

# GREENHOUSE GAS FLUXES IN TROPICAL AND TEMPERATE AGRICULTURE: THE NEED FOR A FULL-COST ACCOUNTING OF GLOBAL WARMING POTENTIALS

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**Abstract.** Agriculture's contribution to radiative forcing is principally through its historical release of carbon in soil and vegetation to the atmosphere and through its contemporary release of nitrous oxide (N<sub>2</sub>O) and methane (CH<sub>4</sub>). The sequestration of soil carbon in soils now depleted in soil organic matter is a well-known strategy for mitigating the buildup of CO<sub>2</sub> in the atmosphere. Less well-recognized are other mitigation potentials. A full-cost accounting of the effects of agriculture on greenhouse gas emissions is necessary to quantify the relative importance of all mitigation options. Such an analysis shows nitrogen fertilizer, agricultural liming, fuel use, N<sub>2</sub>O emissions, and CH<sub>4</sub> fluxes to have additional significant potential for mitigation. By evaluating all sources in terms of their global warming potential it becomes possible to directly evaluate greenhouse policy options for agriculture. A comparison of temperate and tropical systems illustrates some of these options.

**Key words:** carbon dioxide, carbon sequestration, global warming potential, greenhouse policy, liming, methane, nitrous oxide, soil carbon, trace gas flux.

## 1. Introduction

Potentials for reducing the buildup of greenhouse gases in the atmosphere by sequestering carbon in soil – thereby keeping additional carbon dioxide (CO<sub>2</sub>) out of the atmosphere – have received widespread attention in the past 5 years, and have recently led to the initiation of carbon credit markets (e.g. McCarl and Schneider, 2001; CAST, 2003). In developed regions most of the attention has focused on no-till agriculture (e.g. Lal, 1999) because of its established capacity in many cropping systems and soils to build soil carbon (C) towards levels that existed prior to agricultural conversion (Paul et al., 1997). Recently other means for sequestering soil C have been suggested, including cover cropping and natural fallows that remove land from cultivation for a period of time.

While the focus on soil C and in particular on no-till cultivation systems has been useful for stimulating policy discussions, in some respects it is short-sighted. First, there are other potentials for mitigating greenhouse gas emissions that are commonly overlooked in discussions of policy options. These other potentials can



be as or more effective than soil C capture in many systems, and may be especially suitable for regions and cropping systems for which no-till agriculture is agronomically unsuitable or economically prohibitive. For example, no-till is by definition unsuitable for root crops such as potatoes and groundnuts, and where soil pathogens persist in the absence of soil disturbance. No-till is economically prohibitive where the added operational costs for herbicides and the capital costs of specialized equipment cannot be justified by better yields or are hard to finance – both of these factors are at play in many developing regions of the tropics.

Second, changes in tillage practices may have unanticipated and unwanted effects on other sources or sinks of greenhouse gases. If, for example, soil water conservation associated with no-till were to provide more moisture for nitrifying and denitrifying bacteria as well as plants, then production of the greenhouse gas  $N_2O$  might increase, offsetting some or all of the mitigation potential of carbon storage (Robertson, 1999).

Third and finally, managing systems specifically for soil C storage by boosting the production of crop residues to enhance soil organic matter inputs can be counter-productive. In particular, if greenhouse-gas generating inputs are used to stimulate residue production (if yield increases are not the primary goal), then the mitigation gained with such production can be more than offset by the greenhouse costs of that production (Schlesinger, 1999).  $CO_2$  released during fertilizer manufacture and during the generation of power for irrigation pumps are examples of such offsetting practices (cf. Izaurralde et al., 2000).

The need to include all sources of greenhouse warming potentials in cropping systems is acute – without a complete cost-benefit analysis with respect to a cropping system's capacity to affect the radiative forcing of the atmosphere, it is difficult to judge the appropriateness of one mitigation strategy over another. It is also otherwise easy to overlook additional mitigation options that may be particularly well suited to specific cropping systems or regions, especially for those in the developing tropics.

## 2. Global warming potential

Global warming potential (GWP) provides a means for comparing the relative effects of one source or sink of greenhouse gas against another. By placing all fluxes in common terms, one can directly evaluate the relative cost of, for example, increased carbon storage due to residue production (GWP mitigation) against increased  $N_2O$  from additional fertilizer application (GWP source).

By convention, GWP is measured in  $CO_2$ -equivalents (IPCC, 1996a, 2001). Conversions from other gases to  $CO_2$  are based on the effect of a particular gas on the radiative forcing of the atmosphere relative to  $CO_2$ 's effect. GWP is largely a function of a molecule's ability to capture infrared radiation, its current concentration in the atmosphere, the concentration of other greenhouse gases, and its atmospheric lifetime. All else being equal, a gas molecule with a greater atmospheric lifetime

TABLE I. GWPs of greenhouse gases in agriculture (IPCC, 2001).

Greenhouse gas	Atmospheric lifetime (years)	20-year GWP	100-year GWP	500-year GWP
Carbon dioxide (CO <sub>2</sub> )		1	1	1
Methane (CH <sub>4</sub> )	12	62	23	7
Nitrous oxide (N <sub>2</sub> O)	114	275	296	156

will have a higher GWP than one that cycles rapidly. For example, N<sub>2</sub>O is long-lived relative to CH<sub>4</sub>, the 100-year N<sub>2</sub>O GWP (296 CO<sub>2</sub>-equivalents) is not much different from its 20-year GWP (275 CO<sub>2</sub>-equivalents), whereas the GWP for methane (CH<sub>4</sub>) falls off rapidly over this period, from 62 to 23 CO<sub>2</sub>-equivalents. Likewise, relatively novel molecules with high IR capture capacities will have higher GWPs. Sulfur hexafluoride (SF<sub>6</sub>), for example, has a 100-year GWP that is 22 200 times that of CO<sub>2</sub> owing to its radiative properties, its novelty in the atmosphere, and an atmospheric lifetime of 3200 years.

In general, only three greenhouse gases are affected by agriculture: CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>. Although CH<sub>4</sub> and especially N<sub>2</sub>O are at far lower atmospheric concentrations than CO<sub>2</sub>, their GWPs are sufficiently high that small changes have a disproportionate effect on radiative forcing (Table I). Over a 20-year time horizon, the GWP of CH<sub>4</sub> is 62 while that of nitrous oxide (N<sub>2</sub>O) is 275; this means that a molecule of contemporary N<sub>2</sub>O released to the atmosphere will have 275 times the radiative impact of a molecule of CO<sub>2</sub> released at the same time. Thus, an agronomic activity that reduces N<sub>2</sub>O emissions by 1 kg ha<sup>-1</sup> is equivalent to an activity that sequesters 275 kg ha<sup>-1</sup> CO<sub>2</sub> as soil C.

### 3. Sources of GWP in agricultural ecosystems

Sources of GWP arise from a number of agronomic practices. Some, such as soil CO<sub>2</sub> emission following clearing and plowing and such as CO<sub>2</sub> emitted by diesel farm machinery, are direct sources of CO<sub>2</sub>. Others, such as CO<sub>2</sub> emitted during fertilizer and pesticide manufacture, are indirect. Still others, such as CH<sub>4</sub> emitted by livestock and N<sub>2</sub>O emitted from soil bacteria following cropping, are non-CO<sub>2</sub> based. All must be considered when calculating the total contribution of agriculture to global warming.

Mitigation occurs when existing sources of GWP are reduced. A GWP of zero means that no net GWP is attributable to a particular cropping system or agronomic practice. A negative GWP implies mitigation, but mitigation only occurs when GWP is less than the GWP of the pre-existing cropping condition – regardless of whether the pre-existing, business-as-usual condition was net positive or net negative.

In the remainder of this section we describe the specific sources of GWP in modern cropping systems.

## 3.1. SOIL C CHANGE

Conversion of natural, unmanaged ecosystems to agriculture releases substantial  $\text{CO}_2$  to the atmosphere. The release of  $\text{CO}_2$  from cleared vegetation that is burned or left to decompose is one of the most well-documented and important sources of the atmospheric  $\text{CO}_2$  increase (e.g. IPCC, 2002). Historically, land clearing has been a major contributor to atmospheric  $\text{CO}_2$  loading; today it still accounts for about 25% ( $1.6 \text{ Gt C yr}^{-1}$ ) of the total global  $\text{CO}_2$  loading, which includes  $6.3 \text{ Gt C yr}^{-1}$  from fossil fuel use and cement production (IPCC, 2002). Most of the contemporary flux is from land clearing in tropical regions.

Soil C is also lost upon agricultural conversion. Forests and savannahs newly cultivated tend to lose a substantial fraction of their original carbon content in the decades following initial cultivation (Figure 1). This occurs for a number of reasons: reduced plant residue inputs, tillage-induced soil disturbance, erosion, and the creation of more favorable conditions for microbial decomposition (CAST, 2003). Generally soil C contents stabilize at 40–60% of original pre-cultivation values; the new equilibrium state is a function of climate, soil physical and chemical characteristics, and agronomic management factors such as tillage, crop types and cover, and residue management (Robertson and Paul, 2000).

Because soil represents about 80% of the carbon stocks in terrestrial ecosystems (ranging from 50% in tropical forests to 95% in tundra; IPCC, 2002), the global impact of soil C loss due to agriculture is considerable. Recent estimates suggest that 50–100 Gt C (CAST, 2003) have been lost from soils in the past few hundred years, although higher estimates range to 142 Gt C (Lal et al., 1999).

Soils can also gain carbon. The soil C balance is the net difference between carbon inputs from plant roots and aboveground litter (that remaining after harvest or fire), and carbon loss from microbial respiration and erosion. In agricultural

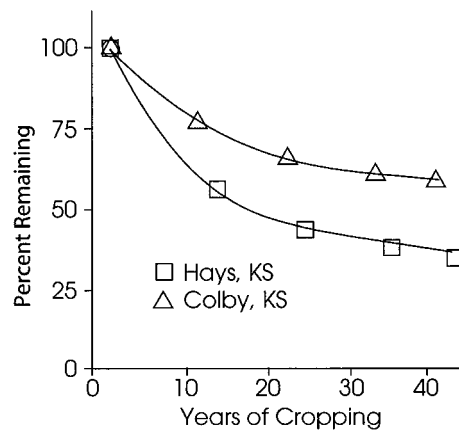


Figure 1. Soil organic matter loss following cultivation at two sites (Hays and Colby, Kansas) in the Midwestern US. Redrawn from Haas et al. (1957).

systems, manure and compost can represent additional inputs. Because erosion repositions carbon in the landscape rather than converts it to CO<sub>2</sub>, erosion is not in itself a source of GWP. Microbial respiration, on the other hand, is a major source of GWP – where respiration is slowed, as in no-till systems, carbon can accumulate at slow but significant rates to some new equilibrium (Paustian et al., 1997).

Estimates of historic soil C loss provide a reference point for carbon sequestration potentials. Models suggest that 60–80% of the soil C lost as CO<sub>2</sub> could be regained under no-till conditions over a period of 50 years (IPCC, 1996a); if this is the case, then as much as 60–85 Gt C could be regained by agricultural soils at a rate of about 1.1–1.7 Gt C yr<sup>-1</sup>. In soils of the US Midwest, the median rate of annual carbon gain under no-till is 30 g C m<sup>-2</sup> (Franzleubbers and Steiner, 2002), which is equivalent to a GWP of –110 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>.

### 3.2. NITROGEN FERTILIZER

The Haber–Bosch process for producing fertilizer nitrogen results in the production of 0.375 mol of CO<sub>2</sub> per mole of N produced at 100% efficiency (Schlesinger, 1999); at normal efficiencies a mole of N is manufactured at a cost of about 0.58 mol of CO<sub>2</sub> (IPCC, 1996b). Additional CO<sub>2</sub> produced during the processing, transport, and application of N fertilizer pushes this value to around 1.4 mol of CO<sub>2</sub> released per mole of N applied (Schlesinger, 1999; Izaurrealde et al., 2000).

Nitrogen fertilizer is thus a significant source of GWP in cropping systems fertilized with synthetic nitrogen. Worldwide, nitrogen fertilizer use is increasing rapidly, especially in developing regions of the tropics (with the notable exception of subsaharan Africa). Rates of nitrogen application vary widely, largely as a function of market availability, crop value, and national subsidies; typical rates in developed regions range from 50 kg N ha<sup>-1</sup> for wheat to 200 kg N ha<sup>-1</sup> for maize. For every 100 kg N ha<sup>-1</sup> that is applied, the GWP cost is 45 g CO<sub>2</sub>-equivalents m<sup>-2</sup>.

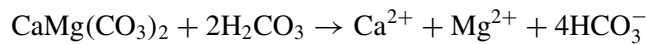
### 3.3. AGRICULTURAL LIME

Agricultural lime in the form of calcium carbonate (CaCO<sub>3</sub>) and dolomite (CaMg(CO<sub>3</sub>)<sub>2</sub>) are commonly applied to agricultural soils to counteract soil acidity. These carbonate minerals are mined from geologic reservoirs, ground, and applied to agricultural soils in humid regions at several-year intervals.

In regions where lime is inexpensive and readily available, lime requirements are estimated based on simple soil tests and generalized relationships, and generally strive to maintain soil pH in the range of 5.5–6.5, depending on the soil and the crop (Coleman and Thomas, 1967; van Lierop, 1990). Most varieties of alfalfa or lucerne (*Medicago sativa*), for example, perform best at pH > 6.5. Additionally, in variable charge soils typical of large areas of the tropics, soil acidity can reduce a soil's cation exchange capacity (CEC) to nil (Uehara and Gillman, 1981; Sollins et al., 1988), and raising the pH can restore CEC. In addition to raising soil pH, liming also

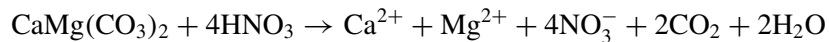
supplies  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  for plant uptake. Additionally, in highly weathered soils the precipitation of reactive  $\text{Al}^{3+}$  by reaction with lime ( $2\text{Al}^{3+} + 3\text{CaCO}_3 + 6\text{H}_2\text{O} \rightarrow 3\text{Ca}^{2+} + 2\text{Al}(\text{OH})_3 + 3\text{H}_2\text{CO}_3$ ) can be as or more beneficial than raising soil pH per se.

Lime applications to neutralize undesirable acidity are commonly in the range of 5–10  $\text{Mg ha}^{-1}$ , and re-application is usually required every few years as the pH drops following fertilizer additions, nitrification, plant harvest, and leaching. As lime dissolves the fate of its carbon is difficult to predict. Carbonic acid formed in the presence of  $\text{CO}_2$  from root and microbial respiration reacts with solid carbonates to consume  $\text{H}^+$ . For dolomite:



In this case, lime weathers to bicarbonate, which is then leached out of the soil profile.

If, on the other hand, carbonate comes into contact with a strong mineral acid such as nitric acid ( $\text{HNO}_3$ ), the end product will be  $\text{CO}_2$  rather than bicarbonate:



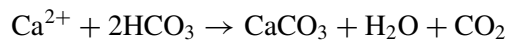
Nitric acid is formed by nitrifying bacteria in most soils (Robertson, 1982) including acid tropical soils (Sollins et al., 1988). Added lime thus seems likely to be a source of  $\text{CO}_2$  where it is applied, but no data is available today to verify this.

The GWP of every metric ton of  $\text{CaCO}_3$  added to soil is thus  $-44$  to  $+44$   $\text{g CO}_2\text{-equivalents m}^{-2}$ ; likewise, the GWP for  $\text{MgCO}_3$  is  $-52$  to  $+52$   $\text{g CO}_2\text{-equivalents m}^{-2}$ .

### 3.4. IRRIGATION

The GWP of irrigation is the result of fuel use during pumping and of carbonate reactions when calcium-saturated groundwater is sprayed on calcareous surface soils (Schlesinger, 1999). For irrigated land in the United States, the fossil fuel cost of pumping totals 22–83  $\text{g C m}^{-2} \text{yr}^{-1}$  (Maddigan et al., 1982), equivalent to a GWP of 81–304  $\text{g CO}_2\text{-equivalents m}^{-2}$ .

In arid regions groundwater often contains as much as 1% Ca and  $\text{CO}_2$ . When this water reaches the surface, the  $\text{CO}_2$  (at 10 000  $\text{ppm}_v$ ) equilibrates with atmospheric  $\text{CO}_2$  (365  $\text{ppm}_v$ );  $\text{CaCO}_3$  precipitates and  $\text{CO}_2$  is released to the atmosphere:



Schlesinger (1999) uses the average water use efficiency of arid-land plants to estimate that the net  $\text{CO}_2$  released from the formation of soil carbonate due to irrigation would be 8.4  $\text{g C m}^{-2}$  annually. This represents a GWP of 31  $\text{g CO}_2\text{-equivalents m}^{-2} \text{yr}^{-1}$ .

### 3.5. FUEL

Diesel ( $C_{16}H_{34}$ ) is 85% C, almost all of which is oxidized to  $CO_2$  when burned. Agronomic activities that are mechanized, including plowing, cultivating, hoeing, spraying, planting, baling, chopping, and harvesting, exact a  $CO_2$  cost. Every liter of fuel (at a density of  $832\text{ g L}^{-1}$ ) releases 706 g C. Annual fuel use of  $100\text{ L ha}^{-1}$  would thus have a GWP of  $26\text{ g CO}_2\text{-equivalents m}^{-2}$ .

### 3.6. NITROUS OXIDE

Nitrous oxide is produced during nitrification and denitrification in agricultural soils. Nitrification is a soil microbial process in which ammonium is converted to nitrite ( $NO_2^-$ ) and then to nitrate ( $NO_3^-$ ) by aerobic autotrophic bacteria collectively known as nitrifiers;  $N_2O$  is a minor byproduct. Denitrification is a soil microbial process in which nitrate is converted to dinitrogen gas ( $N_2$ ) by heterotrophic, facultatively anaerobic bacteria collectively known as denitrifiers;  $N_2O$  is a requisite intermediate that under some environmental conditions and for some denitrifier taxa is the end product (Cavigelli and Robertson, 2000).

Nitrification occurs whenever soil ammonium is available and environmental conditions such as temperature and moisture are favorable for nitrifier activity, which in many agronomic situations prevail most of the time (Robertson, 1982). Denitrification occurs whenever soil C and nitrate are available and oxygen is in short supply – denitrifiers can use nitrate rather than oxygen as a terminal electron acceptor if oxygen is unavailable (Robertson, 2000). This occurs in wet soils when diffusion of oxygen to microsites is slowed by saturated conditions, and inside soil aggregates in even well-drained soils. In the center of aggregates oxygen demand is often greater than can be provided by diffusion through the aggregate from the surrounding soil atmosphere (Sexstone et al., 1985). In general, controls on nitrification and denitrification in tropical soils are no different from those in temperate soils (Robertson, 1989).

Nitrous oxide can also be produced from livestock waste, though only when stored under relatively aerobic conditions such as in compost heaps. Under anaerobic conditions, as in waste lagoons, nitrification is inhibited by lack of oxygen and denitrification by the consequent lack of nitrate; further, any nitrate that is available tends to be denitrified all the way to  $N_2$  rather than stop at  $N_2O$  (CAST, 2003) due to the low availability of electron acceptors.

Of all the sources of GWP in cropping systems, none are more poorly quantified than  $N_2O$  production. This is especially true for tropical agriculture, with the possible exception of lowland rice systems (e.g. Buresh and Austin, 1988; Bronson et al., 1997). This is mainly because of the difficulty with which  $N_2O$  fluxes are measured. Unlike for  $CO_2$  and  $CH_4$ ,  $N_2O$  flux is not suited to micrometeorological measurement (Holland et al., 1999); rather, fluxes must be measured using small chambers placed on the soil surface for 1–2 h intervals. High temporal and spatial

variability means that many chambers must be deployed simultaneously at weekly or more frequent intervals in a given cropping system; sampling and analysis costs are thus high.

However, for the few cropping systems for which we have reliable N<sub>2</sub>O fluxes, N<sub>2</sub>O loss is frequently the major source of GWP. Robertson et al. (2000), for example, found for a 9-year measurement campaign in several annual and perennial cropping systems in the US that N<sub>2</sub>O was the single greatest source of GWP in all four of their annual crop systems, ranging from 50 to 60 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>. IPCC methodology assumes that 1.25% of nitrogen inputs to most cropping systems is subsequently emitted as N<sub>2</sub>O-N; if true, then for every 100 kg N ha<sup>-1</sup> applied as fertilizer, about 1.25 kg N will be emitted as N<sub>2</sub>O, for a GWP (over a 20-year time horizon) of 54 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>.

Soil nitrogen availability appears to be the single best predictor of N<sub>2</sub>O flux in most terrestrial ecosystems including agricultural. Any activity or process that acts to keep available soil nitrogen low should thus lead to smaller N<sub>2</sub>O flux. Plant demand for nitrogen is therefore one of the most important determinants of N<sub>2</sub>O flux, and more precise application of N fertilizer – to maximize plant uptake of added N both spatially and temporally – is one of our most important means for mitigating current N<sub>2</sub>O fluxes from agriculture.

### 3.7. METHANE

Methane is produced by anaerobic bacteria in soil, animal waste, and ruminant stomachs, and agricultural sources of CH<sub>4</sub> are thus a significant fraction of the global CH<sub>4</sub> budget. About 15% of the 598 Tg global CH<sub>4</sub> flux is from lowland rice systems, and another 15% is from enteric fermentation during livestock digestion (Hein et al., 1997; IPCC, 2001). Because methanogenesis is a strictly anaerobic process, under normal conditions upland cropping systems are not a direct source of CH<sub>4</sub>, and CH<sub>4</sub> flux in paddy rice can be partly mitigated through water level and residue management and cultivar selection (Mosier et al., 1998a). Nevertheless, in rice systems CH<sub>4</sub> emissions can be the dominant source of GWP.

Methane is also consumed, but by a different class of soil bacteria, the methanotrophs, and CH<sub>4</sub> consumption in soils is a small but significant part of the global CH<sub>4</sub> budget, comparable in magnitude to the annual atmospheric increase in CH<sub>4</sub>. In rice paddies and wetlands the total CH<sub>4</sub> flux is the net difference between methanogenesis in submerged anaerobic horizons and CH<sub>4</sub> consumption at or above the soil–water interface. In upland soils the net flux appears to be largely a function of CH<sub>4</sub> consumption. Agricultural conversion tends to reduce natural rates of CH<sub>4</sub> consumption in soils by a factor of 5–10 (Bronson and Mosier, 1993; Smith et al., 2000), and at our current state of knowledge there is no known way to restore consumption other than allowing natural revegetation. By attenuating a natural source of mitigation, agriculture thus creates an indirect source of GWP.



Robertson et al. (2000) found for a US Midwest landscape that the GWP of CH<sub>4</sub> oxidation in old-growth forest was  $-25 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ ; for various cropping systems on the same soil type they found GWPs ranging from  $-4$  to  $-6 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ . Similar changes have been documented for a variety of soil and climates (e.g. Smith et al., 2000), including tropical (Keller and Reiners, 1994).

#### 4. A temperate – tropical comparison

There are as yet very few cropping systems for which all significant sources of GWP have been measured. Below we contrast systems from two different regions: a temperate-region maize–soybean–wheat rotation (Robertson et al., 2000) and a tropical rice–wheat–cowpea system in the Indian Indo-Gangetic Plain (Grace et al., 2003). Except for soil C change, GWP values in the Indian systems are estimated based on IPCC methodologies; GWP values for the US systems are measured.

Table II presents GWP values for three Midwest US cropping systems and a late successional forest. In the conventional tillage system N<sub>2</sub>O is the principal source of GWP, accounting for 52 of the system's total of  $114 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ . Contributions of N fertilizer ( $60 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  on average) and agricultural lime were each about half of N<sub>2</sub>O's contribution to total GWP ( $23\text{--}27 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ ), and fuel use accounted for about half again of this ( $16 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ ). Because soil C in this system was equilibrated (at about 1% C), soil C did not contribute to GWP; likewise, CH<sub>4</sub> oxidation contributed very little mitigation capacity, about  $-4 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ .

GWP values in the no-till system were equivalent to those in the conventional system for most sources of GWP except soil C, lime, and fuel. In the no-till system soil C had accumulated at  $30 \text{ g m}^{-2} \text{ yr}^{-1}$ , providing a GWP mitigation of  $-110 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ . Slightly lower fuel costs ( $12 \text{ g CO}_2\text{-equivalents m}^{-2} \text{ yr}^{-1}$ ) were offset by somewhat higher lime

TABLE II. Sources of GWP – in a maize–soybean–wheat cropping system of the US Midwest based on 9 years of measurements (Robertson et al., 2000). The system had been cropped for decades earlier, depleting soil organic matter to 1% C. N<sub>2</sub>O and CH<sub>4</sub> fluxes are measured. N fertilizer was added only to maize ( $120 \text{ kg N ha}^{-1}$ ) and wheat ( $60 \text{ kg N ha}^{-1}$ ) crops. Only wheat residue was removed. GWPs for N<sub>2</sub>O and CH<sub>4</sub> are based on 20-year time horizons using IPCC (1996a) values of 280 and 56, respectively (cf. Table I).

System	CO <sub>2</sub>				N <sub>2</sub> O	CH <sub>4</sub>	Net GWP
	Δ Soil C	N fertilizer	Lime	Fuel			
	(g CO <sub>2</sub> -equivalents m <sup>-2</sup> yr <sup>-1</sup> )						
Conv. till	0	27	23	16	52	-4	114
No-till	-110	27	34	12	56	-5	14
Organic	-29	0	0	19	56	-5	41
Forest	0	0	0	0	21	-25	-4

requirements (34 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>), providing a net GWP for this system of 14 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>, substantially lower than the 114 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup> GWP of the conventional tillage system.

The organic system, which used legumes rather than synthetic fertilizer for nitrogen inputs, was midway between the conventional and no-till systems, having a net systemwide GWP of 41 g CO<sub>2</sub>-equivalent m<sup>-2</sup> yr<sup>-1</sup>. N<sub>2</sub>O flux was the same as in the other systems, but there were neither N fertilizer nor lime inputs in this system, and carbon accumulated at a moderate rate (8 g m<sup>-2</sup> yr<sup>-1</sup>) owing to cover crop residue. The forested system, in contrast, had a net GWP of -4 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup> - soil C neither accumulated nor disappeared, there were no agronomic inputs, and the GWP of N<sub>2</sub>O flux (1.3 g N<sub>2</sub>O-N ha<sup>-1</sup> d<sup>-1</sup> on average for a GWP of 21 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>) was counterbalanced by the GWP of CH<sub>4</sub> oxidation (-9.2 g CH<sub>4</sub>-C ha<sup>-1</sup> d<sup>-1</sup> on average for a GWP of -25 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>).

In Table III is a similar analysis for three rice-wheat-cowpea systems of the Indo-Gangetic Plain in India (Grace et al., 2002). Positive values for soil C in this example indicate loss of soil organic matter over the course of the 20-year experiment - soil C had not yet equilibrated at this site. Rates of soil C loss were similar for conventionally cultivated systems regardless of whether crop residue was burned or retained, indicating that soil microbial activity and burning are equally effective for oxidizing crop residue in these systems. But under no-till cultivation, over 100 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup> were lost each year. However most of the GWP cost of this system is associated with the loss of CH<sub>4</sub> during flooded rice cropping; some 560 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup> are lost during rice cultivation due to CH<sub>4</sub> emission; burning crop residues releases another 167 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup> CH<sub>4</sub>.

It is remarkable that the total net GWP in these systems (893-1189 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>) is an order of magnitude greater than that for the temperate-region maize-soybean-wheat system (Table II; 14-114 g CO<sub>2</sub>-equivalents m<sup>-2</sup> yr<sup>-1</sup>). Three factors unique to the tropical system play into these differences: (1) persistent soil C loss, (2) CH<sub>4</sub> loss during rice cultivation

TABLE III. Sources of GWP - in a rice-wheat-cowpea cropping system of the Indian Indo-Gangetic Plain based on a 20-year trial (Ram, 2000, as reported in Grace et al., 2003). N<sub>2</sub>O and CH<sub>4</sub> fluxes are estimated based on IPCC methodologies. N fertilizer (120 kg N ha<sup>-1</sup>) was added only to rice and wheat crops. Crop residues were either retained or burned, as noted in table. GWPs for N<sub>2</sub>O and CH<sub>4</sub> are the same as for Table II (recalculated from Grace et al., 2003).

System	CO <sub>2</sub>				N <sub>2</sub> O	CH <sub>4</sub>	Net GWP
	Δ Soil C	N fertilizer	Lime	Fuel			
	GWP (g CO <sub>2</sub> -equivalents m <sup>-2</sup> yr <sup>-1</sup> )						
Conv. till, residues burned	229	36	0	26	171	727	1189
Conv. till, residues retained	229	36	0	26	174	560	1025
No-till, residues retained	114	36	0	9	174	560	893

and crop residue combustion, and (3) potentially greater N<sub>2</sub>O fluxes. The greater N<sub>2</sub>O fluxes may be illusory-actual fluxes may be lower than those estimated here because of relatively conservative fertilizer rates. Nevertheless, even if N<sub>2</sub>O fluxes are in fact equivalent, and after soil C equilibrates such that its annual contribution to GWP is nil, these tropical systems will continue to have higher GWP on account of CH<sub>4</sub> produced during rice cultivation and crop residue burning. However, even though the tropical system is not nearly as close to GWP-neutral as the temperate-region system, the 25% reduction in GWP achievable by retaining residues and implementing no-till cultivation is very significant.

This type of analysis is extremely valuable from a policy and management perspective because it shows that in both the temperate and tropical systems mitigation could achieve even greater GWP savings. Cropping systems in both regions could benefit substantially from efforts to mitigate N<sub>2</sub>O production; these efforts could take the form of better nitrogen conservation by basing fertilizer rates on seasonal soil and plant tests, by applying fertilizers closer to the time of crop uptake, by planting cover crops to remove nitrogen from the soil solution during the non-growing season, and possibly by using nitrification inhibitors (CAST, 2003). Significant savings could also result from using nonsynthetic N fertilizers such as leguminous cover crops or manure; by reducing diesel use with either biogas production or better mechanical efficiencies; by managing soil acidity to reduce the need for lime applications; and by using cover crop and other residue management strategies in addition to no-till to increase soil C. Additionally, in the tropical system CH<sub>4</sub> mitigation could take the form of better water, residue, and rice cultivar management.

In all of these cases a whole-system analysis would also serve to identify the value and costs of trade-offs. Such analysis might show, for example, that soil C gained by adding manure or compost to soil might be offset by a concomitant increase in soil N<sub>2</sub>O flux. Only a full-cost, whole-system GWP accounting can fully calculate the true net value of various cropping strategies for greenhouse gas mitigation.

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