Mitigation potential and costs for global agricultural greenhouse gas emissions

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Abstract

Agricultural activities are a substantial contributor to global greenhouse gas (GHG) emissions, accounting for about 58% of the world’s anthropogenic non-carbon dioxide (non-CO₂) emissions (84% of nitrous oxide [N₂O], 47% of methane [CH₄]), and make up roughly 14% of all anthropogenic GHG emissions (U.S. Environmental Protection Agency [EPA], 2006; Prentice et al., 2001; Scheehle and Kruger, 2006). In many developing countries, the agricultural sector is the largest source of GHG emissions. In addition, GHG emissions from agriculture are projected to increase significantly over the next 20 years, especially in Asia, Latin America, and Africa, due to increased demand for agricultural products as a result of population growth, rising per capita caloric intake, and changing dietary preferences.

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1. Introduction and background

Agricultural activities generate the largest share, 58%, of the world’s anthropogenic non-carbon dioxide GHG emissions and 14% of all anthropogenic GHG emissions, and agriculture is often viewed as a potential source of relatively low-cost emissions reductions. We estimate the costs of GHG mitigation for 36 world agricultural regions for the 2000–2020 period, taking into account net GHG reductions, yield effects, livestock productivity effects, commodity prices, labor requirements, and capital costs where appropriate. For croplands and rice cultivation, we use biophysical, process-based models (DAYCENT and DNDC) to capture the net GHG and yield effects of baseline and mitigation scenarios for different world regions. For the livestock sector, we use information from the literature on key mitigation options and apply the mitigation options to emission baselines compiled by EPA.

As an important source of global emissions, the agricultural sector also potentially offers relatively low-cost opportunities for GHG mitigation. However, there are 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. First, there is a high degree of spatial and temporal heterogeneity in biophysical and management conditions that affect both production and emissions. Second, many agricultural activities emit multiple GHGs, and there are often complex interactions between these emissions. Third, there is a paucity of regionally specific cost data from which one can estimate the economic implications of implementing GHG mitigation practices, in terms of changes in inputs, revenue, and labor. Fourth, estimating the expected level of implementation of the mitigation options in response to financial incentives (e.g., carbon price) is difficult given the implementation barriers that exist in different regions.

Nonetheless, agricultural net GHG and non-CO₂ mitigation analyses have been developed for several countries and the
world. Some include a relatively comprehensive set of GHG mitigation options with dynamic economic feedbacks (see EPA [2005a] and McCarl and Schneider [2001] for the United States), whereas others have targeted individual agricultural emission sources with static engineering mitigation estimation methods (see Kroese and Mosier [1999] for global cropland N₂O and enteric CH₄; Riemer and Freund [1999] for global rice emissions; see also Table 3.27 in Moosmaw et al. [2001] of IPCC Working Group III). Our previous analysis, DeAngelo et al. (2006) developed global mitigation estimates for cropland N₂O, livestock enteric and manure CH₄, and rice CH₄; these values were used by many participants of the Energy Modeling Forum-21 study to represent the agricultural sector in global multisector, multitogas mitigation scenarios (Van Vuuren et al., 2006).

This analysis improves on DeAngelo et al. in a number of areas. Biophysical, process-based models (DAYCENT and DNDC) are used to better capture the net GHG effects of cropland and rice emissions (i.e., soil carbon, CH₄, N₂O) under baseline and mitigation scenarios. The previous analysis often assumed uniform changes in emissions and/or yields between baseline and mitigation scenarios (based on literature studies) across regions. They also focused on a single gas for each mitigation option. Although process-based models account for heterogeneous and dynamic emission and yield effects of adopting mitigation practices, while at the same time tracking multiple GHG fluxes, they require detailed data on local conditions in order to accurately simulate site-specific yields and daily emission fluxes. Rather than attempt to calibrate to site-specific data for regions around the world, we use these models to capture the broad trends between baseline and mitigation scenarios over large temporal and spatial scales, adjusting for regional conditions. Using process-based models to generate both baseline and mitigation scenarios provides consistency in underlying assumptions. We emphasize the estimated differences between baseline and mitigation scenarios rather than absolute values. In addition, this analysis provides results for individual major crops (rice, maize, wheat, and soybeans) under both irrigated and rain-fed conditions, and we estimate results for 36 different regions of the world, which is more spatially disaggregated than previous studies in the literature.

2. Emissions characterization

The majority of agricultural non-CO₂ GHG emissions are from one of four sources: cropland soil management (primarily N₂O), ruminant livestock enteric fermentation (primarily CH₄), rice cultivation (primarily CH₄ for flooded rice paddies, though N₂O is also important under certain growing conditions), and livestock manure management (both CH₄ and N₂O, with CH₄ from anaerobic manure management systems dominating). Changes in soil carbon (C) are also important determinants of net GHG emissions for soil management and rice cultivation.

N₂O emitted by cropland soils is typically the largest source of GHG from agricultural systems. It is produced naturally through the processes of nitrification and denitrification. Application of nitrogen (N)-based fertilizers is a key determinant of N₂O emissions, as excess N not used by the plants is subject to gaseous emissions, as well as leaching and runoff. Other soil management activities such as irrigation, drainage, tillage practices, and fallowing of land, can also affect N₂O fluxes as well as soil C and fossil fuel CO₂ emissions.

Methane is produced as part of the normal enteric fermentation process in animals. During digestion, microbes in an animal’s digestive system ferment food consumed by the animal. This process produces CH₄ as a by-product, which can be exhaled or eructated by the animal. The amount of CH₄ emitted by an animal depends primarily on the animal’s digestive system and the amount and type of feed it consumes. Ruminant animals (e.g., cattle, buffalo, sheep, goats, and camels) are the major emitters because of their unique digestive system.

Most rice in Asia and the rest of the world is grown in flooded paddy fields, where aerobic decomposition of organic material gradually depletes the oxygen present in the soil and floodwater, causing anaerobic conditions. Anaerobic decomposition of soil organic matter by methanogenic bacteria generates CH₄. The water management system under which rice is grown is therefore one of the most important factors affecting CH₄ emissions. In addition, other practices (e.g., tillage, fertilization, manure amendment) alter soil conditions and therefore soil C and N driving processes such as decomposition, nitrification, and denitrification.

The management of livestock manure can produce both CH₄ and N₂O emissions. Methane is produced by the anaerobic decomposition of manure. N₂O is produced through the nitrification and denitrification of the organic nitrogen in livestock manure and urine. When manure is stored or treated in systems that promote anaerobic conditions (e.g., as a liquid or slurry in lagoons, ponds, tanks, or pits), the decomposition of materials in the manure tends to produce CH₄. In addition, a small portion of the total nitrogen excreted in manure and urine is expected to convert to N₂O. The production of N₂O from livestock manure depends on the composition of the manure and urine, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system (EPA, 2005b).

3. Methods

We apply a set of mitigation options identified in the literature for each emission category: croplands (N₂O and soil C); livestock enteric fermentation (CH₄); rice cultivation (CH₄, N₂O, and soil C); and livestock manure management (CH₄ and N₂O). Emissions, yields, productivity changes, labor requirement changes, and other factors from the mitigation scenarios are compared with baseline conditions for years 2000, 2010, and 2020, and for all major world agricultural regions. If a mitigation option is considered technically feasible for a given region,
it is assumed to be adopted immediately, that is, in data year 2000, and the change in management is continuous for the entire 2000–2020 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. Each set of mitigation options for each emission category in each region is assumed to be implemented simultaneously but without any overlap among the options. For example, six mitigation options are applied to rice emissions in China; each option is therefore applied to one-sixth of applicable baseline emissions. 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. However, it is used in the absence of region-specific data on adoption feasibility.

The break-even price for each mitigation option is calculated according to Eq. (1), which sets total benefits equal to total costs, and solves for the present-value, break-even price (P), expressed in 2000 US$/tCO2eq.

\[
\sum_{t=1}^{T} \left[ \frac{(P \cdot E) + R}{(1 + \delta)^t} \right] = C_K + \sum_{t=1}^{T} \left[ \frac{(C_A)}{(1 + \delta)^t} \right]
\]

(1)

E is the absolute net GHG emission reduction. R is the revenue effect as a result of the mitigation option (e.g., yield changes, electricity generation). C_E is capital cost for each option. C_A includes annual costs (scaled to different regions based on agricultural labor wages) and input costs such as fertilizers. T is the assumed useful life of capital equipment used for mitigation, which applies only to the small number of options identified that involve purchases of capital (primarily manure management options involving the purchase of anaerobic digesters). \( \delta \) is the real discount rate, assumed to be 5% in all cases.

3.1. Cropland soil GHG mitigation options

Options have been identified that could decrease N2O while maintaining yields (Mosier et al., 2002). The mitigation options used in this analysis involve more efficient or simply reduced N-based fertilizer application (e.g., N-inhibitors, split fertilization, reducing N-fertilization to 70, 80, or 90% of baseline levels) and adoption of no-till cultivation.

Baseline N2O emissions, soil carbon levels, and crop yields are estimated for all world regions with the DAYCENT model (Del Grosso et al., 2001; Parton et al., 1998) for years 2000, 2010, and 2020. Underlying data for the DAYCENT simulations include global data sets of weather, soils, cropland area, and native vegetation, mapped to an approximate 2° × 2° resolution. Current and historic nitrogenous fertilization data for each region and country are from FAOSTAT (2004) and the International Fertilizer Industry Association (IFA) (2002). Projected fertilization rates are taken from FAO (2000) and FAOSTAT (2004).

The mitigation options are simulated with DAYCENT and those results are compared with the baseline to calculate the impacts of each mitigation option on fertilizer use, crop yields, and net GHG emissions. Revenue changes are estimated by using the percentage yield changes, from DNDC applied to baseline yields and crop prices from IFPRI’s IMPACT model. Labor requirements to implement the mitigation options are based on a review of relevant literature and associated cost implications are calculated using regional agricultural wages from IMPACT data.

3.2. Rice GHG mitigation options

The DNDC model (DNDC 8.6; Li et al., 2004) is used to estimate baseline and mitigation option emissions of CH4, N2O, and soil carbon, as well as yield and water resource changes, for Asian rice systems. Greenhouse gas emissions from non-Asian rice systems, which represent about 10% of the world’s total rice area (Wassmann et al., 2000), are excluded. The mitigation options involve a change in water management (to reduce anaerobic conditions), fertilizers or amendments (to inhibit methanogenesis), or switching from flooded to upland rice. Revenue changes are estimated by using the percentage yield changes from DNDC applied to baseline yield and rice prices from IFPRI’s IMPACT model. Some options require soil amendments (e.g., phosphogypsum) or an alternative fertilizer (e.g., ammonium sulfate instead of urea) (Denier van der Gon et al., 2001). These additional input costs are included by using baseline application rates from Wassmann et al. (2000) to calculate incremental requirements for amendments or fertilizer switching and regional prices from FAOSTAT. Labor requirements to implement the mitigation options are estimated using a study on labor requirements for adopting rice intensification practices (Barrett et al., 2004). The cost implications of any labor requirement changes are calculated using agricultural wages for each region from IMPACT data.

3.3. Enteric CH4 mitigation options

Enteric CH4 mitigation options examined fall into four general categories: (1) improvements to food conversion efficiency by increasing energy content and digestibility of feed; (2) increased animal productivity through the use of natural or synthetic compounds that enhance animal growth and/or lactation (e.g., bovine somatotropin [bST], antibiotics); (3) feed supplementation to combat nutrient deficiencies that prevent animals from optimally using the potential energy available in their feed; and (4) changes in herd management (e.g., use of intensive grazing). In each case, the production of CH4 per unit of product (meat, milk, or work [for draft animals]) is decreased, but emissions of CH4 per animal may increase. Thus, emission reductions at the national or regional level are calculated assuming that total production of meat, milk, or work remain constant after implementation of the mitigation options.
Table 1
Distribution of net GHG 2000–2020 emissions reductions across major river basins in China from conversion to shallow water flooding

<table>
<thead>
<tr>
<th>Waterbasin name</th>
<th>Average annual proportion of baseline emissions reduced</th>
<th>Average annual change in emissions (1,000 kg CO₂eq)</th>
<th>Proportion of national paddy rice acreage</th>
<th>Proportion of average annual national reduction</th>
<th>Average annual change in emissions per hectare (kg CO₂eq ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inland</td>
<td>0.52</td>
<td>−415,395</td>
<td>0.00</td>
<td>0.00</td>
<td>−9,213</td>
</tr>
<tr>
<td>Haihe</td>
<td>0.58</td>
<td>−2,346,338</td>
<td>0.01</td>
<td>0.01</td>
<td>−11,248</td>
</tr>
<tr>
<td>Songliao</td>
<td>0.46</td>
<td>−13,522,372</td>
<td>0.10</td>
<td>0.08</td>
<td>−7,116</td>
</tr>
<tr>
<td>Huaihe</td>
<td>0.55</td>
<td>−30,545,538</td>
<td>0.13</td>
<td>0.18</td>
<td>−12,729</td>
</tr>
<tr>
<td>Huanghe</td>
<td>0.58</td>
<td>−1,674,906</td>
<td>0.01</td>
<td>0.01</td>
<td>−8,349</td>
</tr>
<tr>
<td>ZhuJiang</td>
<td>0.58</td>
<td>−78,540,207</td>
<td>0.17</td>
<td>0.46</td>
<td>−25,232</td>
</tr>
<tr>
<td>Southeast</td>
<td>0.53</td>
<td>−26,681,240</td>
<td>0.08</td>
<td>0.16</td>
<td>−17,640</td>
</tr>
<tr>
<td>Changjian</td>
<td>0.56</td>
<td>−16,825,005</td>
<td>0.48</td>
<td>0.10</td>
<td>−1,899</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.44</td>
<td>−996,033</td>
<td>0.02</td>
<td>0.01</td>
<td>−3,257</td>
</tr>
</tbody>
</table>

Source: Li et al. (2006).

These mitigation options are applied to EPA (2006) baseline emission projections for the 2000–2020 period. The percentage emission reductions, and incremental net cost per tCO₂eq, for each option in each region are drawn directly from, or calculated based on, either Gerbens (1998), Bates (2001), Johnson et al. (2003a, 2003b), or personal communication with Johnson.

3.4. Manure CH₄ mitigation options

All manure CH₄ mitigation options included involve the capture and use of CH₄ through anaerobic digesters. Anaerobic digesters are currently in limited use, though primarily as a means of controlling odor and pathogens. The types of digesters are aggregated based on a categorization from EPA’s AgStar program. These options are applied to the estimated share of baseline emissions from swine and dairy cattle. Methane reduction efficiencies and capital costs are taken from Bates (2001) for non-U.S. regions. Revenues (or cost savings) are generated from the use of captured CH₄ for either heat or electricity on the farm. Revenues are scaled to other regions based on a U.S. Energy Information Agency (EIA, 2003) electricity price index.

4. Results

We generate estimates of net GHG mitigation potential and costs for 36 different world regions for each agricultural emission category, and construct marginal abatement cost curves for each region and for the world for 2000, 2010, and 2020. Owing to space constraints, we present a limited number of representative global results here. We find major differences in these curves across regions and time due to differing baseline emissions, biophysical soil and crop conditions, and potential for mitigation, confirming the importance of considering heterogeneity.

Even within a country, the baseline emissions per hectare and percentage and absolute reductions in emissions from adoption

Source: Li et al. (2006).

Fig. 1. Impacts of alternatives on net GWP for rice cultivation in China, 2000–2020.
of a single mitigation option can differ significantly, as shown in Table 1 for shallow flooding in nine regions of China. Reductions in net GHG emissions per hectare range from 1,899 kgCO₂eq in Changjian to 25,232 kgCO₂eq in ZhuJiang. Fig. 1 shows, again for China, changes in the baseline over time as well as in emissions attributable to the mitigation options. In some cases, mitigation options are estimated to increase emissions relative to the baseline in some regions. This is generally due to offsetting interactions among GHGs; these options are removed for construction of the marginal abatement cost curves unless they temporarily increase emissions and then lead to a decrease.

Fig. 2 shows the globally aggregated marginal abatement curve for soil management GHG mitigation. Over 25% of baseline emissions are mitigated at less than $40/tCO₂eq, but costs begin to rise rapidly beyond that point. Negative costs result from options with cost savings due to more efficient fertilizer application that more than offset any revenue losses from lower yields, whereas high-cost options are those for which yields fall substantially in response to suboptimal fertilizer applications. Negative cost options are consistent with previous studies finding large potential agricultural mitigation from “no-regrets” options, but the fact that farmers are not adopting options that seemingly would increase profitability indicates that there may be costs and barriers to adoption that are not being captured in this analysis.

Fig. 3 provides similar curves for rice cultivation. There is a large outward shift between 2000 and 2010. This primarily reflects the large decrease in net emissions over the first decade after implementation of several options having dynamic impacts on soil C. Changes in baseline emissions, commodity prices, labor rates, and other factors also contribute to this shift over time. Total global mitigation for rice cultivation is estimated to be above 20% in 2010 and 2020 at about $10/tCO₂eq. After that level, costs rise very rapidly.

Total global mitigation for livestock management is estimated to be about 10–12% at $50/tCO₂eq (Fig. 4). If other GHG benefits were included (e.g., soil C increases, cropland N₂O reductions for less feed), the mitigation estimates would be higher, but no model was identified to allow estimation of multigas impacts for livestock analogous to the DNDC and DAYCENT models used for soil management and rice cultivation.
5. Conclusions

This study contributes estimates of the potential for and costs of global agricultural GHG mitigation. There are many challenges in developing these estimates due to the high degree of heterogeneity in management practices and resultant emissions in the agricultural sector. Our unique combination of biophysical process-based models, consistent global data sets (to the extent possible), and disaggregated crops and irrigation conditions employed in this study allow us to estimate the costs of numerous GHG mitigation options throughout the world, while reflecting multigas effects and making adjustments for changing production conditions. Future research will lead to continued evolution of mitigation estimates for agriculture as data regarding baseline management practices, resultant emissions, net GHG effects of mitigation options, implementation costs, implementation barriers, and agricultural commodity effects are refined.

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