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**Preliminary Mitigation Estimates for Soil N₂O,
Enteric CH₄, Rice CH₄ and Manure CH₄ Emissions
for Major World Agricultural Regions**

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1. Introduction and Goals of the Analysis

Agriculture accounts for a significant portion of the world's anthropogenic greenhouse gas (GHG) emissions, and emissions in this sector are projected to increase for the foreseeable future. Though many mitigation options for agricultural GHG emissions can be readily identified, it has been more difficult to assess mitigation options in agriculture than in most other sectors. The difficulty has been due to 1) the relative uncertainty in quantifying emissions—and changes in emissions due to mitigation—in a sector characterized by emissions that are spatially dispersed, not directly monitored, and highly variable, not only from region to region but from farm to farm; 2) the lack of regionally specific cost data for implementing mitigation options; and 3) the difficulty in estimating the appropriate level of mitigation response to carbon prices (or other values for GHG mitigation).

This analysis aims to improve our understanding of agricultural GHG mitigation for nitrous oxide (N₂O) and methane (CH₄) emissions from soils, livestock and rice, for major regions of the world. This paper provides general background information on non-CO₂ GHG emissions from global agriculture, describes the methods used in our mitigation analysis, presents results in the form of marginal abatement curves (MACs) for major regions in year 2010, and outlines important caveats and next steps for this project. We characterize these results as “preliminary” because 1) they have not undergone expert review; and 2) we made many simplifying assumptions in order to scale the mitigation estimates across regions.

2. Background on Agricultural N₂O and CH₄ Emissions

The primary GHGs of concern from the agricultural sector, and the gases included in this analysis, are N₂O and CH₄. Agriculture also affects carbon dioxide (CO₂) emissions through soil carbon changes and fossil fuel use for farm equipment and, more indirectly, through the energy-related emissions associated with the manufacturing of fertilizer. However, unless noted otherwise, these CO₂ effects are not included in our estimates.

Agricultural soil N₂O, enteric CH₄, rice CH₄ and manure CH₄—the emission sources addressed in our analysis—account for approximately 14% of total global GHG emissions¹ (Prentice et al. 2001; EPA 2002; EPA 2001). Of the world's total N₂O and CH₄ emissions, agriculture is responsible for approximately 90% and 50%, respectively (EPA 2002; EPA 2001).

Projected increases in global agriculture GHG emissions will be driven by continued increases in demand for agricultural products, due to continued population growth, increases in per capita caloric intake, and changes in diet preferences. These changes will be most pronounced in developing countries. The rate of increasing demand for agricultural products is, however, declining. According to FAO (2002), growth in world demand for agricultural products has been 2.2%/yr over the last 30 years but is projected to grow at 1.5%/yr for the next 30 years.

N₂O emissions from soils are the largest agricultural GHG source. In 2000, global N₂O emissions from agricultural soils were estimated to be 712 MtC, and are projected to increase

¹ Total estimate includes CO₂ emissions due to fossil fuel combustion, cement manufacturing, and land-use change, all CH₄ and N₂O sources, as well as the synthetic gases (HFCs, PFCs and SF₆).

36% by 2020². CH₄ emissions from enteric fermentation are the second largest global agricultural GHG source, estimated to be 476 MtC in 2000. These emissions are projected to increase by approximately 40% by 2020. CH₄ emissions from rice cultivation are the third largest global agricultural GHG source. In 2000, global emissions of rice CH₄ are estimated to be 177 MtC; by 2020 these emissions are projected to increase by 15%. CH₄ and N₂O emissions from livestock manure are the fourth largest global agricultural GHG source. In 2000, global CH₄ emissions from livestock manure are estimate to be 61 MtC, while N₂O emissions are estimated to be about 56 MtC. Our methods and mitigation estimates described below only capture the CH₄ emissions from livestock manure because only these emissions are captured in the underlying analyses. By 2020, global manure CH₄ emissions are projected to increase by 32%.

3. Methods

3.1 General Framework to Estimate Total Emission Reductions

The general framework used for the agriculture N₂O and CH₄ mitigation estimates is consistent with EPA's methodology for the non-CO₂ mitigation estimates for coal mining, natural gas systems, oil production, and solid waste management, also being presented in EMF 21 (Delhotal et al 2003). This framework is an engineering, bottom-up approach, where individual mitigation studies from one region are assumed to be representative of that region, and are then extrapolated to other regions of the world, adjusting for regional cost and revenue differences, as well as regional activity data. Emission reductions are either derived with IPCC default emission factors or taken as a percentage directly from the underlying studies and applied to 2010 baseline emissions for each region. Results are presented as marginal abatement curves (MACs) in the year 2010 for each region for soil N₂O, enteric CH₄ and rice CH₄.

Table 1 below lists the key parameters used to calculate the emission reduction (ER) for each mitigation option in each region. This can be summarized as follows: Because the mitigation options we chose (described in more detail below) were analyzed for one particular region, expert judgment is used to ascertain whether or not those same mitigation options are available in the other regions of our analysis. A "No" for availability means no further analysis is done for that option in that region.

In the first approach, technical applicability (TA) is estimated to be the percentage of baseline emissions to which the mitigation option could apply (e.g., the percentage of baseline manure CH₄ emissions to which a centralized digester could apply). In the second approach, TA is addressed by only including those activity data to which our mitigation options apply. For example, the soil N₂O mitigation options only address the N₂O emissions that result from the application of N-based fertilizers; other activities that contribute to N₂O baseline emissions, but not applicable for our mitigation estimates, include N-fixing crops, crop residues and livestock manure applied to soils.

² Unless noted otherwise, all emission data presented in this section are from EMF 21 web site: <http://www.stanford.edu/group/EMF/home/index.htm>

Table 1: Characterization of Mitigation Options in General Framework:

- (1) Literature gives % emission reduction when mitigation option is applied (manure & rice CH₄).
 (2) Literature gives activity data from which emission reduction is derived (soil N₂O & enteric CH₄).

Characteristic	Unit	Definition
Availability (A)	Yes/No	Projected availability of a specific option in a given region and year.
Technical Applicability (TA)	(1) Percent (%) (2) unitless	% of baseline emissions to which a given option can be applied. Include only activity data to which mitigation option applies.
Economic Applicability (EA)	Percent (%)	(1) Remaining emissions (baseline * TA) segmented by 1/n where n = number of mitigation options, to avoid overlapping options. (2) Activity data segmented by 1/n where n = number of mitigation options, to avoid overlapping options.
Reduction Efficiency (RE)	(1) Percent (%) (2) varies	% of remaining emissions (baseline * TA * EA) reduced when mitigation option is applied, taken directly from literature. % reduction in activity data taken directly from literature.
Lifetime (L)	Years	Average technical lifetime of an option or the capital equipment used in an option. Assumed 15 in all cases.
Abatement Potential (AP)	Percent (%)	(1) % (TA * EA * RE) of baseline emissions reduced by option. (2) % of baseline emissions reduced by option after comparing absolute emission reduction from activity data to baseline.
Emission Reduction (ER)	MtC	(1) Absolute amount of baseline emissions reduced by an option per year (baseline * AP). (2) Absolute amount of emissions reduced by option, derived through underlying activity data.

Economic applicability (EA) of the mitigation option is assumed to be the percentage of baseline emissions (baseline * TA) to which an option could apply, taking into account economic and infrastructure factors and barriers. In the first approach, EA is $1/n$ where n is the number of mitigation options. This assumes all mitigation options are overlapping and thus applicable to a uniform segmentation of baseline emissions, notwithstanding their net costs and benefits. In our second approach, EA is addressed by segmenting the appropriate activity data by 1/n (e.g., for our soil N₂O options, the applicable cropland base in hectares is segmented by 1/n).

Reduction efficiency (RE) refers to the percentage of baseline emissions reduced after the mitigation option has been applied, which, in the first approach, is taken directly from the literature. In our second approach, RE is the reduction in appropriate activity data (e.g., for our soil N₂O options, RE is expressed as the percent reduction in N-based fertilizer application).

The total emission reduction (ER) is the absolute magnitude of mitigation, expressed as million metric tons of carbon equivalent (MtC).³ In our first approach, ER is the product of the abatement potential percentage (TA * EA * RE) and baseline emissions. In our second approach, ER is calculated with the appropriate activity data, as discussed above, and IPCC default emission factors.

3.2 Estimating Costs to Establish Marginal Abatement Curves

Total emission reductions, estimated through the general approach described above, and other parameters are fed into the equation below to determine the present value, break-even mitigation cost (P), in 2000 \$US, per unit emission reduction in a given region, expressed as \$ per tonne of carbon equivalent (\$/tC). The analysis solves for P:

PV (Benefits) = PV (Costs) or more specifically,

$$\sum_{t=1}^T \left[\frac{(PxER) + R + TB}{(1 + DR)^t} \right] = CC + \sum_{t=1}^T \left[\frac{(RC)}{(1 + DR)^t} \right]$$

- where:
- P = break even price of the option in \$/tC (in \$US2000)
 - ER = absolute emission reduction achieved by the option (see Table 1 above)
 - R = revenue changes due to mitigation option (e.g., yields, electricity generation).
 - T = option lifetime (15 years assumed for all options)
 - DR = selected discount rate (5% for our estimates)
 - CC = capital cost of the option (fixed across regions; only applicable for manure options)
 - RC = recurring (O&M) cost of the option (scaled based on regional agricultural wages)
 - TB = tax break equal to CC/T * TR (applied only to manure CH₄ options)

Costs include capital costs (CC), recurring or operation and maintenance (O&M), and changes in input costs (e.g., fertilizers). Capital costs remain fixed across regions (and only occur in our manure CH₄ options), whereas O&M costs are scaled according to different labor ratios using the small number of agricultural wages available from the World Bank (2003) and extrapolating those to similar regions (e.g., using China's agricultural wages for Rest of Asia). FAO's database, FAOSTAT (<http://apps.fao.org/default.htm>), is used to estimate regionally-specific changes in input costs, such as fertilizer changes for our soil N₂O and rice CH₄ options.

Positive and negative effects on revenues are also calculated. Revenue effects include changes in crop yields (for soil N₂O and rice CH₄ options), changes in milk and beef production (for enteric CH₄ options) and electricity generation (for manure CH₄ options). More detail on how the costs and benefits were determined for each mitigation option is given below.

³ We use 100-year global warming potentials (GWPs) from IPCC's Second Assessment Report to convert N₂O (GWP = 310) and CH₄ (GWP = 21) to CO₂ (Schimel et al. 1996). We convert CO₂ to C equivalent units by multiplying by the ratio (12/44).

The exception to this method is for the EU enteric CH₄ options, where we take the costs per unit emission reduction directly from the underlying study (Bates 2001).

3.3 Regional Application of Mitigation Estimates

We selected a set of core regions for each emission source where we collected regionally-specific data in order to apply the chosen mitigation studies. For soil N₂O options, these regions include Africa, Brazil, Rest of Latin America, China, India, Japan, Rest of Asia, the EU-15, the US, Russia, CIS, and Other Annex I. For rice CH₄, mitigation estimates were conducted for only three core regions: China, India and Rest of Asia. For enteric CH₄, mitigation options analyzed in the US (Johnson et al. 2003; see below) were only directly applied to the US. Enteric CH₄ mitigation options analyzed in the EU (Bates 2001; see below) are only directly applied to the EU, but are then extrapolated to all other regions to reduce 2010 baseline emissions proportionately. This simplified approach for enteric CH₄ was taken to provide very preliminary estimates, but this will be a particular area for further work.

3.4 Selected Mitigation Options

Though there are numerous studies in the literature on agricultural N₂O and CH₄ emissions and potential mitigation options, our review uncovered only a handful of studies where cost information was presented in addition to associated emission reductions. For this reason, our analysis draws from a small number of studies, and extrapolates these to other regions using the general methodology described above.

3.4.1 Soil N₂O Mitigation Options

All soil N₂O mitigation options in our analysis involve adopting a more efficient N-based fertilizer application rate or reducing total consumption of N-based fertilizer. We derive reductions in N₂O for each option based on the reduction efficiency in N applied from Bates (2001) (see Table 2). These percentage reductions are applied to average baseline N application rates per ha, which we calculate with the appropriate hectares from FAOSTAT and either the projected 2010 total N consumption (for the US, China, India and Brazil) or historical N consumption. Total regional N reductions are then estimated by taking the average reduction in N per ha multiplied by total applicable hectares. These reductions in N are converted to N₂O reductions through the IPCC Tier I default factors (IPCC 1997) for both direct emissions and indirect emissions due to volatilization and leaching and runoff.

All N₂O mitigation options in our analysis incur cost savings due to less N-based fertilizer inputs. These cost savings are calculated by multiplying the total regional reductions in N (described above) by the average price for all nitrogenous fertilizers in that region from FAOSTAT. Regional prices are converted to 2000 \$US.

Some soil N₂O mitigation options result in loss of revenue due to declines in crop yields brought on by applying suboptimal levels of fertilizer (see Table 2). For these options, revenue losses are calculated using the estimated percentage loss in crop yield based on the EC (1998) report, and

applying that percent reduction to baseline crop yields from FAOSTAT. Yield reductions are multiplied by the region specific crop price from FAOSTAT to estimate total revenue loss.

Table 2: Summary of Selected Mitigation Options for Soil N₂O Emissions (Bates 2001 and EC 1998)

Mitigation Option	Description	Reduction Efficiency (N applied)*	Cost Implications	Revenue Implications
Spreader maintenance	More uniform spreading to increase efficiency; avoid over-application and under-application	22%	Additional labor; Less fertilizer	Yields remain same
Fertilizer free zone	Avoid fertilizer loss by leaving fertilizer free zone at field edges	4%	Less fertilizer	Yields decline 1%
Precision farming	Combination of above two options	26%	Additional labor; Less fertilizer	Yields decline 1%
Suboptimal application for winter wheat 1	N-based fertilizer reduced by 50kg/ha for winter wheat only	26%	Less fertilizer	Yields decline 5.5%
Suboptimal application for winter wheat 2	N-based fertilizer reduced by 100kg/ha for winter wheat only	51%	Less fertilizer	Yields decline 20.3%

* Note that this refers to reductions in N applied, not to reductions in N₂O emissions. Reductions in N₂O were derived from reduced N applications through IPCC default factors.

An important caveat we want to stress here is that it is questionable to assume that the same percentage reduction in N-based fertilizers in the EU and other regions will result in a uniform percentage decrease in crop yields across all regions. This will depend largely on the extent to which baseline N application rates are either in excess of crop needs or already at some efficient level. These data, however, are difficult to obtain which is why we adhere to the percentage yield changes from EC (1998).

3.4.2 Enteric CH₄ Mitigation Options

Our approach with enteric CH₄ mitigation is different from the other options, in that we rely on separate underlying studies for different regions: work by Johnson et al. (2003) for the US and reports commissioned by the EC for EU-15 (Bates 2001). As described above in section 3.3, US results are extrapolated to Canada, and EU results are extrapolated to all remaining EMF regions. We take this approach because most of our mitigation options for the US are not applicable in developing countries (where there are less confined feeding operations), and there was inadequate time to deconstruct the mitigation options from the EC report and apply elsewhere.

All of the enteric CH₄ mitigation options in our analysis actually result in more CH₄ per animal. However, CH₄ per unit of product (milk or beef) declines due to efficiency gains in the digestive system of livestock brought about by these mitigation options. Total CH₄ reductions occur when we strictly assume that aggregate (regional) levels of milk and beef production remain the *same* after implementation of the mitigation options, which then leads to a reduction in overall regional herd size due to efficiency gains on a per animal basis. It can be argued that this would occur at the national or regional level, i.e., that the more efficient producers would squeeze out the less efficient ones. This does, however, ignore the possibility of some emissions increase as a result of lower costs per unit through the efficiency gains, which could in turn increase the quantity demanded.

Table 3a: Summary of Selected Mitigation Options for Enteric CH₄ Emissions, for US only and extrapolated to Canada (Johnson et al. 2003)

Mitigation Option	Description	Reduction efficiency (tC/kg milk or beef)*	Cost Implications	Revenue Implications
Increase milk production by 20%	Increase production per animal by altering nutrition. Applies to dairy.	4×10^{-5}	Reduces costs	Reduces revenue
Use of BST	Bovine somatotropin: metabolic modifier enhances milk production. Applies to dairy.	3×10^{-5}	Reduces costs	Reduces revenue
Reduce cull rate by 10%	Reduce the number of culled heifers by 10%. Applies to dairy.	2×10^{-5}	Reduces costs	Reduces revenue
Skipping the stocker phase	Placing young cattle directly into the feedlot rather than allowing them to develop for a few years in a stocker program. Applies to non-dairy.	9×10^{-4}	Increases costs	Reduces revenue
Skipping the stocker phase & intensive grazing	Same as above but including intensive grazing. Applies to non-dairy.	1×10^{-3}	Reduces costs	Reduces revenue
Increasing body fat to 29%	Increase the body weight of cattle to 29% at time of slaughter. Applies to non-dairy.	1×10^{-4}	Increases costs	Increases revenue
Reduce herd size by 20%	Reduce herd size while maintaining beef production. Applies to non-dairy.	3×10^{-4}	Increases costs	Reduces revenue
Intensive grazing	Change the feeding to include grazing in pasture rather than all processed feed mixture. Applies to non-dairy.	3×10^{-4}	Increases costs	Increases revenue

* Note that this refers to reductions in carbon equivalent per unit milk or beef, not directly to total reductions in CH₄. Reductions in CH₄ had to be derived from reduced emissions per unit product.

For the U.S., we derive total CH₄ reductions based on emissions reductions (in metric tons of carbon equivalent) per kg milk and beef provided by Johnson et al. (2003) for each mitigation option (Table 3a). These per kg product emission reductions are then applied to projected 2010 milk and beef production for the U.S. As mentioned above, the emissions per animal may increase, but fewer animals are required to produce a given level of output. Thus, emission reductions are the net effect of decreases from the reduction in livestock populations and increases from the more productive animals being used to produce milk and beef after adoption of the options.

Input costs either increase or decrease depending on enteric CH₄ option. Johnson et al. (2003) provides costs per unit product in the baseline and mitigation case for the U.S., to give net costs due to the mitigation option. Revenue implications are calculated in a similar manner. Future versions of this analysis will further deconstruct and identify the cost and revenue implications of the Johnson et al. mitigation options.

Table 3b summarizes the enteric CH₄ mitigation options from the EU (Bates 2001). These options, and not those from Johnson et al., are extrapolated to all other remaining EMF regions because they were considered to be more applicable across regions. In general, these options increase the amount of feed that is converted to product and decrease the amount of feed converted to CH₄. Here too, CH₄ per animal unit increases, but aggregate emissions decrease with the assumption that production levels remain constant. Table 3b also provides the costs in

\$/tC (after converting from Euros) which, unlike our approach for all other options, we take directly from Bates (2001) rather than using assumptions from Bates and estimating our own regionally-specific \$/tC per option.

Table 3b: Summary of Selected Mitigation Options for Enteric CH₄ Emissions (Bates 2001), for EU only and extrapolated to remaining regions

Mitigation Option	Description	Reduction efficiency (dairy)	Cost (\$/tC)	Reduction efficiency (non-dairy)	Cost (\$/tC)
Improved feed conversion efficiency 1	Replacement of roughage that contains high portions of structural carbohydrates with concentrates to improve propionate generation in rumen.	6.2%	-51	8.2%	-51
Improved feed conversion efficiency 2	Addition of fats to diet meets energy requirements and increases propionate in rumen.	7.3%	-17	4.3%	-17
Improved feed conversion efficiency 3	Include more non-structural carbohydrates in concentrate; leads to lower rumen pH.	13.1%	-4	7.8%	-4
Improved level of feed intake with improved genetics	Increasing level of feed intake to change volatile fatty acid (VFA) in rumen to generate more propionate with improved genetics.	7.8%	-12	9.6%	-12
Increased rumen efficiency	Addition of propionate precursors in daily supplements.	25%	8	10%	16

3.4.3 Rice CH₄ Mitigation Options

All rice CH₄ mitigation options in our analysis based on Wassmann et al. (2000) assume the baseline conditions to be continuous flooding with organic amendments; the last option in Table 4 based on Van der Gon et al. (2001) assumes irrigated (which may or may not be continuous flooding) and rainfed rice to be the baseline conditions. Most of these options involve changing the water management regime to reduce the time over which anaerobic conditions in flooded fields occur, or alter the amendments to the soils to inhibit methanogenesis.

The CH₄ reduction efficiencies for each mitigation option are taken directly from Wassmann et al. (2000) and Van der Gon et al. (2001). In the Van de Gon et al (2001) study several reduction efficiencies were reported for each of the options. In these cases the efficiency reduction factor used in the analysis was generated by taking the average of the reduction efficiencies that were determined to be statistically significant.

Wassmann et al. (2000) do not provide capital or implementation cost data for most mitigation options but they do provide data for the revenue side of the equation, by showing any changes in rice yields (we did not include any mitigation option which decreased yields). We took those percent changes in rice yields and calculated the revenue implications for each region with FAOSTAT data on baseline rice yields per ha, total harvested rice area, and prices for rice, converted to 2000 \$US. Recurring costs could be calculated for the option to add phosphogypsum and the option to replace the commonly used urea fertilizer with ammonium

sulfate (AS). In these cases, we used the regional prices of phosphogypsum and AS (relative to urea) from FAOSTAT and the appropriate application rates per ha from Wassmann et al. and Van der Gon et al.

Table 4: Summary of Selected Mitigation Options for Rice CH₄ Emissions

Mitigation Option	Description	Reduction efficiency	Cost Implications*	Revenue Implications	Ref.
Midseason drainage	Reduces anaerobic conditions	33%	19% labor increase	Yield increases 7%	Wassmann et al. 2000
Alternate flooding/drainage	Reduces anaerobic conditions	60%	38% labor increase	Yield increases 12%	Wassmann et al. 2000
Rice straw compost	Substitutes for fresh rice straw; lowers organic matter	61%	28.5% labor increase	Yields remain same	Wassmann et al. 2000
Phosphogypsum	Addition of this byproduct (3t/ha) releases sulfate which inhibits methanogenesis	32%	19% labor increase; cost for phosphogypsum	Yields remain same	Wassmann et al. 2000
Midseason drainage and no organic matter	Reduces anaerobic conditions; lowers organic matter source	76%	19% labor increase	Yields remain same	Wassmann et al. 2000
Replace urea with ammonium sulfate (AS)	Replaces commonly used urea; sulfate inhibits methanogenesis	20%	Labor remains same; AS costs more than urea	Yields remain same	Van der Gon et al. 2001

* Labor assumptions based on Moser and Barrett (2002) or Pandey and Valesco (1999).

Because we thought it unreasonable to assume many of these mitigation options implied zero changes in labor inputs, we based our estimates of the implications for labor requirements on a separate study from Moser and Barrett (2002), who investigated labor requirements for the adoption of rice intensification practices. Moser and Barrett estimate these practices, consisting of early transplantation, planting of single seedlings, wide spacing, intermittent irrigation, and frequent weeding, would require 38-54% more labor than traditional cultivation practices. While these practices are not exactly the same as the CH₄ mitigation options, the labor estimate provides guidance on the approximate magnitude of labor requirements. Because the options in our analysis consist of fewer activities than the full set of practices in Moser and Barrett (2002), we use fewer labor hours, ranging from 19-38% above baseline conditions (Table 4). The direct wet seeding option is expected to require 27% less labor based on the average reduction in labor hours per hectare between transplanting and direct wet seeding calculated from Pandey and Velasco (1999). For the option combining direct wet seeding and midseason drainage, the change in labor requirement was estimated to be the sum of the direct wet seeding and midseason drainage options, or an 8% reduction in labor. Finally, the option to replace urea applications with ammonium sulfate (from Van der Gon et al. 2001) was assumed to require no incremental labor.

3.4.4 Manure CH₄ Mitigation Options

All manure CH₄ mitigation options in our analysis involve the management, capture and use of manure CH₄ through anaerobic digesters. Emission reduction efficiencies and capital costs are taken directly from Bates (2001). The higher emission reduction efficiencies for the warm-climate digesters reflect the fact that baseline emissions from liquid manure storage in warm conditions are assumed to be much higher than in colder climates (Table 5). Capital costs for implementing an anaerobic digester are based on a small number of representative systems in the

EU. These capital costs remain fixed across regions. Revenues are generated from the use of captured CH₄ for either heat or electricity on the farm; these revenues are scaled to other regions based on an EIA electricity price index relative to the EU.

Table 5: Summary of Selected Mitigation Options for Manure CH₄ Emissions (Bates 2001)

Mitigation Option	Description	Reduction efficiency	Cost Implications	Revenue Implications
Farm scale digesters A: cool	A type of anaerobic digester for individual farms in cool climates	50%	Capital costs incurred	Elec. generation
Farm scale digesters A: warm	Same as above but in warm climates	75%	Capital costs incurred	Elec. generation
Farm scale digesters B: cool	A second type of digester in cool climates	50%	Capital costs incurred	Elec. generation
Farm scale digesters B: warm	Same as above but in warm climates	75%	Capital costs incurred	Elec. generation
Centralized digesters: cool	Large centralized digesters in cool climates where individual farmers transport their waste to in order for large scale digestion and dispersion of capital costs.	50%	Capital costs incurred	Elec. generation
Centralized digesters: warm	Same as above but in warm climates.	75%	Capital costs incurred	Elec. generation

4. Mitigation Results

Mitigation results are presented as marginal abatement curves (MACs) for each region in 2010, showing absolute reductions in terms of MtC, using 2000 USD per ton of carbon equivalent (\$/tC). A sample of MACs are presented in the appendix.

Options for rice CH₄, though only the third largest agriculture GHG source, actually mitigate the greatest amount of emissions in this preliminary analysis. These options were only applied to China, India and Rest of Asia, but these regions comprise about 90% of the world's rice production. For each region, cumulative mitigation amounts to 47% of 2010 baseline emissions. The same proportion of baseline emissions is reduced in every case because we assume the mitigation options apply to 100% of baseline emissions in every region (i.e., those from flooded rice fields) and that the CH₄ reduction efficiencies of the options are constant across regions. This is a very high-end estimate because our methods do not constrain mitigation potential due to likely implementation barriers; therefore, this could be considered the technical mitigation potential for these options. Absolute mitigation in China is estimated to be 32 MtC, at costs that range from \$5-200/tC. Low-cost options include those with no or very little additional labor requirements and increased or steady rice yields (e.g., replacing urea with ammonium sulphate and midseason drainage); and high-cost options include those with greater labor requirements and input costs (e.g., addition of phosphogypsum).

Mitigation options for soil N₂O emissions, agriculture's largest GHG source, reduce world emissions by slightly less than the rice CH₄ options, but significantly less compared to 2010 baseline emissions. For the EU, where our soil N₂O mitigation options were originally assessed, cumulative mitigation is 4.3 MtC or about 8.5% of 2010 baseline emissions. Results are similar for the US: mitigation is estimated at 7.8 MtC or 9% of 2010 baseline emissions. The low

mitigated portion of baseline emissions can be partly explained by the fact that our mitigation options are addressing only a portion of total N₂O baseline emissions, i.e., emissions due to N-based fertilizers and not due to N-fixing crops, agriculture residues and manure applications. Costs for the five options in our analysis range from negative or low to highly positive (e.g., for EU: -\$74 to 1,500/tC; for US: -\$33 to 935/tC; for China: \$2 to 260/tC). Negative costs are due to cost savings as a result of using less fertilizers without yield reductions (spreader maintenance), whereas the high costs are due to revenue losses when crop yields decline as a result of sub-optimal fertilizer application (fertilizer free zone).

Globally, our enteric CH₄ mitigation options reduce emissions by the least amount in absolute terms. This is because we use results from the EU to reduce 2010 baseline emissions for all regions (except for the US and Canada) by the same proportion. Total mitigation for the EU is estimated to be 2 MtC or 5.8% of 2010 baseline emissions. This relatively low level of mitigation is largely because the original analysis (Bates 2001) assumed strict constraints on implementation of the options by 2010; and we adhere to these same limits. These results therefore represent more of an economic mitigation potential, whereas most of our other estimates represent technical mitigation potential. Further work on this project will ensure greater consistency across options in this regard. Costs of the EU options range from negative to slightly positive (-\$51 to \$16/tC), due to savings in feed requirements and improvements in productivity per animal.

Enteric CH₄ mitigation for the US, based on work in the US (Johnson et al. 2003), is estimated to reduce emissions by 8.2 MtC or 22% of 2010 baseline emissions. A higher portion of baseline emissions are reduced here due in part to the fact that we do not impose constraints for implementation feasibility. Costs range from highly negative to highly positive: -\$361 to \$509/tC.

The results for the manure CH₄ mitigation options are the same as those presented to EMF 21 previously, along with the other methane sources like coal. The four options applicable to the US mitigated a cumulative total of 1.8 MtC or 16% of 2010 baseline emissions. Results are nearly identical for the EU, where the study for these mitigation options originated: cumulative mitigation is estimated to be 1.6 MtC or 15% of 2010 baseline emissions. A smaller number of these options is applicable to other countries like China, India and Brazil. In China, mitigation from the two applicable options for farm-scale digesters is 1.5 MtC or 20% of 2010 baseline emissions. Costs in the US range from \$113-488/tC; in the EU the range is -\$6-220/tC; and in China \$41-73/tC.

5. Caveats and Next Steps for Non-CO₂ International Agriculture Mitigation Project

This preliminary analysis has many caveats. These include 1) accounting for net GHG effects; 2) accounting for spatial and temporal heterogeneity in agricultural GHG emissions; 3) the paucity of regionally-specific cost data to implement mitigation options; 4) choosing the appropriate availability and applicability of the options across regions; 5) additional mitigation options not included in our analysis; and 6) taking into account broader socioeconomic and environmental co-effects of the mitigation options.

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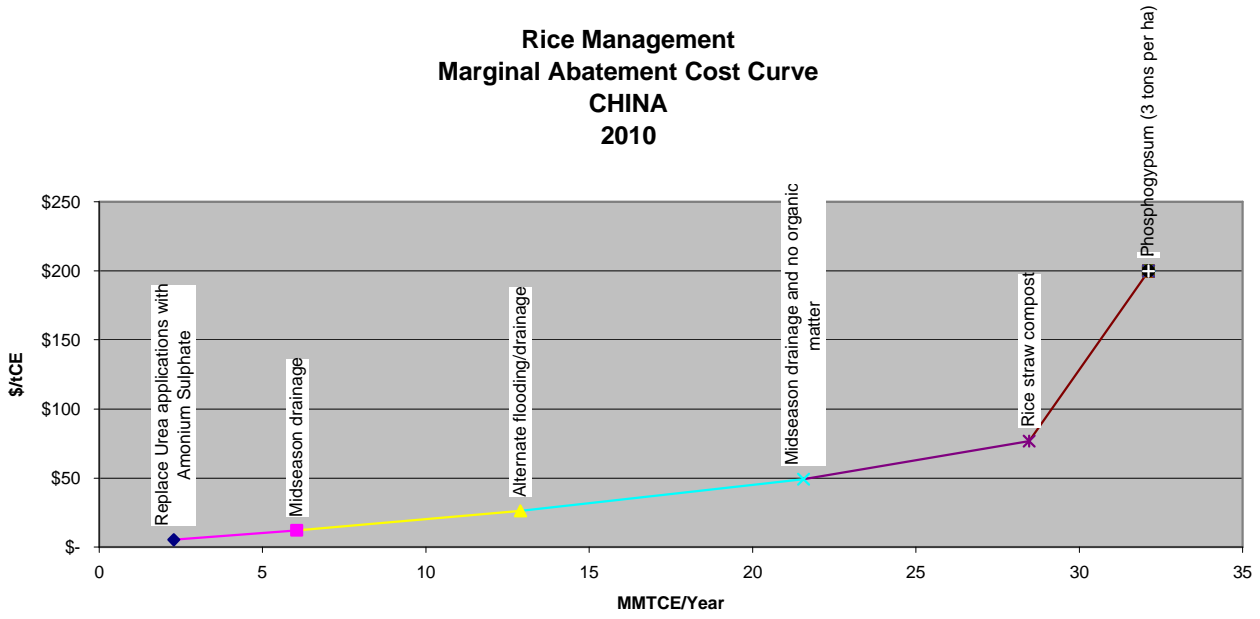
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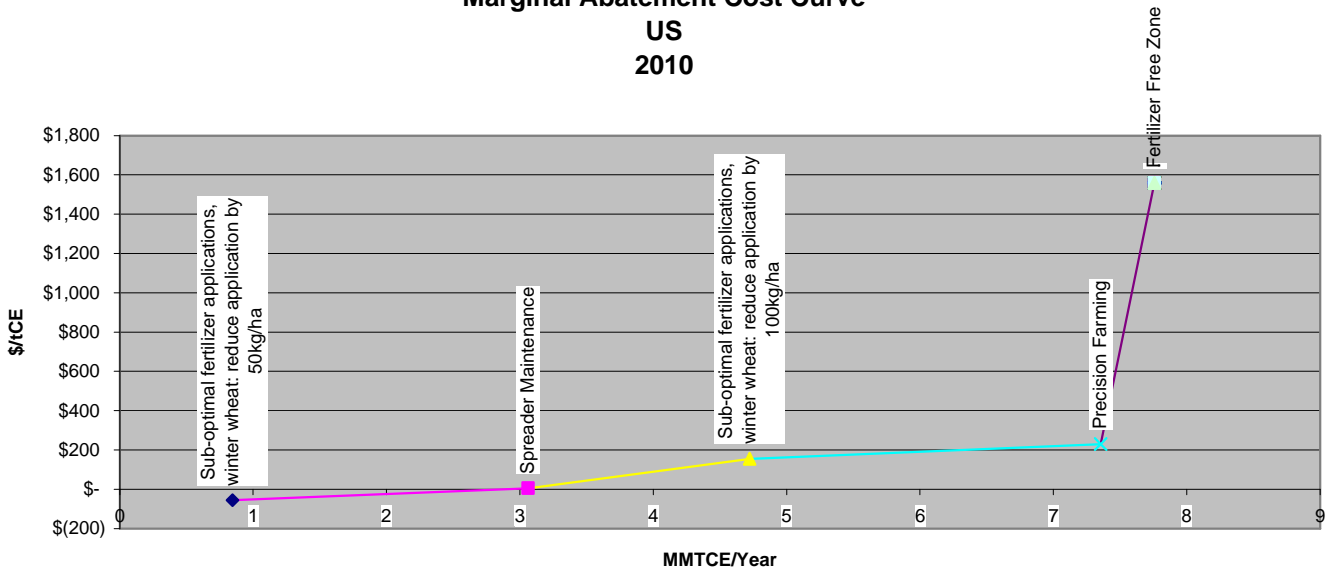
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Rice Management Marginal Abatement Cost Curve CHINA 2010



Soil Management Marginal Abatement Cost Curve US 2010



Enteric Fermentation Marginal Abatement Cost Curve US 2010

