, $CH_4$ is produced when manure decomposes under anaerobic conditions, for example in lagoons, ponds or pits. The quantity of $CH_4$ emitted from manure management operations is determined by the type of treatment or storage facility, the ambient climate, and the composition of the manure (USEPA, 2012). Higher ambient temperature and moisture conditions favor $CH_4$ production.

#### *Manure Management $N_2O$ Emissions*

In addition to $CH_4$, livestock waste management produced about 135 $MtCO_2e$ of $N_2O$ in 2010. Nitrous oxide is produced from livestock waste through nitrification and denitrification. Nitrous oxide emissions from livestock waste depend on the composition of the waste, the type of bacteria involved in the decomposition process, and the oxygen and liquid content of waste (USEPA 2012). Nitrous oxide generation is most likely to occur in dry manure handling systems.

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[2] Global CH4 emissions in 2010 totaled 7,549.2 MTCO2e (USEPA, 2012, Table A2)

### V.3.2.3 Baseline $CH_4$ and $N_2O$ Emissions Estimates

This section discusses the historical and projected baseline emissions for the livestock sector. Historical emissions are characterized as those released between 1990 and 2005. Projected emissions cover the 20-year period 2010 – 2030.[3]

#### *Historical Emissions Estimates*

Over the 1990 – 2005 period, total non-$CO_2$ GHG emissions from livestock operations increased by 4% between 1990 and 2005, from 2,201 to 2,292 $MtCO_2e$ (USEPA, 2012). This modest growth is caused by two opposing trends: growth in Africa and Central and South America has been partially offset by the effects of market restructuring in non-OECD Europe. Enteric fermentation $CH_4$ emissions increased 7% between 1990 and 2005 while emissions of $CH_4$ and $N_20$ from livestock waste management decreased 9% between 1990 and 2005.

#### *Projected Emissions Estimates*

This analysis uses the 2005 country-level livestock population data from the Global Anthropogenic Non-$CO_2$ Emissions Report ("GER") as a starting point (USEPA, 2012). However, for the period 2010—2030 an alternate business-as-usual forecast was constructed using livestock production and market price projections generated by the International Food Policy Research Institute (IFPRI)'s International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) (Nelson et al., 2010) to derive projected livestock populations. A key rationale for relying directly on these model outputs is that the IFPRI IMPACT model projections provide a set of prices and global production patterns consistent with their livestock population and productivity assumptions. Using these data improves the internal consistency of the MAC analysis.[4]

Table 3-1 shows projected baseline emissions from livestock management for the top 5 emitting countries and the rest of the world, divided into major regions.[5] Global emissions from livestock management are projected to grow at an average annual rate of 0.9%. In general, emissions are growing much more rapidly in developing countries than in the developed world.

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[3] The year 2010, although historical, is the first year of the modeling forecast period.

[4] The IMPACT outputs separated the world into 116 regions, with larger countries defined individually and smaller countries combined into regions. A mapping was created between IMPACT regions and the 195 countries in this analysis, using shares of country-level livestock population in 2010 based on USEPA (2012) to disaggregate regional projections from the IMPACT model to individual countries within each region.

[5] Regional totals exclude the top 5 emitting countries that are presented separately in the table.

**Table 3-1: Projected Baseline Emissions from Livestock Management: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| India | 300 | 311 | 322 | 333 | 344 | 0.7% |
| China | 242 | 253 | 262 | 271 | 278 | 0.7% |
| Brazil | 235 | 247 | 248 | 247 | 246 | 0.2% |
| United States | 174 | 179 | 181 | 184 | 186 | 0.3% |
| Pakistan | 80 | 89 | 99 | 110 | 122 | 2.1% |
| **Rest of Regions** | | | | | | |
| Asia | 259 | 283 | 307 | 335 | 367 | 1.8% |
| Africa | 293 | 320 | 343 | 369 | 395 | 1.5% |
| Europe | 257 | 257 | 257 | 257 | 257 | 0.0% |
| Middle East | 28 | 30 | 32 | 35 | 38 | 1.6% |
| Central & South America | 227 | 245 | 258 | 271 | 284 | 1.1% |
| Eurasia | 118 | 120 | 121 | 124 | 126 | 0.3% |
| North America | 74 | 77 | 80 | 83 | 85 | 0.8% |
| **World Totals** | **2,286** | **2,411** | **2,512** | **2,619** | **2,729** | **0.9%** |

Table 3-2 summarizes projected baseline emissions from enteric fermentation. Worldwide $CH_4$ emissions from enteric fermentation are projected to increase at an average annual rate of 0.9% between 2010 and 2030. The top five countries, India, Brazil, China, the United States, and Pakistan, combine for about 44% of global totals in 2010, but the baseline projection has emissions from all of these countries except Pakistan growing at a slower rate than the global average. Annualized growth rates in the top five countries average 0.7%, lower than the average 0.9% growth projected in the rest of regions. By 2030, the top five countries are the source of 42% of global enteric fermentation emissions.

**Table 3-2: Projected Baseline Emissions from Enteric Fermentation: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| India | 265 | 274 | 283 | 293 | 301 | 0.7% |
| Brazil | 225 | 236 | 237 | 236 | 234 | 0.2% |
| China | 162 | 172 | 179 | 186 | 191 | 0.8% |
| United States | 132 | 136 | 138 | 141 | 143 | 0.4% |
| Pakistan | 73 | 81 | 90 | 100 | 111 | 2.1% |

(continued)

**Table 3-2: Projected Baseline Emissions from Enteric Fermentation: 2010–2030 ($MtCO_2e$) (continued)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| **Rest of Regions** | | | | | | |
| Asia | 211 | 231 | 251 | 275 | 303 | 1.8% |
| Africa | 277 | 302 | 325 | 349 | 374 | 1.5% |
| Europe | 195 | 196 | 197 | 198 | 198 | 0.1% |
| Middle East | 26 | 28 | 30 | 33 | 36 | 1.6% |
| Central & South America | 218 | 235 | 248 | 261 | 272 | 1.1% |
| Eurasia | 97 | 99 | 101 | 103 | 105 | 0.4% |
| North America | 64 | 68 | 71 | 73 | 76 | 0.8% |
| **World Totals** | **1,945** | **2,059** | **2,150** | **2,246** | **2,345** | **0.9%** |

Similarly, worldwide emissions from manure management are projected to increase at an average annual rate of 0.6% between 2010 and 2030, but that world average combines slower growth in the top-emitting countries with faster growth in the rest of regions. In 2010, the top five countries combine to account for 51% of global emissions from manure management. By 2030, these same five are projected to account for just under 50% of global emissions, equivalent to annual growth of 0.4%. In the rest of regions, global emissions grow at an average annual growth rate of 0.8%.

**Table 3-3: Projected Baseline Emissions from Manure Management: 2010–2030 ($MtCO_2e$)**

| Country | 2010 | 2015 | 2020 | 2025 | 2030 | CAGR (2010–2030) |
|---|---|---|---|---|---|---|
| **Top 5 Emitting Countries** | | | | | | |
| China | 79 | 81 | 83 | 85 | 87 | 0.5% |
| United States | 43 | 43 | 43 | 43 | 43 | 0.0% |
| India | 35 | 37 | 39 | 40 | 42 | 0.9% |
| Brazil | 10 | 10 | 11 | 11 | 12 | 0.8% |
| France | 8 | 8 | 8 | 8 | 8 | -0.4% |
| **Rest of Regions** | | | | | | |
| Asia | 56 | 60 | 65 | 70 | 76 | 1.5% |
| Africa | 16 | 17 | 19 | 20 | 21 | 1.4% |
| Europe | 53 | 53 | 52 | 52 | 52 | -0.1% |
| Middle East | 2 | 2 | 2 | 2 | 2 | 1.3% |
| Central & South America | 9 | 10 | 10 | 11 | 11 | 1.2% |
| Eurasia | 21 | 21 | 21 | 21 | 21 | 0.1% |
| North America | 9 | 9 | 10 | 10 | 10 | 0.3% |
| **World Totals** | **341** | **352** | **362** | **373** | **384** | **0.6%** |

## V.3.3 Abatement Measures and Engineering Cost Analysis

A significant number of livestock GHG mitigation measures can be identified in the literature (e.g., Hristov et al., 2013; Archibeque et al. 2012; UNFCCC 2008, Whittle et al, 2013). However, developing consistent and regional-specific cost estimates for emerging mitigation measures or options that are not widely adopted has proven a challenging task. The measure cost data are scarce and often reflect anecdotal experience reported in a specific country, region or livestock production system. Assumptions have to be made to extrapolate the estimates in other countries, regions and production systems. This review uncovered only a few studies where cost information was presented in addition to associated emission reductions for a number of mitigation measures. Moreover, for some mitigation measures, such as those that potentially reduce livestock enteric fermentation $CH_4$ emissions, the literature varies on the estimated magnitude of emissions reductions as well as the long-term mitigation effects and animal and human health impacts.

Based on the availability and quality of mitigation measure cost and emission reduction efficiency information, this analysis evaluates six mitigation options for enteric fermentation $CH_4$ emissions and ten options for manure management $CH_4$ emissions. Each technology is briefly characterized followed by a discussion of abatement measures' implementation costs, potential benefits, and system design assumptions used in the MAC analysis.

### V.3.3.1 Enteric Fermentation $CH_4$ Mitigation Technologies

This section characterizes the mitigation technologies that can be applied to reduce enteric $CH_4$ emissions. Many of the currently available enteric fermentation mitigation options, summarized in Table 3-4, work indirectly by increasing animal growth rates and reducing time-to-finish (or increasing milk production for dairy cows). The potential GHG mitigation estimated here depends on the assumption that total production of meat or milk remains the same as in the baseline. Simply put, these strategies work because increased productivity means fewer animals are required to produce the same amount of meat or milk, and fewer animals mean reduced GHGs.

Unfortunately, many of the productivity enhancing options in this group are not without controversy (Hristov et al., 2013; Grainger et al., 2010). Some, such as bST and antibiotics, have raised concerns outside than their potential role in reducing GHGs. Most have greater than usual uncertainty about costs and effectiveness, especially under long term use. For example, Whittier et al. (2013), in developing MAC curves for Australia, assume that feed supplements (analogous to Improved Feed Conversion here) and antimethanogen vaccines will become available by 2020 for some types of livestock operations. However, ICF international, writing in a report prepared for the USDA, provides only a qualitative description of enteric fermentation GHG mitigation options, excluding them from cost or break-even analysis because "more research is needed to evaluate the potential GHG impacts of changes in diets, use of feed additives, and breeding (ICF International, 2013, p 3.62)."

In what follows we present descriptions and economic information used to derive the MAC curves. We examine the sensitivity of these results to productivity assumptions in Section V.3.5 which replaces the assumption of constant production with an assumption of constant animal population and also examines a no antimethanogen case.

Table 3-4: Abatement Measures for Enteric Fermentation $CH_4$

| Abatement Option | Total Installed Capital Cost (2010 USD) | Annual O&M Cost (2010 USD) | Capital Lifetime (Years) | Reduction Efficiency (change in emissions per head) | Benefits (Changes in Livestock or Energy Revenue) |
|---|---|---|---|---|---|
| Improved Feed Conversion | 0 | 25–295 per head | NA | $CH_4$: –39.4% to +39.6% | 0–79% increase in animal yield |
| Antibiotics | 0 | 4–9 per head | NA | $CH_4$: –0.4% to –6% | 5% increase in animal yield |
| bST | 0 | 123–300 per head | NA | $CH_4$: –0.2% to +10.3% | 12.5% increase in animal yield |
| Propionate Precursors | 0 | 40–120 per head | NA | $CH_4$: –10% beef cattle and sheep; –25% dairy animals | 5% increase in animal yield |
| Antimethanogen | 0 | 9–33 per head | NA | $CH_4$: –10% | 5% increase in animal yield |
| Intensive Grazing | 0 | –180 to +1 per head | NA | $CH_4$: –13.3% beef cattle; –15.5% dairy cattle | –11.2% reduction in dairy cattle yield |

### *Improved Feed Conversion*

This mitigation measure encompasses a number of management practices that would improve the proportion of feed energy converted to final products. The practices include increased amount of grain fed to livestock, and inclusion of dietary additives. This option is more effective in reducing emissions in regions where baseline feed is of relatively low quality.

- **Annual Cost:** Typical annual costs for improving feed are between \$2 and \$295 per head for beef and dairy cattle. No data were identified for other species. One of the primary costs for this option, as well as most of the others below, is for additional labor costs necessary for implementation. Differences in labor input share and labor costs per hour are also major reasons for the wide variation in costs between regions and livestock production systems.
- **Annual Benefits:** Ration improvements result in an increase in yield (kg of meat or milk per animal) between 0 and 79%. There is considerable variation in the productivity impacts, primarily related to differences in baseline feed quality and productivity. Livestock raised in countries with low quality feeds in the baseline tend to have much greater productivity benefits from improved feed conversion than those in developed countries where feed conversion is already highly efficient.
- **Applicability:** This option applies to beef and dairy cattle in areas where baseline livestock growth rates and milk production are low, primarily developing regions including Africa. This option is assumed to be available only for urban livestock production or intensively managed livestock production and only applied in regions where the yield gains associated with the option are greater than baseline yield increases (typically limited to regions that do not already feed mixed rations).

- **Technical Efficiency:** This analysis assumes a change in emissions per head between -39% and +40%. Cases with increased emissions are excluded from the MAC analysis.[6]

### Antibiotics

Feed antibiotics (e.g., monensin) to promote increased weight gain and reduce feed intake per metric ton of meat produced.

- **Annual Cost:** Typical annual costs for providing antibiotics are between $4 and $9 per head for beef cattle including the costs of antibiotics and increased labor costs for implementation. No data exist for other species.
- **Annual Benefits:** Ration improvements result in an increase in yield of 5% kg/animal
- **Applicability:** This option applies to beef cattle in all regions, but is restricted to urban livestock production and intensively managed livestock production.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head between 0% and 6%.

### Bovine Somatrotropin (bST)

This measure administers bST to dairy cattle to increase milk production. Because of opposition to the use of growth hormones like bST in many countries, this option was only applied in a subset of countries.

- **Annual Cost:** Typical annual costs for purchasing and administering bST were estimated to be between $123 and $300 per head for dairy cows. This cost is based on the cost of purchasing bST and the additional labor costs required for administering.
- **Annual Benefits:** Using bST results in an average annual increase in yield (kg milk per head) of 12.5%
- **Applicability:** This option applies to dairy cows in all countries that currently approve the use of bST or are likely to do so in the near future. This option is assumed to be available only for urban or intensively managed livestock production.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head between 0% and 6%.

### Propionate Precursors

This option involves administering propionate precursors (malate, fumarate) 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.

- **Annual Cost:** Typical annual costs for purchasing and administering propionate precursors are between $40 and $120 per head for beef cattle, sheep, and dairy animals.
- **Annual Benefits:** Administering propionate precursors results in an increase in yield (kg of meat or milk per animal) of 5%.

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[6] For the primary scenario where production is held constant, options that increase emissions per unit of output are excluded from the MAC calculations. Thus, mitigation options that increase emissions per head are still included in the MAC calculations if they increase productivity more than then they increase emissions, resulting in a reduction in emissions intensity per unit of output.

- **Applicability:** This option applies to beef cattle, sheep, and dairy animals in all regions. However, as with other options, it is only applied in urban and intensive livestock production systems.
- **Technical Efficiency:** This analysis assumes a reduction in $CH_4$ emissions per head of 10% for beef cattle and sheep and a reduction of 25% for dairy animals.

### *Antimethanogen*

Antimethanogen is a vaccine that can be administered to animals to suppress $CH_4$ production in the rumen. The vaccine is currently in infancy of development with limited information on emission reduction efficiency and long-term mitigation effects and animal health impacts.

- **Annual Cost:** Typical annual costs for providing antimethanogens are between $9 and $33 per head for purchasing and administering antimethanogens.
- **Annual Benefits:** Increases yields by 5% as more of the energy contained is feed is used by the animals to produce for meat or milk rather than producing methane
- **Applicability:** This option applies to all ruminants in all regions, though again it is assumed that only urban and intensively managed systems can adopt this option.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of 10%.

### *Intensive Grazing*

Improving nutrition through more intensive pasture management and cattle rotations to allow for regrowth while decreasing reliance upon prepared rations.

- **Annual Cost:** Estimated reduction in yield of 11.2% for dairy cattle. Beef yields are assumed to remain unchanged under this option.
- **Annual Benefits:** Estimated annual cost savings of between $0 and $180 per head for reduced expenditures on feed.
- **Applicability:** This option applies only to beef and dairy cattle in developed regions and Latin America. It was assumed to be available only in intensively managed systems within livestock production system categories that receive relatively large amounts of annual rainfall such that intensive grazing is feasible.
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 13-15%.

## V.3.3.2 Manure Management $CH_4$ Mitigation Technologies

Mitigation options for reducing $CH_4$ from livestock manure focus on changes in manure management practices that capture the $CH_4$ to flare or use for energy production (see Table 3-5). There are fewer options for reducing $N_2O$ emissions from manure because these emissions tend to result from decomposition under aerobic conditions, such as from pasture, range, and paddock where manure is much less concentrated and more difficult to manage.

This analysis includes both large capital-intensive digesters applied in developed regions and small-scale digesters for developing regions. Revenues are generated from the use of captured $CH_4$ for either heat or electricity on the farm; these revenues are scaled to other regions based on an electricity price index. Capital costs and O&M costs for digester systems are mainly based on the USEPA AgSTAR program data and experience in the U.S. and the developing countries (USEPA, 2010; Roos, personal communication 2012; Costa, personal communication 2012), supplemented by information from USDA (2007, 2011). For the EU, technology cost and performance parameters are based on Bates et al. (2009). For developing countries, the U.S. technology cost data are assumed for large digester systems with adjustments made to represent O&M costs in the developing countries. Capital costs for small-scale systems are based on USEPA (2006), which estimates the capital cost per 1,000 pounds liveweight. Because liveweight tends to be much smaller in developing countries, the capital cost per animal generally ends up being lower than in developed regions.

**Table 3-5: Abatement Measures for Manure Management**

| Abatement Option | Total Installed Capital Cost (2010 USD) | Annual O&M Cost (2010 USD) | Capital Lifetime (Years) | Reduction Efficiency (change in emissions per head) | Benefits (Changes in Livestock or Energy Revenue) | Technical Applicability | Adjustments Across Regions |
|---|---|---|---|---|---|---|---|
| **Complete-mix Digester, Hogs** | | | | | | | |
| With Engine | 100 per head (US) | 0.11 per head (US) | 20 | $CH_4$: -85% | $8 energy revenue/ savings per head (US) | Hogs in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 61 per head (US) | 0.07 per head (US) | 20 | $CH_4$: -85% | none | Hogs in selected LPS and management intensities | Labor costs, labor share |
| **Complete-mix Digester, Dairy Cattle** | | | | | | | |
| With Engine | 958 per head (US) | 3.35 per head (US) | 20 | $CH_4$: -85% | $65 energy revenue/ savings per head (US) | Dairy cattle in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 588 per head (US) | 2.06 per head (US) | 20 | $CH_4$: -85% | none | Dairy cattle in selected LPS and management intensities | Labor costs, labor share |
| **Plug-flow Digester, Dairy Cattle** | | | | | | | |
| With Engine | 1288 per head (US) | 2.3 | 20 | CH4: -85% | $65 energy revenue/ savings per head (US) | Dairy cattle in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 790 per head (US) | 8.9 | 20 | CH4: -85% | none | Dairy cattle in selected LPS and management intensities | Labor costs, labor share |

(continued)

**Table 3-5: Abatement Measures for Manure Management (continued)**

| Abatement Option | Total Installed Capital Cost (2010 USD) | Annual O&M Cost (2010 USD) | Capital Lifetime (Years) | Reduction Efficiency (change in emissions per head) | Benefits (Changes in Livestock or Energy Revenue) | Technical Applicability | Adjustments Across Regions |
|---|---|---|---|---|---|---|---|
| **Fixed-film Digester, Hogs** | | | | | | | |
| With Engine | 128 per head (US) | 0.15 per head (US) | 20 | $CH_4$: -85% | $8 energy revenue/ savings per head (US) | Hogs in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 102 per head (US) | 0.12 per head (US) | 20 | $CH_4$: -85% | none | Hogs in selected LPS and management intensities | Labor costs, labor share |
| **Covered Lagoon, Large-Scale, Hogs** | | | | | | | |
| With Engine | 43 per head (US) | 0.13 per head (US) | 20 | $CH_4$: -85% | $8 energy revenue/ savings per head (US) | Hogs in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 25 per head (US) | 0.06 per head (US) | 20 | $CH_4$: -85% | none | Hogs in selected LPS and management intensities | Labor costs, labor share |
| **Covered Lagoon, Large-Scale, Dairy Cattle** | | | | | | | |
| With Engine | 1182 per head (US) | 3.43 per head (US) | 20 | $CH_4$: -85% | $65 energy revenue/ savings per head (US) | Dairy cattle in selected LPS and management intensities | Labor costs, labor share, energy prices |
| Without Engine | 773 per head (US) | 2.01 per head (US) | 20 | $CH_4$: -85% | none | Dairy cattle in selected LPS and management intensities | Labor costs, labor share |
| Dome Digester, Cooking Fuel and Light | 50 per 1000 lbs liveweight | 1.25 per 1000 lbs liveweight | 10 | $CH_4$: -50% | $7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle | Hogs and dairy cattle in selected LPS and management intensities in developing countries | Labor costs, labor share, energy prices |

(continued)

Table 3-5: Abatement Measures for Manure Management (continued)

| Abatement Option | Total Installed Capital Cost | Annual O&M Cost | Capital Lifetime (Years) | Reduction Efficiency (change in emissions per head) | Benefits (Changes in Livestock or Energy Revenue) | Technical Applicability | Adjustments Across Regions |
|---|---|---|---|---|---|---|---|
| | (2010 USD) | (2010 USD) | | | | | |
| Polyethylene Bag Digester, Cooking Fuel and Light | 20 per 1000 lbs liveweight | 0.5 per 1000 lbs liveweight | 10 | $CH_4$: -50% | $7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle | Hogs and dairy cattle in selected LPS and management intensities in developing countries | Labor costs, labor share, energy prices |
| Centralized Digester | 163 per head average for hogs across the EU, 1007 per head average for dairy cattle across the EU | 0.07 per head for hogs, 2.06 dairy cattle | 20 | $CH_4$: -85% | $7 energy revenue/ savings per head hogs, $48 energy revenue/ savings per head dairy cattle | Hogs and dairy cattle in selected LPS and management intensities in the EU-27 region | Labor costs, labor share, energy prices |

### *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 and 10%. 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 gas flow.

- **Capital Cost: $61/$100 per head (swine), $588/$958 per head (cattle) depending on optional engine**
- **Annual O&M Cost:** Estimated $0.07--$0.11 per head (swine), $2.06/3.35 (cattle)
- **Annual Benefits:** $8 per head (swine), $65 per head (cattle) if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine and cattle managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

### *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 to 13%. As with complete-mix digesters, they are maintained at constant temperatures throughout the year to maintain constant gas production.

- **Capital Cost: $790/$1288 per head**
- **Annual O&M Cost:** Estimated $2.30 -- $8.90 per head
- **Annual Benefits:** $65 per head if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to dairy cattle in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

### Fixed-film Digester

This digester option may be appropriate where concentrations of solids are very low, such as in swine 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.

- **Capital Cost: $102/$128 per head**
- **Annual O&M Cost:** Estimated $0.06 -- $0.13 per head
- **Annual Benefits:** $8 per head if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

### Large-scale Covered Lagoon

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%) 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.

- **Capital Cost**: $25/$43 per head (swine), $773/$1,182 (cattle)
- **Annual O&M Cost:** Estimated $0.06/$0.13 per head (swine), $2.01/$3.43 (cattle)
- **Annual Benefits:** $8 per head (swine), $65 per head (cattle) if equipped with an engine and used to displace purchased power
- **Applicability:** This option applies only to swine and dairy cattle managed in intensive production systems in developed regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

### Small-scale Dome Digester

These are small, unheated digesters used in some developing countries, 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.

- **Capital Cost:** $50 per 1,000 lbs liveweight
- **Annual O&M Cost:** Estimated $1.25 per 1,000 lbs liveweight

- **Annual Benefits:** $7 per head (swine), $48 per head (cattle)
- **Applicability:** This option applies to swine and dairy cattle in developing regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 50%.
- **Capital Lifetime:** 10 years

### *Centralized Digester*

Large centralized digesters where individual farmers transport their waste to in order for large scale digestion and dispersion of capital costs.

- **Capital Cost:** $163 per head (swine) , $1,007 per head (cattle)
- **Annual O&M Cost:** Estimated $0.07 per head (swine), $2.06 per head (cattle)
- **Annual Benefits:** Assumed to provide the same annual benefits per head of livestock as the large individual systems described above.
- **Applicability:** This option applies only to swine and dairy cattle in intensively managed production systems in EU-27 regions
- **Technical Efficiency:** This analysis assumes a reduction in emissions per head of about 85%.
- **Capital Lifetime:** 20 years

## V.3.4 Marginal Abatement Costs Analysis

The MAC analysis assimilates the abatement measures' technology costs, expected benefits, and emission reductions presented in Section X.3 to compute the cost of abatement for each measure. Similar to the approach used in other non-$CO_2$ sectors of this report, we compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the technical, net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

This section describes the general modeling approach applied in this sector, which serve as additional inputs to the MAC analysis that adjust the abatement project costs, benefits, and the technical abatement potential in each country.

### V.3.4.1 Development of Disaggregated Baseline Livestock Populations

Livestock population projections at a disaggregated level are a key component of estimating potential emissions reductions from livestock production. Tables 3-6 and 3-7 present baseline projected livestock populations by species at the global and regional levels, respectively. As noted earlier in this chapter, these projections are based on country-level livestock population data from USEPA (2012), adjusted using livestock production and market price projections from Nelson et al. (2010) to derive projected livestock populations.

**Table 3-6: Projected Global Livestock Populations by Species**

| Species | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Asses | 43,694,545 | 44,710,040 | 46,511,983 | 49,232,861 | 53,072,574 |
| Mules | 10,687,809 | 9,719,699 | 9,087,894 | 8,688,065 | 8,454,990 |
| Buffalo | 181,068,216 | 190,207,386 | 200,872,941 | 213,277,930 | 227,690,865 |
| Camels | 25,230,544 | 27,116,465 | 29,660,950 | 33,095,191 | 37,758,103 |
| Cattle | 1,141,799,067 | 1,233,755,944 | 1,293,778,238 | 1,348,359,726 | 1,392,273,902 |

(continued)

**Table 3-6: Projected Global Livestock Populations by Species (continued)**

| Species | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---:|---:|---:|---:|---:|
| Dairy cattle | 247,195,753 | 248,770,901 | 250,894,992 | 253,588,443 | 256,874,692 |
| Goats | 882,119,170 | 947,475,133 | 1,035,241,803 | 1,151,801,402 | 1,306,127,535 |
| Horses | 58,864,443 | 59,669,740 | 61,198,242 | 63,481,024 | 66,580,631 |
| Other camelids | 6,926,082 | 7,090,544 | 7,260,388 | 7,435,790 | 7,616,931 |
| Pigs | 947,222,554 | 963,684,813 | 981,443,858 | 1,000,597,025 | 1,021,251,228 |
| Sheep | 1,126,923,912 | 1,264,771,843 | 1,421,729,708 | 1,600,736,874 | 1,805,223,246 |
| Turkeys | 488,712,578 | 506,073,755 | 524,421,101 | 543,822,679 | 564,352,297 |
| Chickens | 18,934,787,428 | 20,500,590,776 | 22,251,209,335 | 24,210,358,750 | 26,405,046,832 |
| Ducks | 1,156,375,916 | 1,288,661,778 | 1,437,928,802 | 1,606,439,449 | 1,796,773,159 |
| Geese | 365,742,348 | 404,547,438 | 447,801,893 | 496,016,058 | 549,759,182 |

The livestock populations were disaggregated into 14 categories of livestock production systems (LPSs) based on the Gridded Livestock of the World (Robinson et al., 2011), along with an "UNKNOWN" category that was added to account for cases where there were no data available to assign a livestock species to an LPS:

- LGA – livestock only grassland arid and semiarid
- LGH – livestock only grassland humid and subhumid
- LGT – livestock only grassland highland temperate
- LGY – livestock only grassland hyper arid
- MIA – irrigated mixed crop-livestock systems arid and semiarid
- MIH – irrigated mixed crop-livestock systems humid and subhumid
- MIT – irrigated mixed crop-livestock systems highland temperate
- MIY – irrigated mixed crop-livestock systems hyper arid
- MRA – rainfed mixed crop-livestock systems arid and semiarid
- MRH – rainfed mixed crop-livestock systems humid and subhumid
- MRT – rainfed mixed crop-livestock systems highland temperate
- MRY – rainfed mixed crop-livestock systems hyper arid
- URBAN – built-up areas
- OTHER – other systems
- UNKNOWN – no data available to assign to LPS

## Table 3-7: Regional Livestock Populations by Species, 2010 and 2030

| | Asses | Mules | Buffalo | Camels | Cattle | Dairy Cattle | Goats | Horses | Pigs | Sheep | Turkeys | Chickens | Ducks | Geese |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2010** | | | | | | | | | | | | | | |
| AFRC | 19,060,943 | 1,077,045 | 5,339,864 | 21,477,486 | 220,327,356 | 58,488,802 | 299,505,213 | 4,709,306 | 27,178,558 | 304,049,685 | 17,230,236 | 1,452,628,008 | 16,880,560 | 12,657,925 |
| MIEA | 2,749,155 | 198,708 | 753,069 | 1,247,756 | 8,021,314 | 5,567,448 | 45,065,821 | 225,902 | 214,307 | 109,243,396 | 6,102,128 | 845,345,519 | 1,886,081 | 2,092,632 |
| CSAM | 3,798,475 | 2,955,700 | 1,111,814 | 309,916,289 | 37,138,939 | 25,161,984 | 17,250,838 | 6,926,082 | 69,414,647 | 79,203,085 | 57,089,883 | 2,434,716,295 | 8,424,513 | 425,747 |
| EURO | 846,866 | 281,198 | 425,943 | 1,208 | 76,446,634 | 30,849,246 | 20,260,700 | 4,593,009 | 163,465,255 | 141,794,134 | 101,594,263 | 1,660,083,208 | 44,889,390 | 14,050,300 |
| EURA | 677,880 | 1,068 | 343,107 | 221,501 | 29,855,690 | 23,418,817 | 12,030,080 | 4,071,274 | 28,727,659 | 78,557,745 | 18,007,749 | 664,246,895 | 11,508,213 | 8,305,203 |
| ASIA | 13,249,225 | 2,862,090 | 173,094,419 | 2,282,593 | 362,788,699 | 79,456,157 | 468,038,089 | 11,512,981 | 563,373,447 | 398,701,823 | 2,955,455 | 9,099,019,576 | 1,056,093,702 | 327,903,127 |
| NAAM | 3,312,000 | 3,312,000 | — | — | 134,443,085 | 12,276,345 | 12,057,283 | 16,501,133 | 94,848,681 | 15,374,043 | 285,732,864 | 2,778,747,928 | 16,693,456 | 307,414 |
| **2030** | | | | | | | | | | | | | | |
| AFRC | 28,605,408 | 1,410,927 | 9,840,993 | 33,269,240 | 266,035,319 | 73,540,139 | 432,866,460 | 7,753,070 | 37,167,402 | 537,137,245 | 19,285,366 | 1,916,766,477 | 21,622,904 | 15,777,661 |
| MIEA | 2,742,926 | 197,774 | 1,165,203 | 1,503,917 | 10,420,595 | 6,127,068 | 53,996,856 | 238,226 | 212,496 | 181,275,748 | 7,462,777 | 993,216,019 | 2,251,984 | 2,547,450 |
| CSAM | 3,525,580 | 2,565,528 | 876,235 | 363,165,169 | 34,416,861 | 24,447,270 | 17,058,230 | 7,616,931 | 87,526,659 | 123,946,758 | 79,940,136 | 3,293,431,862 | 11,572,205 | 620,925 |
| EURO | 609,117 | 234,846 | 1,008,184 | 4,597 | 78,327,604 | 27,596,465 | 20,202,782 | 5,548,271 | 153,126,179 | 192,995,324 | 102,791,593 | 1,706,164,516 | 44,614,600 | 13,888,742 |
| EURA | 849,921 | 844 | 282,435 | 442,251 | 33,053,022 | 21,338,795 | 24,550,502 | 5,634,282 | 27,922,758 | 130,930,762 | 18,608,201 | 700,410,055 | 12,039,543 | 8,669,961 |
| ASIA | 13,427,623 | 733,070 | 214,517,815 | 2,538,098 | 487,150,416 | 82,381,796 | 735,097,827 | 10,892,381 | 624,250,619 | 614,909,005 | 3,991,403 | 14,449,006,323 | 1,683,405,389 | 507,862,027 |
| NAAM | 3,312,000 | 3,312,000 | — | — | 154,121,776 | 11,473,568 | 14,965,839 | 19,456,171 | 91,045,115 | 24,028,403 | 332,272,820 | 3,346,051,579 | 21,266,535 | 392,416 |

Note: AFRC = Africa; MIEA = Middle East; CSAM = Central and South America; EURO = Europe; EURA = Eurasia; ASIA = Asia; NAAM = North America

The LPSs capture major combinations of livestock production systems of the world with respect to land use type and climate. Livestock populations across livestock production systems were assigned for pigs, goats, sheep, dairy cattle, and beef cattle based on the country-level data from Robinson et al. (2011). Approximation was made for the distribution of selected species where LPS data were not available.

In addition to disaggregation by LPS, certain livestock species were further disaggregated into production intensity categories. For pigs, data were provided by the Food and Agriculture Organization (FAO) that separated country-level pig populations into three intensity categories for each LPS: intensive, semi-intensive, and extensive. Those data were used to assign intensity levels to pig populations and this distribution was used as a proxy for poultry production intensity in countries with both pig and poultry production. For beef and dairy cattle, regional allocation of cattle across intensity categories in Robinson et al. (2011) was used to assign intensity levels to each country located within that region. For other species, all intensity levels were defined as unknown. As an example, Table 3-8 presents the assumed distribution of livestock across livestock production systems and intensity classifications for India, the largest emitter for the livestock production sector.

The detailed disaggregation of baseline populations allows for better definition of the technical applicability of mitigation options. For instance, this study only applies large-scale digesters to intensive dairy and hog production systems in each country. Intensive grazing is assumed to be applicable only to relatively high productivity mixed crop-livestock systems that rely on irrigation or are in humid and subhumid or temperate highland LPS designations. The use of a highly disaggregated baseline in this study serves to define the share of emissions where mitigation options can potentially be applied.

Enteric fermentation and manure management emissions for each subset of livestock populations were calculated using the IPCC default values consistent with those used in USEPA (2012). The one exception is for enteric fermentation emissions in Africa, where relative emissions reported in Robinson et al. (2011) were used to scale default IPCC emissions per head for different LPS categories.

**Table 3-8: Livestock Distribution by Intensity and Livestock Production System for India, 2010 (% of animals by species)**

| Species | Intensity | LGA | LGH | LGT | LGY | MIA | MIH | MIT | MIY | MRA | MRH | MRT | MRY | URBAN | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Asses | unknown | 0.5% | 0.1% | 0.0% | 0.0% | 31.7% | 6.6% | 0.0% | 0.0% | 40.2% | 11.0% | 1.3% | 0.0% | 7.3% | 1.2% |
| Mules | unknown | 0.5% | 0.1% | 0.0% | 0.0% | 31.7% | 6.6% | 0.0% | 0.0% | 40.2% | 11.0% | 1.3% | 0.0% | 7.3% | 1.2% |
| Buffalo | unknown | 0.5% | 0.1% | 0.0% | 0.0% | 31.7% | 6.6% | 0.0% | 0.0% | 40.2% | 11.0% | 1.3% | 0.0% | 7.3% | 1.2% |
| Camels | unknown | 0.5% | 0.1% | 0.0% | 0.0% | 31.7% | 6.6% | 0.0% | 0.0% | 40.2% | 11.0% | 1.3% | 0.0% | 7.3% | 1.2% |
| Cattle | intensive | 0.3% | 0.1% | 0.0% | 0.0% | 17.7% | 3.7% | 0.0% | 0.0% | 22.4% | 6.2% | 0.7% | 0.0% | 4.1% | 0.7% |
| Cattle | extensive | 0.2% | 0.0% | 0.0% | 0.0% | 12.6% | 2.6% | 0.0% | 0.0% | 16.0% | 4.4% | 0.5% | 0.0% | 2.9% | 0.5% |
| Cattle | unknown | 0.0% | 0.0% | 0.0% | 0.0% | 1.4% | 0.3% | 0.0% | 0.0% | 1.8% | 0.5% | 0.1% | 0.0% | 0.3% | 0.1% |
| Dairy Cattle | intensive | 0.2% | 0.1% | 0.0% | 0.0% | 18.6% | 3.9% | 0.0% | 0.0% | 21.0% | 6.5% | 0.8% | 0.0% | 4.1% | 0.7% |
| Dairy Cattle | extensive | 0.2% | 0.0% | 0.0% | 0.0% | 13.3% | 2.8% | 0.0% | 0.0% | 15.0% | 4.6% | 0.5% | 0.0% | 3.0% | 0.5% |
| Dairy Cattle | unknown | 0.0% | 0.0% | 0.0% | 0.0% | 1.5% | 0.3% | 0.0% | 0.0% | 1.7% | 0.5% | 0.1% | 0.0% | 0.3% | 0.1% |
| Goats | unknown | 1.8% | 0.0% | 0.0% | 0.0% | 34.6% | 7.0% | 0.0% | 0.0% | 39.0% | 7.9% | 1.3% | 0.0% | 7.2% | 1.3% |
| Horses | unknown | 0.5% | 0.1% | 0.0% | 0.0% | 31.7% | 6.6% | 0.0% | 0.0% | 40.2% | 11.0% | 1.3% | 0.0% | 7.3% | 1.2% |
| Pigs | intensive | 0.0% | 0.5% | 0.1% | 0.0% | 13.8% | 3.0% | 0.3% | 0.0% | 7.1% | 16.9% | 5.2% | 0.0% | 2.6% | 0.5% |
| Pigs | extensive | 0.0% | 0.0% | 0.0% | 0.0% | 14.6% | 2.0% | 0.0% | 0.0% | 12.0% | 4.3% | 0.5% | 0.0% | 4.1% | 0.5% |
| Pigs | semi-intensive | 0.0% | 0.1% | 0.0% | 0.0% | 3.3% | 0.7% | 0.1% | 0.0% | 1.7% | 4.0% | 1.2% | 0.0% | 0.6% | 0.1% |
| Sheep | unknown | 3.4% | 0.0% | 0.0% | 0.0% | 30.8% | 5.0% | 0.1% | 0.0% | 45.5% | 5.1% | 2.6% | 0.0% | 6.8% | 0.7% |
| Chickens | intensive | 0.0% | 0.5% | 0.1% | 0.0% | 13.8% | 3.0% | 0.3% | 0.0% | 7.1% | 16.9% | 5.2% | 0.0% | 2.6% | 0.5% |
| Chickens | extensive | 0.0% | 0.0% | 0.0% | 0.0% | 14.6% | 2.0% | 0.0% | 0.0% | 12.0% | 4.3% | 0.5% | 0.0% | 4.1% | 0.5% |
| Chickens | semi-intensive | 0.0% | 0.1% | 0.0% | 0.0% | 3.3% | 0.7% | 0.1% | 0.0% | 1.7% | 4.0% | 1.2% | 0.0% | 0.6% | 0.1% |
| Ducks | intensive | 0.0% | 0.5% | 0.1% | 0.0% | 13.8% | 3.0% | 0.3% | 0.0% | 7.1% | 16.9% | 5.2% | 0.0% | 2.6% | 0.5% |
| Ducks | extensive | 0.0% | 0.0% | 0.0% | 0.0% | 14.6% | 2.0% | 0.0% | 0.0% | 12.0% | 4.3% | 0.5% | 0.0% | 4.1% | 0.5% |
| Ducks | semi-intensive | 0.0% | 0.1% | 0.0% | 0.0% | 3.3% | 0.7% | 0.1% | 0.0% | 1.7% | 4.0% | 1.2% | 0.0% | 0.6% | 0.1% |

### V.3.4.4 MAC Analysis Results

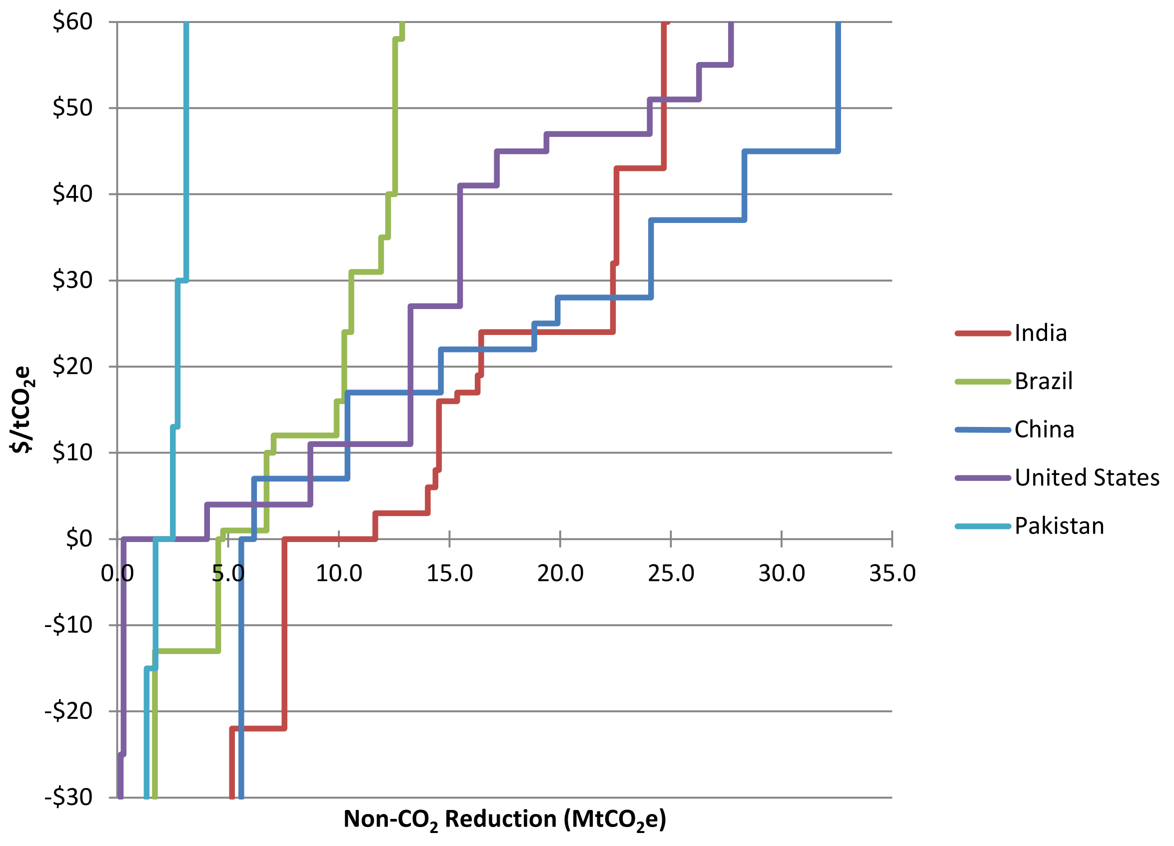
As highlighted at the beginning of this chapter, global abatement potential in the livestock sector equates to approximately 3% of its total annual emissions between 2010 and 2030 at no or a relatively low carbon price of $5 per ton of $CO_2$ equivalent ($/tCO$_2$e). In 2030, total abatement potential in the livestock sector is 70 MtCO$_2$e at no carbon price, 86 MtCO$_2$e at a carbon price of $5/tCO$_2$e, and 128 MtCO$_2$e at a carbon price of $20/tCO$_2$e, representing 2.6%, 3.2% and 4.7% of the total sector emissions, respectively. Table 3-9 presents the estimated mitigation potential at various break-even prices for the top-five emitting countries and rest of regional groups in 2030 under an assumption that livestock populations adjust to maintain production at baseline levels when mitigation options result in changing productivity.

**Table 3-9: Abatement Potential by Region at Selected Break-Even Prices in 2030 (MtCO$_2$e), Baseline Production Case**

| Country/Region | Break-Even Price ($/tCO$_2$e) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | –10 | –5 | 0 | 5 | 10 | 15 | 20 | 30 | 50 | 100 | 100+ |
| **Top 5 Emitting Countries** | | | | | | | | | | | |
| India | 7.6 | 7.6 | 11.7 | 14.0 | 14.5 | 14.5 | 16.4 | 22.4 | 24.7 | 25.0 | 27.4 |
| China | 5.6 | 5.6 | 6.2 | 6.2 | 10.4 | 10.4 | 14.6 | 24.1 | 32.6 | 35.5 | 38.3 |
| Brazil | 4.6 | 4.6 | 4.8 | 6.7 | 7.1 | 9.9 | 10.2 | 10.6 | 12.5 | 13.2 | 13.6 |
| United States | 0.3 | 0.3 | 4.1 | 8.7 | 8.7 | 13.2 | 13.2 | 15.5 | 24.0 | 37.5 | 43.2 |
| Pakistan | 0.7 | 1.7 | 2.5 | 2.5 | 2.5 | 2.7 | 2.7 | 3.1 | 3.1 | 4.4 | 5.6 |
| **Rest of Region** | | | | | | | | | | | |
| Africa | 8.7 | 9.3 | 11.8 | 12.3 | 12.6 | 12.9 | 13.1 | 13.3 | 13.6 | 14.0 | 14.6 |
| Asia | 12.3 | 13.6 | 18.1 | 21.2 | 24.8 | 26.3 | 30.2 | 35.0 | 38.1 | 40.4 | 45.5 |
| Central & South America | 5.8 | 6.4 | 7.8 | 8.9 | 10.4 | 11.1 | 12.6 | 13.1 | 14.2 | 14.8 | 15.2 |
| Eurasia | 1.2 | 1.3 | 1.4 | 1.5 | 1.6 | 1.6 | 1.6 | 1.6 | 1.8 | 2.0 | 2.7 |
| Europe | 6.2 | 6.4 | 10.7 | 11.0 | 11.3 | 12.4 | 15.5 | 16.4 | 20.9 | 29.7 | 50.6 |
| Middle East | 1.5 | 1.5 | 1.6 | 1.6 | 1.6 | 1.6 | 1.7 | 1.7 | 1.7 | 1.7 | 1.9 |
| North America | 1.3 | 1.7 | 2.5 | 2.5 | 2.6 | 3.8 | 4.4 | 5.0 | 6.2 | 9.2 | 10.0 |
| **World Total** | **55.7** | **60.0** | **83.3** | **97.2** | **108.1** | **120.5** | **136.3** | **161.6** | **193.3** | **227.5** | **268.6** |

Mitigation potential and its cost-effectiveness vary significantly by country or region. At the regional level, Asia (in particular South and Southeast Asia), Africa, Central and South America and the European Union show the most significant potential for reducing GHG emissions from livestock operations. For instance, in 2030 mitigation potential in Asia is estimated to be 27 MtCO$_2$e with no carbon price and 34 MtCO$_2$e at a carbon price of $20/tCO$_2$e. Central and South America can achieve mitigation potential of 12 MtCO$_2$e in 2030 at no carbon price, and mitigation potential can increase to 22 MtCO$_2$e at a carbon price of $20/tCO$_2$e. Figure 3-5 shows the MAC curves for the top-five emitting countries in 2030.

**Figure 3-5: Marginal Abatement Cost Curve for Top 5 Emitters in 2030 (Baseline Production Case)**

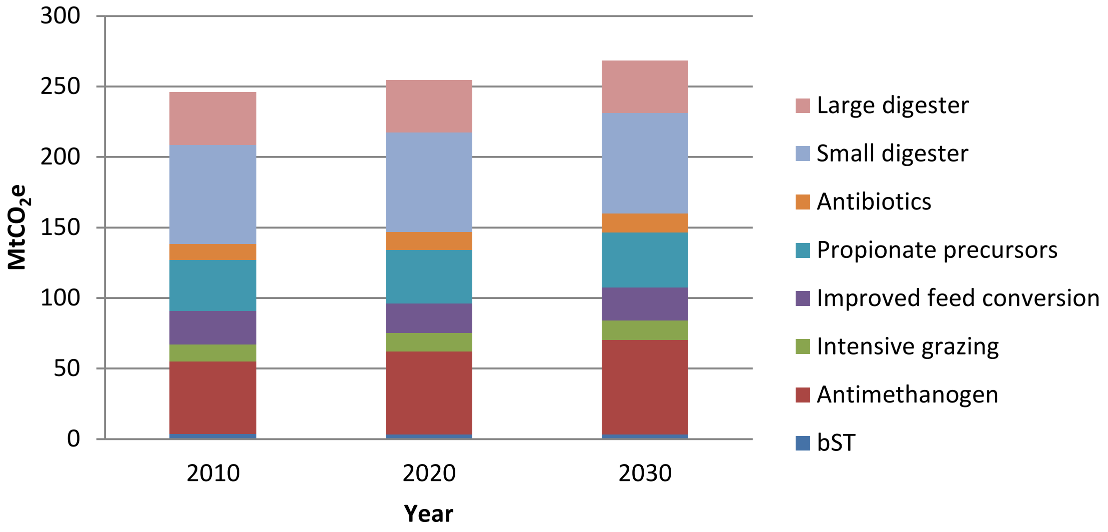


The MAC analysis also suggests that mitigation of enteric fermentation methane emissions presents the most cost-effective mitigation opportunity for options evaluated in this report. Manure management mitigation measures mostly require additional investments or financial incentives to achieve emissions reductions. The most cost-effective mitigation options for the livestock sector (i.e., measures that dominate the MAC curves at break-even carbon prices at or below $0/MtCO$_2$e) include:

- intensive grazing in East Asia (e.g., Japan, Korea and China) and Central and South America;
- BST administered to dairy cattle in developing regions;
- antimethanogens administered to sheep and goats as well as beef and dairy cattle;
- improved feed conversion efficiency of the cattle populations; and
- propionate precursors administered to beef and dairy cattle in developing regions

Figure 3-6 shows the distribution of mitigation potential across individual types of options at a global scale based on total technical potential (regardless of price) calculated in the MAC analysis.

**Figure 3-6. Global Net GHG Livestock Emissions Reduction Potential by Mitigation Option (Baseline Production Case)**



## V.3.5 Sensitivity Analyses

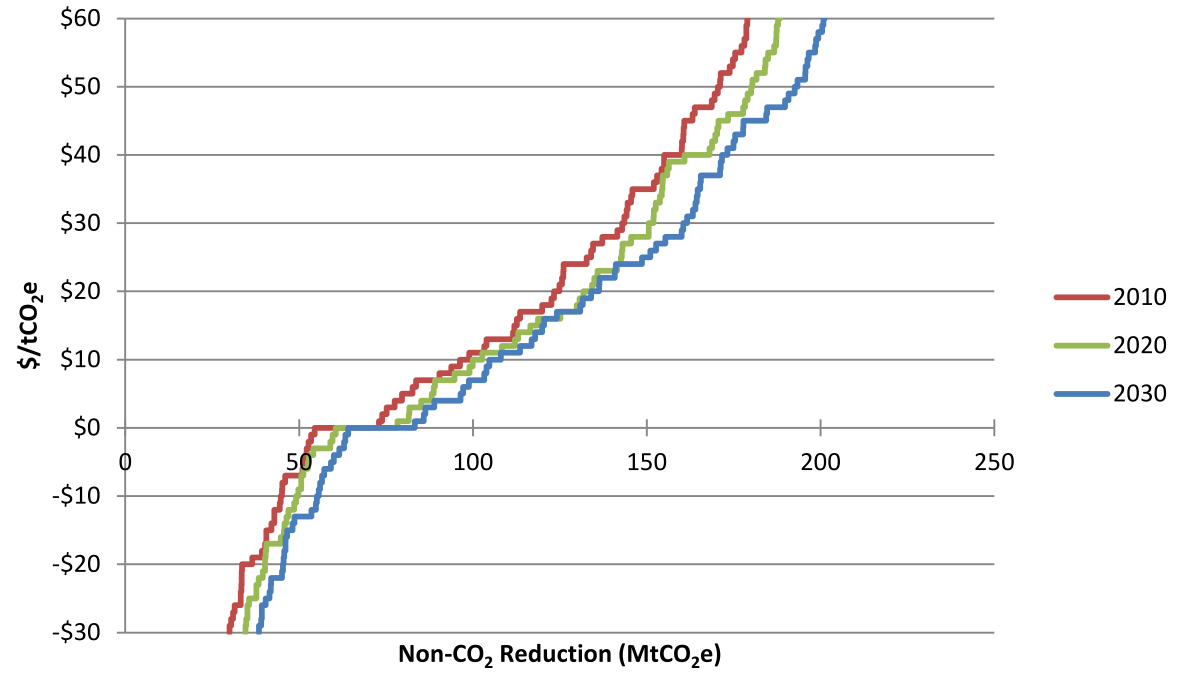
In this section, we explore sensitivity analyses to examine the potential effects on estimated mitigation potential. Although many of the mitigation options examined are expected to increase productivity and would therefore require fewer animals to produce the same amount of output, livestock populations may not decrease accordingly. Due to increasing demand for livestock products and potential reductions in the price of these products with higher productivity, the quantity of livestock products demanded may increase. Thus, we examine an alternative scenario that holds the number of livestock constant at the projected baseline populations. To the extent that productivity is increased by adoption of the GHG mitigation options considered, this scenario will result in higher global production. In addition, given mixed conclusions on the near-term prospects of antimethanogens, we also present mitigation estimates developed excluding antimethanogens as an option.

### *Baseline Number of Animals*

As noted above, many of the mitigation options in the baseline production case reduce the emissions per unit of meat or milk but may increase the emissions per animal. This section explores this relationship further by presenting an alternative scenario built around a constraint on the number of animals, keeping the herd sizes the same as estimated in the baseline.

As before, the MAC model only includes options that result in lower emissions. But with the number of animals held constant, those mitigation strategies that increase emissions per animal in a given region are excluded in that region. The result is 15 to 39% lower mitigation potential as shown in Figure 3-7 and Table 3-10.

## Figure 3-7: Global Abatement Potential in Livestock Management, Baseline Number of Animals : 2010, 2020, and 2030



## Table 3-10: MAC Results and Differences from Constant Production Case for Baseline Number of Animals Scenario

| | 2010 | | 2020 | | 2030 | |
|---|---|---|---|---|---|---|
| $/tCO$_2$e | Total Reduction MTCO$_2$e | Difference from Constant Production (%) | Total Reduction MTCO$_2$e | Difference from Constant Production(%) | Total Reduction MTCO$_2$e | Difference from Constant Production (%) |
| 0 | 49 | -21% | 54 | -19% | 60 | -15% |
| 5 | 58 | -20% | 61 | -22% | 65 | -25% |
| 10 | 65 | -27% | 68 | -27% | 73 | -25% |
| 15 | 79 | -25% | 78 | -29% | 81 | -26% |
| 20 | 84 | -29% | 88 | -31% | 87 | -31% |
| 25 | 86 | -33% | 91 | -33% | 97 | -33% |
| 30 | 90 | -35% | 97 | -34% | 101 | -35% |
| 35 | 93 | -37% | 98 | -34% | 106 | -33% |
| 40 | 96 | -39% | 101 | -39% | 109 | -35% |
| 45 | 98 | -39% | 103 | -39% | 113 | -37% |
| 50 | 102 | -39% | 108 | -39% | 118 | -38% |

### No Antimethanogen

The science and policy literature varies in its treatment of antimethanogens. The Australian government included them in their recent study (Whittle et al., 2013). However ICF International, in a recent analysis for USDA, concludes that "more research is needed to evaluate the potential GHG impacts of changes in diets, use of feed additives, and breeding." (ICF International, 2013) For comparison purposes we estimated MAC curves as above except by assuming antimethanogens are unavailable in all regions and time periods. Results are shown in Figure 3-8 and Table 3-11. Globally, the mitigation potential in the livestock sector is reduced 16 to 31% in the scenario with no antimethanogens and baseline production.

**Figure 3-8: Global Abatement Potential in Livestock Management, Baseline Production with No Antimethanogen: 2010, 2020, and 2030**

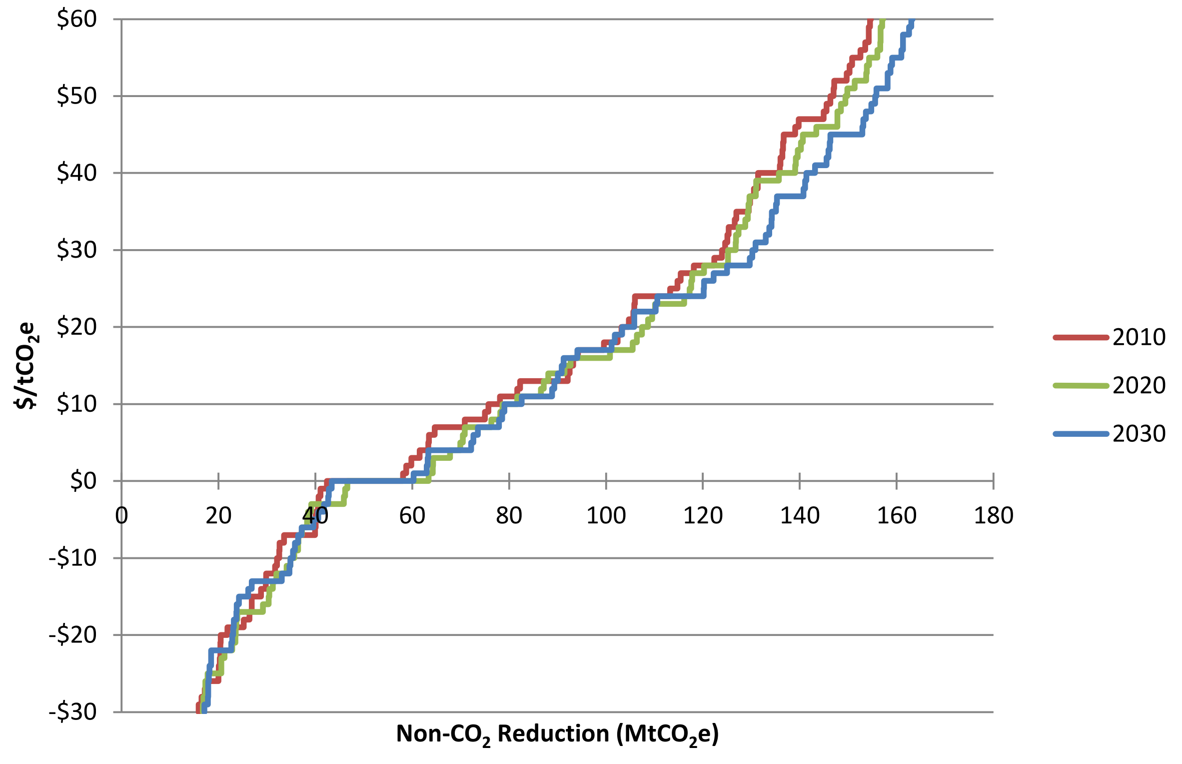


**Table 3-11: MAC Results and Differences from Constant Production Case for No Antimethanogen Scenario**

| | 2010 | | 2020 | | 2030 | |
|---|---|---|---|---|---|---|
| $/tCO$_2$e | Total Reduction MTCO$_2$e | Difference from Constant Production (%) | Total Reduction MTCO$_2$e | Difference from Constant Production(%) | Total Reduction MTCO$_2$e | Difference from Constant Production (%) |
| 0 | 48 | -28% | 53 | -20% | 49 | -31% |
| 5 | 54 | -31% | 61 | -22% | 62 | -28% |
| 10 | 70 | -25% | 73 | -21% | 73 | -25% |
| 15 | 87 | -21% | 85 | -23% | 82 | -26% |
| 20 | 99 | -22% | 103 | -19% | 98 | -23% |
| 25 | 110 | -19% | 113 | -18% | 115 | -20% |
| 30 | 120 | -18% | 122 | -16% | 126 | -19% |
| 35 | 126 | -15% | 125 | -16% | 130 | -18% |
| 40 | 133 | -19% | 136 | -17% | 139 | -17% |
| 45 | 136 | -20% | 140 | -17% | 149 | -17% |
| 50 | 145 | -18% | 147 | -17% | 152 | -20% |

### *Combined Baseline Number of Animals and No Antimethanogen*

Results for a combined scenario including both an assumption that the number of livestock under the mitigation scenario remains equal to the baseline and no applicability of antimethanogens are presented in Figure 3-9 and Table 3-12. Under this scenario, there is a reduction in mitigation potential of between 16 and 43% relative to the primary case where production of livestock products is assumed to remain equal to baseline levels.

**Figure 3-9: Global Abatement Potential in Livestock Management, Baseline Number of Animals with No Antimethanogen: 2010, 2020, and 2030**

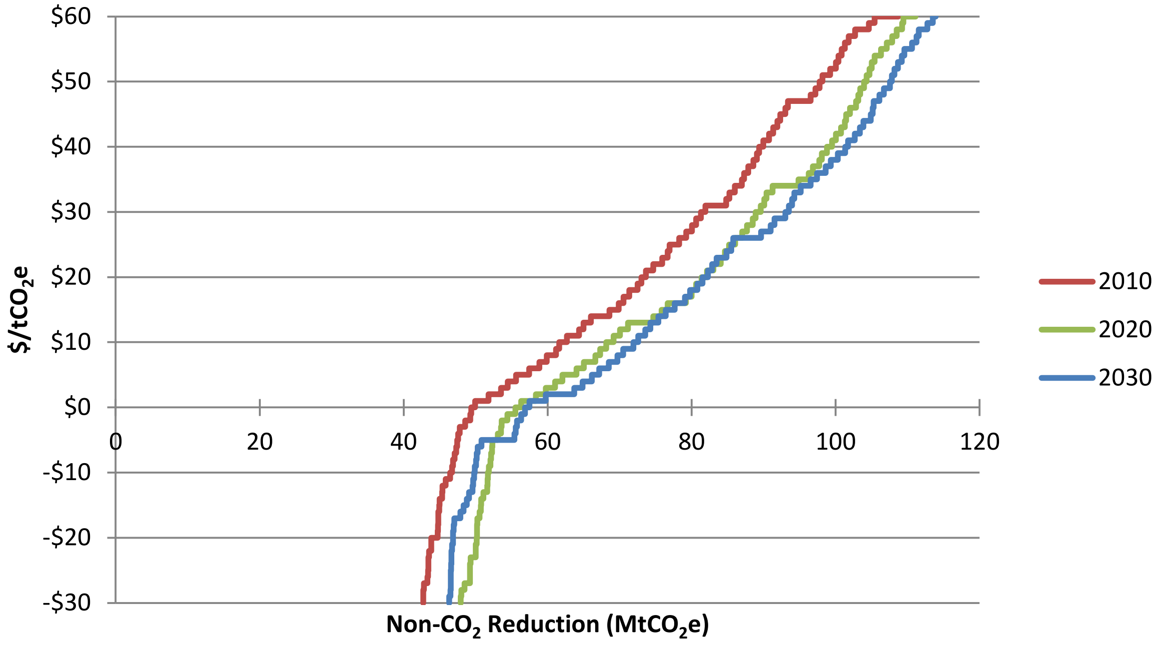


**Table 3-12: MAC Results and Differences from Constant Production Case for Combined Baseline Number of Animals and No Antimethanogen Case**

| | 2010 | | 2020 | | 2030 | |
|---|---|---|---|---|---|---|
| $/tCO$_2$e | Total Reduction MTCO$_2$e | Difference from Constant Production (%) | Total Reduction MTCO$_2$e | Difference from Constant Production (%) | Total Reduction MTCO$_2$e | Difference from Constant Production (%) |
| 0 | 50 | -20% | 56 | -16% | 57 | -18% |
| 5 | 57 | -21% | 64 | -18% | 67 | -22% |
| 10 | 63 | -30% | 69 | -26% | 73 | -26% |
| 15 | 70 | -34% | 77 | -31% | 78 | -30% |
| 20 | 74 | -38% | 82 | -36% | 82 | -35% |
| 25 | 78 | -39% | 86 | -37% | 86 | -41% |
| 30 | 82 | -41% | 90 | -39% | 94 | -40% |
| 35 | 87 | -41% | 96 | -35% | 97 | -39% |
| 40 | 90 | -42% | 100 | -39% | 102 | -39% |
| 45 | 93 | -42% | 102 | -40% | 105 | -41% |
| 50 | 98 | -42% | 104 | -41% | 108 | -43% |

### *Change in Production of Livestock Products with Number of Animals Held at Baseline Levels*

For the scenario where livestock populations are kept at projected baseline levels, there will be changes in production of livestock products due to changes in output per head for many options. Figures 3-10 and 3-11 show the change in global beef production and global milk production from dairy cattle estimated if all production were to switch from baseline management into that option.

**Figure 3-10: Global Beef Production under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant**

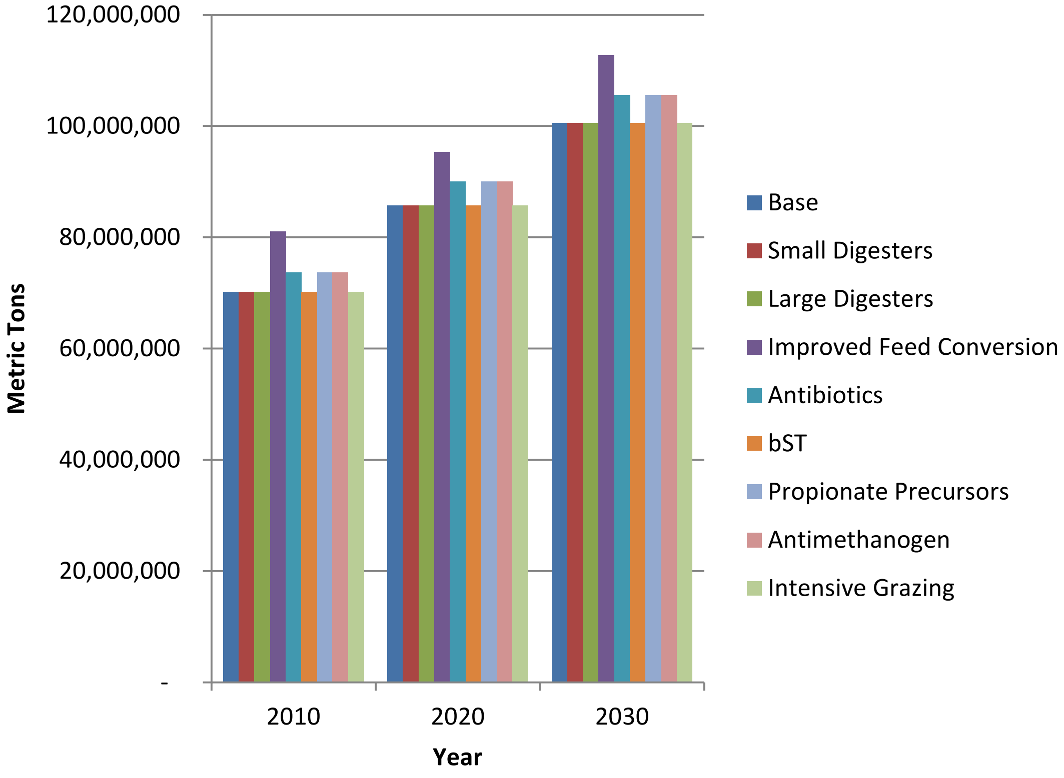
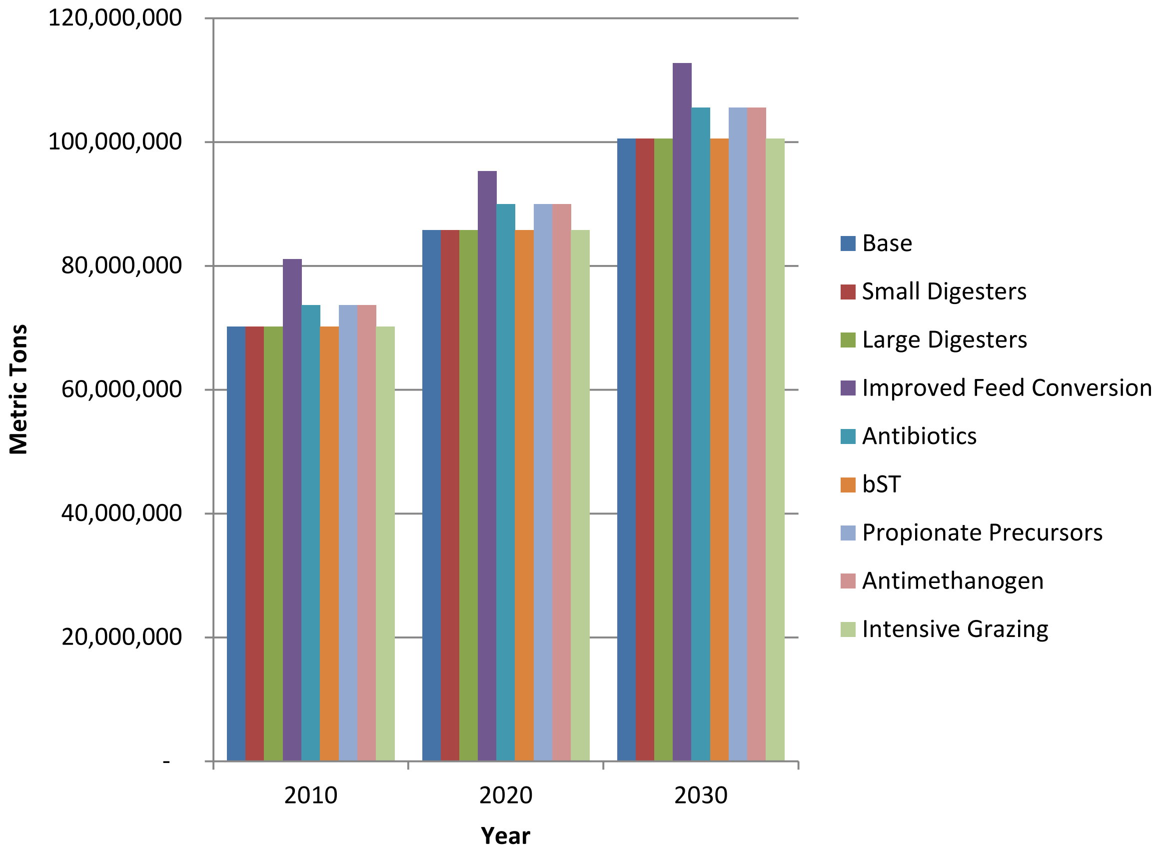


Figure 3-11: Global Production of Milk from Dairy Cattle Under Baseline and Mitigation Options, Assuming Full Adoption of Individual Options and Holding the Number of Animals Constant



## V.3.4.5. Uncertainties and Limitations

Given the complexities of the global livestock sector, the estimated GHG mitigation potential and marginal abatement cost curves are subject to a number of uncertainties and limitations:

- ***Availability and quality of data to represent the highly complex and heterogeneous livestock production systems of the world.*** Although there are major improvements in the characterization of the business-as-usual baseline conditions since the previous EPA report (USEPA, 2006), data in some areas, such as management practices, are not always available for all countries or regions and approximations must be made based on limited literature or expert judgment.
- ***Availability of mitigation measure cost data and in some cases scientific understanding of mitigation impacts.*** Collecting and developing consistent cost estimates of emerging mitigation measures or options that are not widely adopted has proven to be challenging. Moreover, scientific understanding of the mitigation effects and animal and human health impacts of some mitigation measures is still limited. In addition, some mitigation measures, such as pasture management options that lead to reductions in enteric $CH_4$ emissions and enhancement in soil carbon storage, would require a different analytical framework that is beyond the scope of this study.

- ***Optimistic assumptions on technology adoption.*** The analysis assumes that if mitigation technology is considered feasible in a country or region, it is fully adopted in 2010 and through the analysis period. Research suggests that adoption of new technology in the agricultural sector is a gradual process and various factors potentially inhibit the adoption of a new GHG-mitigating technology (e.g., farm characteristics, access to information and capital, and cultural and institutional conditions). Adoption of the various technologies and management practices (such as supplementation) faces even greater challenges. The mitigation potential presented in this analysis should be viewed to represent the technical potential of the mitigation options analyzed.
- ***Potential market feedback from livestock productivity improvement.*** The analysis assumes constant production level when evaluating mitigation potential of abatement measures. This analysis does not, however, address the possibility of an emissions increase as a result of lower costs per unit through such efficiency gains, which could in turn increase the quantity demanded.
- ***Potential interactions of multiple mitigation measure.*** In this analysis, mitigation options are applied to independent segments of the livestock populations to avoid double counting. In reality, multiple mitigation options can be applied and their potential interactions may affect the aggregate GHG mitigation. For example, various measures can improve feed conversion efficiency (e.g., concentrate inclusion, dietary additives such as oils) and their effectiveness would depend on the other measures implemented; measures that reduce $CH_4$ emissions from manure management (e.g., aeration) would likely increase $N_2O$ emissions; measures that improve feed conversion efficiency would likely change $N_2O$ emissions in livestock manure; measures that improve diet quality for grazing livestock would likely change GHG emissions from agricultural soils. The interactive effects are not fully addressed in this analysis.

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