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Marginal Abatement Cost Curves for Global Agricultural Non-CO_2 Emissions

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Agricultural emissions account for 53% of 2010 global non-CO_2 emissions and are projected to increase substantially in the future, especially in Asia, Latin America and Africa. While agriculture is a substantial source of emissions, it is also a potential source of cost-effective non-CO_2 GHG abatement. Previous "bottom-up" analyses provided marginal abatement cost (MAC) curves for use in modeling these options within economy-wide and global mitigation analyses. In this study, we utilize updated economic and biophysical data and models to extend and improve upon previous work. Key enhancements include incorporation of additional mitigation options, updated baseline emissions projections, greater spatial disaggregation, and development of MAC curves to 2030. MAC curves are generated accounting for net GHG reductions, yield effects, livestock productivity effects, commodity prices, labor requirements, and capital costs where appropriate. MAC curves are developed at the country level and reveal large potential for non-CO_2 GHG mitigation at low carbon prices.

1. Introduction

The agricultural sector is a substantial source of global greenhouse gas (GHG) emissions and the largest source of non-carbon dioxide (non-CO_2) GHG emissions, accounting for 53% of global non-CO_2 emissions in 2010 (USEPA, 2012). However, this sector also offers the potential to provide relatively low-cost opportunities for GHG mitigation. In particular, agriculture may play an important role in GHG abatement portfolios as a cost-effective alternative to reductions in emissions from fossil fuel combustion, industrial activity, and other sources. The agricultural sector has been projected to potentially contribute 7-22% of cumulative abatement in the first few decades of long-run climate stabilization scenarios (Rose et al., 2008). In addition, the sector could potentially receive billions of dollars in farm revenue annually from payments for undertaking mitigation activities (USEPA, 2008; Baker et al., 2010). Given the important impact that the level of agricultural mitigation has on total cost estimates of reaching mitigation targets, as well as the implications for land use, agricultural commodity markets, and sectoral income, there is considerable interest in improving upon existing estimates of the sectoral mitigation potential and associated costs.

Although it is widely thought that there are large potential reductions available from the agricultural sector, there are also unique challenges to developing estimates of mitigation costs over large spatial scales, which are needed to assess agriculture's potential role in reducing global GHG emissions relative to other sectors of the economy (Beach et al., 2008). Among other challenges, agriculture is quite heterogeneous both spatially and temporally, necessitating consideration of biophysical and management conditions that will influence the effectiveness and cost of alternative mitigation options at a disaggregated level. However, obtaining data at this level of detail can be problematic. The agricultural sector also tends to have many activities that emit multiple types of GHGs, with potentially complex interactions between them. Finally, there are typically many implementation barriers, especially for smallholders in developing countries. Nonetheless, engineering or "bottom-up" abatement cost analyses have been developed for the agricultural sector for individual countries, regions, and the world (McCarl and Schneider, 2000; Hyman et al., 2002; DeAngelo et al., 2006; USEPA, 2006; Beach et al., 2008; Moran et al., 2008; Smith et al., 2008; McKinsey & Company, 2009; Vermont and DeCara, 2010). These cost and potential estimates are crucial inputs into top-down modeling of multi-gas mitigation options, where they are incorporated via abatement supply curves or calibration (e.g., Rose et al., 2008; Hertel et al., 2009).

However, there is wide variation across these studies in regional, sectoral, and GHG coverage and disaggregation, as well as in the potential mitigation and cost reported. In order to build upon the existing literature and provide a detailed set of marginal abatement cost (MAC) curves using consistent methods across all countries for all significant non-CO_2 GHG emitting sectors, US Environmental Protection Agency (USEPA) conducted a major study to update previous USEPA estimates of mitigation cost and potential (USEPA, 2013, 2014). In this paper, we summarize the methods and key findings of that report for the agricultural sector. This study utilized updated economic and biophysical data and models to extend and improve upon previous work in this area. We use simulation results from updated versions of the DAYCENT and DeNitrification-DeComposition (DNDC) process bio-geochemical models that reflect disaggregated soil, acreage, crop system, weather, and management data for simulations of cropland management and rice cultivation mitigation alternatives, respectively, and include additional mitigation options. For the livestock sector, we rely on recent literature on the effectiveness of key mitigation options applied to baselines developed by USEPA (USEPA, 2012). MAC curves were generated at an individual country level globally through 2030, taking into account net GHG reductions, yield effects, livestock productivity effects, commodity prices, labor requirements, and capital costs. This analysis allows us to provide more refined estimates of non-CO_2 GHG mitigation potential than have previously been available within a consistent global framework.

2. Background

There has been increasing interest in mitigation of non-CO_2 GHG emissions from the agricultural sector both in the context of comprehensive climate policy discussions as well as in targeted initiatives, such as those described in the President's Climate Action Plan (Executive Office of the President, 2013). For instance, the USEPA and the US Departments of Agriculture (USDA), Energy (USDOE), Interior, Labor, and Transportation are developing a comprehensive, interagency methane strategy, which includes reductions from agriculture. The strategy focuses on assessing current emissions data, addressing data gaps, identifying technologies and best practices for reducing emissions, and identifying existing authorities and incentive-based opportunities to reduce methane emissions. As one component, the USDA, USEPA, and the USDOE developed a Biogas Roadmap that identifies voluntary actions that can be taken to reduce livestock emissions through the increased use of biogas systems. The Biogas Roadmap outlines strategies to accelerate the adoption of methane digesters and other cost-effective technologies in order to achieve a 25% reduction in US dairy sector emissions by 2020 (USDA, USEPA, and USDOE, 2014).

In addition to strategies focused on non-CO_2 GHG mitigation nationally in the US, there is ongoing interest at the international as well as subnational levels. The recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) identifies substantial opportunities for agricultural mitigation to play a part in the global effort to reduce emissions. The IPCC AR5 chapter on mitigation in the agriculture, forestry, and land use sector cites recent multi-model comparisons of idealized comprehensive climate policies that conclude agriculture can contribute substantially to the mitigation of non-CO_2 GHGs while reducing overall policy costs (IPCC, 2014). California is also currently conducting research to improve the state's GHG inventory for agricultural emissions, particularly N_2O emissions from agricultural ecosystems under California specific conditions (e.g., see http://www.arb.ca.gov/ag/fertilizer/fertilizer.htm for a discussion of ongoing efforts).

Despite considerable interest in a better characterization of agricultural sector emissions and GHG mitigation potential, available data on global agricultural sector emissions lags behind data development on fossil fuel emissions (Tubiello et al., 2014). Mitigation potentials and MAC studies across the agricultural sector at the global level are even more difficult to find, particularly at a disaggregated level across the major sources of agricultural GHG emissions. Emissions in the agricultural sector result primarily from four sources: 1) cropland soil management (primarily nitrous oxide [N_2O]), 2) rice cultivation (primarily methane [CH_4] from flooded rice paddies, although N_2O can also be important under certain growing conditions), 3) ruminant livestock enteric fermentation (primarily CH_4), and 4) livestock manure management (both CH_4 and N_2O, with CH_4 from anaerobic manure management systems dominating). Changes in soil carbon are also important determinants of net GHG emissions for soil management and rice cultivation. USEPA has recently completed an updated version of a global mitigation assessment and made the reports and underlying data available to the scientific community. This paper summarizes key findings from that report pertinent to the agriculture sector. Our multi-gas GHG mitigation modeling effort covers each of these four major sources of agricultural emissions and captures CH_4 and N_2O emissions as well as changes in soil carbon, providing an updated dataset of consistent MAC curves at the country level that can be utilized in mitigation studies.

3. Baseline Data

Although USEPA (2012) contains estimates of baseline emissions for agricultural sources, alternative baselines were developed for the purposes of the mitigation report. The primary rationale was to ensure consistency in the area, number of livestock head, production, and price projections used across the entire agricultural sector. Projections provided by the International Food Policy Research Institute (IFPRI) from their IMPACT model of global agricultural markets were used to adjust values for agricultural activities and associated emissions over time. In addition, detailed process-based models—Daily Century (DAYCENT) for croplands and DeNitrification–DeComposition (DNDC) for rice cultivation—were used for both the baseline emissions estimates and the GHG implications of mitigation options, thus allowing for a clear identification of baseline management conditions and consistent estimates of changes to those conditions through mitigation activities. Emissions obtained using these detailed simulation models differ from those obtained in USEPA (2012), which relied upon IPCC default emissions factors (IPCC, 2006). For emissions associated with livestock, this analysis relies on projections similar to those used in USEPA (2012), but with some small differences due to the adjustments made for consistency with IFPRI IMPACT projections across all agricultural sectors. Projected acreage changes from the IMPACT model (Nelson et al., 2010) reflect socio-economic drivers such as population growth and technological changes to meet global food demand that differ from those used in USEPA (2012).The baseline emissions were also disaggregated by livestock production system and intensity using data provided by the United Nations Food and Agriculture Organization (FAO) (Benjamin Henderson, personal communication, December 20, 2011).

The baseline agricultural emissions data utilized for the mitigation analysis in this paper, based on USEPA (2013), are considerably lower than the totals reported in USEPA (2012) or the IPCC (2014) and Tubiello et al. (2013) reports, as shown in Table 1. However, much of the differences are due to differences in the sources included in the total estimates. The baseline emissions for most of the agricultural sources in common across the studies (e.g., rice cultivation, enteric fermentation, manure management) are fairly consistent with the exception of emissions from croplands. There are several reasons for these differences in cropland emissions. For one thing, this study incorporated only the baseline emissions simulated by DAYCENT for the crops available within the model, which captures only about 61% of global cropland areas. Emissions from pasture area were not included in this study due to a lack of DAYCENT results on productivity and emissions impacts associated with mitigation options for pasture. In addition, while the other inventory estimates relied primarily upon Tier 1 emissions estimates, our estimates were based on more complex Tier 3 calculations modeled using DAYCENT. Although there was variation across regions, emissions factors from DAYCENT tended to be lower than IPCC default emissions factors (IPCC, 2006).

[Table 1 about here]

Because we are not applying our mitigation options to the full quantity of baseline emissions from agriculture, it is important to keep in mind that the mitigation estimates presented in this paper reflect reductions only in the portion of baseline emissions captured within the study. Those emissions included do reflect the majority of the emissions sources seen as having a high potential for emissions reductions, but potential mitigation from the agricultural sector would presumably be higher if all sources of emissions could be incorporated.

4. Methods

Agricultural cropping systems are very complex, with soil conditions, microbial activity, and crop growth interacting through a number of processes. Therefore, the relationship between changes in practices and crop yields and GHG emissions are generally non-linear. The majority of assessments of the efficacy of GHG emissions mitigation from cropland management and rice cultivation have focused on site specific field studies. However, extrapolation of results from field studies to watershed, province, or national scales is enhanced by using spatially explicit process models. In this study, we rely on the DAYCENT and DNDC models in combination with literature review to characterize options for cropland management and rice cultivation, respectively. For the livestock sector, we rely on data from USEPA, FAO, IFPRI, the International Institute for Applied Systems Analysis (IIASA), USDA, and others as well as information from the professional literature to develop assessments of mitigation costs and emissions reductions associated with alternative mitigation options. This information is being used as an input into the International Marginal Abatement Cost (IMAC) model to estimate the associated costs of changing production practices, changes in net GHG emissions, and MACs for each of the four major sources of agricultural GHG emissions. The DAYCENT, DNDC, and IMAC models are described in more detail below.

4.1 DAYCENT Model

DAYCENT is a process-based model that simulates biogeochemical carbon (C) and nitrogen (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 at a daily time step (Del Grosso et al., 2001; Parton et al., 1998). For example, plant growth is controlled by nutrient availability, water, and temperature stress. Nutrient supply is a function of soil organic matter decomposition rates and external nutrient additions. Daily maximum/minimum temperature and precipitation, timing, management events (e.g., fertilization, tillage, harvest), and soil texture data are model inputs. Key submodels include plant production, organic matter decomposition, soil water, soil temperature by layer, nitrification and denitrification, and CH_4 oxidation.

DAYCENT's simulation of indirect N_2O emissions accounts for volatilization and leaching/runoff from all N in the soil system, regardless of the N source, according to specific environmental and management conditions. N_2O is emitted indirectly from N applied as commercial fertilizer, sewage sludge, and livestock manure, and other management practices (e.g., plowing, irrigating, harvesting). Nitrogen from managed manure not applied to crops (or pastures) was assumed to volatilize before application to soils. The global spatial data (vegetation, soil, cropland management) was updated for this study to reflect the most recent data available based on a major FAO data collection and synthesis effort.

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°grid resolution for periods 2000-2010 and 2011-2030 at five-year increments for areas where major crop types (e.g., wheat, maize, soybean, barley, sorghum, millet, rapeseed, dry beans, sunflower seed, and oats, which account for about 61% of global cropland) are grown. A baseline scenario is established for each crop production system assuming business-as-usual (BAU) management practices. Seven mitigation scenarios were then analyzed.

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 BAU), decreased N fertilization (20% reduction from BAU), optimal N fertilization, and 100% crop residue incorporation (see Table 2). The N management practices (split N fertilization, nitrification inhibitors, increased and decreased N fertilization, optimal 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. Although soil organic C stock fluxes are negligible in the DAYCENT baseline because they are already in equilibrium, there is considerable opportunity to modify stocks by changing practices. Levels of soil organic matter and soil C both influence and are influenced by cropland productivity. Other things being equal, higher crop yields tend to increase soil C because there is more crop residue available to be incorporated into the soil.

4.2 DNDC Model

DNDC was originally developed to estimate C sequestration and trace gas emissions for non-flooded agricultural lands. The model has been applied in a number of applications to simulate the fundamental processes controlling 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, Frolking, and Frolking, 1992; Li, Frolking, and Harriss, 1994; Li, Narayanan, and Harriss, 1996). 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.

Water management has a major influence on soil conditions in rice paddies. The frequent changes between saturated and unsaturated conditions in paddy soils lead to substantial fluctuations in soil redox potential (Eh), which has a large influence on the activity of methanogenic bacteria. Because CH_4 and N_2O are produced or consumed under certain Eh conditions (-300 to -150 mV for CH_4 and 200 to 500 mV for N_2O), soil Eh dynamics play a key role in CH_4 and N_2O production and consumption (Li et al., 2006). Given the differences in conditions that produce these GHGs, they are generated during different stages of soil Eh fluctuations and some management practices that mitigate one GHG may increase another. To enable DNDC to simulate C and N biogeochemical cycling in paddy rice ecosystems, the model was modified by adding a series of anaerobic processes.[1] By tracking Eh dynamics, DNDC is able to link the soil water regime to trace gas emissions for rice paddy ecosystems. The model simulates the dynamics of biomass growth, which is a major factor affecting CH_4 transport from the soil to the atmosphere. DNDC simulates daily CH_4 and N_2O fluxes from rice paddies through the growing and fallow seasons as fields remain flooded or move between flooded and drained conditions during the season.

A modified version of the DNDC 9.5 Global 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 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. Whereas USEPA (2006) included only major rice-producing countries in Asia, model scenarios conducted for this study were run for all countries in the world that produce a substantial amount of rice.

Twenty-six scenarios were run using DNDC 9.5 (see Table 2). The scenarios addressed management techniques in various combinations hypothesized to reduce GHG emissions from

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[1] The paddy-rice version of DNDC has been described and validated for a number of different world regions and is being used for national trace gas inventory studies in various countries in North America, Europe, and Asia (e.g., Zhang et al., 2002; Li, Frolking, and Frolking, 2002; Cai et al., 2003, Li et al., 2004).

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).

[Table 2 about here]

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.[2] Other practices (e.g., fertilizer applications, tillage practices and residue management) also alter soil conditions and hence affect crop yields and the soil C- and N-driving processes such as 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).

4.3 Livestock Mitigation

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. Cost data for mitigation measures 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

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[2] 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.

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 as summarized in Table 3.

[Table 3 about here]

4.4 IMAC Model

As described in Beach et al. (2008), the break-even price for each mitigation option is calculated by setting total benefits (e.g., higher yields, coproducts) equal to total costs of a given mitigation option and solving for the present-value break-even price within the IMAC model. We have updated the model and moved from an Excel spreadsheet format to a GAMS model to provide additional flexibility and more rapid assessment of alternative specifications. To develop MAC curves, we apply a set of mitigation options identified in the literature for each of the four emissions categories. Emissions, yields, productivity changes, labor requirement changes and other factors from the mitigation scenarios are being compared with baseline conditions for the years 2010, 2020, and 2030, and for all agricultural regions globally with available data. If a mitigation option is considered technically feasible for a given region, it is assumed to be adopted immediately, i.e., in data year 2010, and the change in management is continuous for the entire 2010 – 2030 period. Mitigation estimates therefore represent the technical potential for GHG reductions, with associated costs, without accounting for implementation barriers that would slow adoption of technically feasible options.

As described above, DAYCENT and DNDC are used to estimate baseline and mitigation option emissions of CH_4, N_2O, and soil C, as well as yield and water resource changes for cropping systems. These factors are drawn from the literature for the livestock sectors. Revenue changes are estimated by using the percentage yield changes from biophysical estimates and baseline yield and commodity prices drawn from FAO, IFPRI, IIASA, and other data sources. Some rice mitigation options require soil amendments (e.g., phosphogypsum) or an alternative fertilizer (e.g., ammonium sulfate instead of urea). Baseline input shares are drawn from the Global Trade Analysis Project (GTAP) database and labor requirements to implement the mitigation options are drawn from available sources. Regional prices for fertilizer were obtained from FAOSTAT. The cost implications of any labor requirement changes are calculated using agricultural wages for each region.

Each set of mitigation options for each emission category in each region was assumed to be implemented simultaneously, but without any overlap among the options. This is a simplistic method that avoids double-counting among options but likely underestimates potential penetration of low-cost options and overestimates potential penetration of high-cost options.

4.5 Reference Case and Mitigation Scenarios

For our reference case, we define management practices consistent with our best estimate of typical management practices in 2010, along with baseline improvements in productivity. One key change in management that has been taking place in the baseline is increased adoption of midseason drainage in China and other Asian countries as a water management strategy. This has substantially reduced baseline emissions, while reducing mitigation potential.

Under each mitigation scenario, we simulate cost and GHG emissions impacts associated with adoption of the specified mitigation options, with restrictions placed on adoption of selected options in some regions. These results are compared with the baseline emissions to generate estimates of mitigation potential. We compute a break-even price for each abatement option for 195 countries to construct MAC curves illustrating the net GHG mitigation potential at specific break-even prices for 2010, 2020, and 2030.

5. Results and Discussion

Based on our calculations using each of the models described above, we find substantial potential mitigation from the global agriculture sector. As shown in Figure 1, global mitigation potential from agriculture at a small positive break-even price of $\$5/\text{tCO}_2\text{e}$ is over 210 MtCO_2e in all years. Mitigation potential is almost doubled at $\$60/\text{tCO}_2\text{e}$ with mitigation potential just over 400 $MtCO_2e$. In our analysis, mitigation potential declines slightly over time. The primary reason for that finding is that while we focused on options that reduce non-CO_2 emissions, there are sizable changes in soil C that are being captured within the MACs as well for cropland management and rice cultivation. Changes in practices cause an immediate change in soil C sequestration and then smaller fluxes over time as the soil moves to a new equilibrium.

[Figure 1 about here]

Figure 2 shows the mitigation potential identified at the global level by major subsector considered. Livestock management offers the greatest mitigation potential at negative prices as well as at higher prices, though rice cultivation has a similar potential between \$0/tCO_2e to \$20/tCO_2e. Croplands management offers relatively large mitigation at negative costs, but the MAC curves are relatively vertical within the range displayed so mitigation from rice cultivation and livestock management become considerably larger than croplands management as the carbon price rises.

[Figure 2 about here]

As with any MAC analysis, it is important to consider potential barriers that may need to be overcome in order to achieve adoption options that are identified with low or negative costs.

Table 4 summarizes the abatement potential calculated at \$5/tCO_2e and the maximum technical potential calculated as a percentage of baseline emissions. These results suggest that there are significant opportunities for net GHG reductions in the agriculture sector.

[Table 4 about here]

Overall, the analysis suggests that there are opportunities to reduce agricultural emissions by 5%-7% with incentives equivalent to a low carbon price of \$5/tCO_2e, which is equivalent to over 200 $MtCO_2e$/year. The technical potential calculated achieved reductions of 13%-16%, or over 520 $MtCO_2e$/year. However, it is important to consider potential implications for food security with increasing adoption of mitigation options. Our analysis emphasized options that were considered feasible in terms of the tradeoffs required (e.g., water and other input requirements, yield impacts), but there may be impacts from adoption of options that lower yields on large areas. For instance, rice is a staple crop produced in areas with fast-growing populations that have been plagued by food shortages. Beach et al. (2014) examine the tradeoffs between GHG mitigation and food security for global rice cultivation.

In addition, mitigation potential varies substantially by country/region. One important consideration is variation in mitigation potential across regions with different levels of commitments to mitigation under international negotiations. Table 5 summarizes mitigation potential for the two largest emitters in the world, the US and China, as well as the rest of the Annex I and non-Annex I countries.

[Table 5 about here]

6. Conclusions

This study contributes updated agricultural non-CO_2 MAC curves for the period 2010-2030, reflecting additional mitigation options, more recent biophysical and management data, and a greater level of regional disaggregation than has been available to date. The combination of biophysical process-based models and models of production and abatement costs to estimate costs and mitigation potential for the agricultural sector at a regionally and sectorally disaggregated level for individual GHGs provides an important contribution to the literature. These data can be used in numerous multi-sector models, where the level of disaggregation will facilitate custom aggregations of individual countries, agricultural sources, and gases for consistency with individual models. In addition, our ongoing efforts to account for alternative rates of technological improvement and to reflect sequential and simultaneous adoption of multiple mitigation options for the same emissions stream in future research will lead to continued improvements in the characterization of agriculture mitigation estimates.

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Table 1: Comparison of Agriculture Sector Non-CO_2 Emissions Estimates, 2010 (million metric tons, CO_2e)

	Tubiello et al. (2013); IPCC (2014)	USEPA (2012)	USEPA (2013)
	Tier 1	Tier 1-3	Tier 1-3
Total Agriculture	**4,586**	**5,999**	**3,325**
Croplands	950	1,969[a]	474[b]
Synthetic fertilizer	683	Included in sum	Included in sum
Manure applied to soils	116	Included in sum	Included in sum
Crop residues	151	Included in sum	Included in sum
Organic soils	NA	Included in sum	NA
Grassland soils	NA	Included in sum	NA
Burning of residuals or biofuels	NA	Included in sum	NA
Rice	499	520	565
Livestock[c]	3,135	2,346	2,286
Enteric fermentation	2,018	1,932	1,945
Manure management	353	414	341
Manure left on pasture	764	NA	NA
Other Agricultural Non CO_2	NA	1165	NA

Notes:

NA=not applicable

[a] USEPA (2012) presents estimates of emissions from agricultural soils, which includes both croplands and pasture

[b] DAYCENT baseline includes only maize, wheat, barley, sorghum, oats and related crops, and covers 61% of the global non-rice cropland areas reported by FAOSTAT

[c] Includes emissions from dairy cattle, non-dairy cattle, buffalo, sheep, goats, camels, mules/asses, horses, market swine, breeding swine, and poultry.

Table 2: Croplands Management and Rice Cultivation Mitigation Options

	Croplands Mitigation Options	Rice Production Mitigation Options (combinations of the following)
Irrigation	NA	Midseason Drainage, Continuous Flooding, Alternative wetting/drying, Dry seeding, Dryland Rice
Cropping	100% Residue Incorporation, No till	100% Residue Incorporation, 50% Residue Incorporation, No till
Fertilization	Reduced Fertilization 20%, Increased Fertilization 20%, Optimal Fertilization, Nitrification Inhibitors, Split Nitrogen Fertilization	Ammonium Sulphate Fertilizer, Reduced Fertilization 10%, Reduced Fertilization 20%, Reduced Fertilization 30%, Optimal Fertilization, Nitrification Inhibitors, Slow Release Fertilizer

Table 3: Livestock Mitigation Options

Emissions Source	**Mitigation Options**
Enteric Fermentation	Improved Feed Conversion Antibiotics Bovine somatotropin (bST) Propionate precursors Antimethanogens Intensive grazing
Manure Management	Complete Mix Digester, Hogs Complete Mix Digester, Dairy Cattle Plug-Flow Digester, Dairy Cattle Fixed Film Digester, Hogs Covered Lagoon, Large Scale, Hogs Covered Lagoon, Large Scale, Dairy Cattle Dome Digester Polyethylene Bag Digester Centralized Digester

Table 4: Agriculture Sector Non-CO_2 Technical Mitigation Potential, 2010-2030

	Year	Abatement at $5/ton		Maximum Abatement	
		$MtCO_2e$	% Baseline	$MtCO_2e$	% Baseline
Non Rice Croplands	2010	65.3	13.8	86.9	18.3
	2020	44.4	9.7	70.4	15.3
	2030	30.4	6.4	55.8	11.8
Rice	2010	75.8	13.4	198.7	35.2
	2020	81.2	11.3	203.2	28.1
	2030	87.0	11.5	200.3	26.5
Livestock	2010	82.6	3.6	246.1	10.8
	2020	88.7	3.5	254.8	10.1
	2030	97.2	3.6	268.6	9.8
Total	2010	223.7	6.6	531.7	15.6
	2020	214.3	5.8	528.4	14.2
	2030	214.6	5.5	524.7	13.3

Table 5: Agricultural Non-CO_2 GHG Mitigation Potential by Region at $\$5/tCO_2e$ and $\$50/tCO_2e$, 2010-2030 ($MtCO_2e$)

	2010		**2020**		**2030**	
	$\$5/tCO_2e$	**$\$50/tCO_2e$**	**$\$5/tCO_2e$**	**$\$50/tCO_2e$**	**$\$5/tCO_2e$**	**$\$50/tCO_2e$**
US	24.8	41.3	19.2	36.3	15.0	35.0
China	42.2	80.0	25.1	62.6	20.9	57.3
Rest of Annex I	29.4	54.9	26.1	46.2	23.9	43.0
Non-Annex I	127.1	228.0	143.9	240.8	154.8	248.5
Global Total	223.6	404.3	214.3	386.0	214.6	383.8

Figure 1: Global MAC Curves for Agriculture, 2010-2030

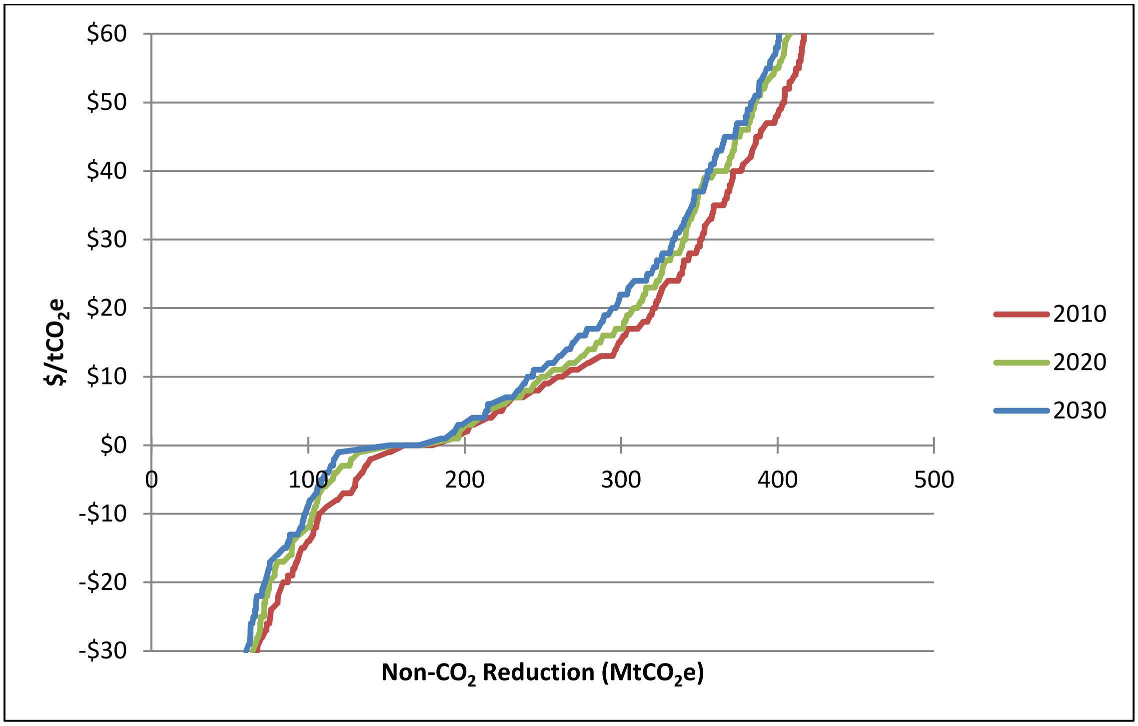

Figure 2: Global MAC Curves for Cropland Soils, Rice Cultivation, and Livestock, 2010-2030