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AP42 Section:	9.2.1
Background Ch	4
Reference:	50
Title:	J.M. Duxbury, "The Significance of Agricultural Sources of Greenhouse Gases," *Fertilizer Research,* 38(2):151-163, 1994.

Sect 4 # 50

Fertilizer Research 38: 151–163, 1994.
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The significance of agricultural sources of greenhouse gases

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Received 13 October 1993; accepted in revised form 13 March 1994

Key words: ammonia, carbon dioxide, climate change, greenhouse gas mitigation strategies, greenhouse gas sources, methane, nitrous oxide, sulfur gases

Abstract

The impact of development of land for agriculture and agricultural production practices on emissions of greenhouse gases is reviewed and evaluated within the context of anthropogenic radiative forcing of climate. Combined, these activities are estimated to contribute about 25%, 65%, and 90% of total anthropogenic emissions of CO_2, CH_4, and N_2O, respectively. Agriculture is also a significant contributor to global emissions of NH_3, CO, and NO. Over the last 150 y, cumulative emissions of CO_2 associated with land clearing for agriculture are comparable to those from combustion of fossil fuel, but the latter is the major source of CO_2 at present and is projected to become more dominant in the future. Ruminant animals, rice paddies, and biomass burning are principal agricultural sources of CH_4, and oxidation of CH_4 by aerobic soils has been reduced by perturbations to natural N cycles. Agricultural sources of N_2O have probably been substantially underestimated due to incomplete analysis of increased N flows in the environment, especially via NH_3 volatilization from animal manures, leaching of NO_3^-, and increased use of biological N fixation.

The contribution of agriculture to radiative forcing of climate is analyzed using data from the Intergovernmental Panel on Climate Change (IPCC)(base case) and cases where the global warming potential of CH_4, and agricultural emissions of N_2O are doubled. With these scenarios, agriculture, including land clearing, is estimated to contribute between 28–33% of the radiative forcing created over the next 100yr by 1990 anthropogenic emissions of CO_2, CH_4, and N_2O. Analyses of the sources of agriculturally generated radiative climate forcing show that 80% is associated with tropical agriculture and that two-thirds comes from non-soil sources of greenhouse gases. The importance of agriculture to radiative forcing created by different countries varies widely and is illustrated by comparisons between the USA, India, and Brazil. Some caveats to these analyses include inadequate evaluations of the net greenhouse effects of agroecosystems, uncertainties in global fluxes of greenhouse gases, and incomplete understanding of tropospheric chemical processes.

Extension of the analytical approach to projected future emissions of greenhouse gases (IPCC moderate growth scenario) indicates that agriculture will become a less important source of radiative forcing in the future. Technological approaches to mitigation of agricultural sources of greenhouse gases will probably focus on CH_4 and N_2O because emissions of CO_2 are essentially associated with the socio-political issue of tropical deforestation. Available technologies include dietary supplements to reduce CH_4 production by ruminant animals and various means of improving fertilizer N management to reduce N_2O emissions. Increased storage of C in soil organic matter is not considered to be viable because of slow accretion rates and misconceptions about losses of soil organic matter from agricultural soils.

Introduction

Human activities, including clearing of land for agriculture and agricultural production systems themselves, have increased emissions of greenhouse gases to the extent that scientists are predicting an average increase in global temperature of 2–4°C by the middle of the next century [13]. Increases in temperature

are expected to vary over the globe, perhaps being as much as 8°C higher at northern latitudes in the winter time. Precipitation is expected to increase globally by up to 15% [41] but predictions of future precipitation patterns are conjectural and often contradictory due to numerous uncertainties associated with the complexities of coupled atmosphere/ocean circulation models [45]. Although climate change and its consequences are uncertain, it's potential importance is such that much effort has been given to assessment of the sources and radiative effects of greenhouse gases, and to possible mitigation and adaptation strategies.

Assessments of climate forcing created by greenhouse gases evolved from agriculture have concentrated on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) because these gases are considered to be the most important and because their effects can be reasonably well quantifed with present knowledge. Soil sources of nitric oxide (NO or NO_x) and ammonia (NH_3) have potentially important, but less well understood, effects on climate forcing through their impacts on atmospheric chemistry and dispersal of nitrogen over landscapes. In general, we have a reasonable understanding of the processes and controls on generation of all of these gases and of their emissions at small scales. Emission estimates are less certain at regional and larger scales. We have much less information about the impact of agriculture on emissions of a range of sulfur containing gases that have indirect radiative effects.

In this paper, I evaluate estimated emissions of CO_2, CH_4, N_2O, and other trace gases from agriculture within the context of total estimated anthropogenic emissions of these gases and radiative climate forcing. Analyses by selected countries, agricultural activity, and climate show the wide variance in greenhouse gas emissions as a function of these parameters and point the way for mitigation efforts. I also comment on some of the uncertainties and gaps in our knowledge of agriculture's contribution to radiative forcing of climate.

Contributions of agriculture to anthropogenic fluxes of CO_2, CH_4, N_2O, and other trace gases

Global budgets for CO_2, CH_4, and N_2O are shown in Table 1. Anthropogenic activities contribute an estimated 3, 64, and 24% to global annual emissions of CO_2, CH_4, and N_2O, respectively [7]. Anthropogenic impacts on sinks include a net uptake of 1.7 Gt C yr^{-1} by the oceans due to increased atmospheric CO_2, and an enhanced terrestrial sink strength for carbon, perhaps caused by a feedback response of photosynthesis to elevated CO_2 or because forest harvest has created immature forests. A reduction of CH_4 oxidation by soils has been suggested [37], but no effects on N_2O sink strength are known.

Table 1. Estimated annual budgets for carbon dioxide, methane, and nitrous oxide[1]

	CO_2	CH_4	N_2O
	Tg C		Tg N
Natural Sources			
Aquatic	105,000	15	2.0
Terrestrial	120,000	101	6.3
Anthropogenic Sources			
Agricultural	1,800	154	2.1
Non-agricultural	6,000	116	1.3
Total Sources	**231,800**	**386**	**11.7**
Sinks			
Oceanic Uptake	106,700		
Terrest. Photosyth	120,000		
Atmos. Destruction		375	10.0
Atmos. Increase	3,000	24	3.7
Total Sinks	**229,700**	**399**	**13.7**
Imbalance	**2,100**	**13**	**2.0**
	(sink)	(source)	(source)

[1]constructed from data in [7, 55].

The budgets of CO_2, CH_4, and N_2O have varying degrees of uncertainty and imbalance. The values presented in Table 1 are "best estimate" single numbers for each category; this provides for ease of comparison and discussion, but implies more certainty than actually exists [7, 55]. With this caveat, it can be seen that the budget for CH_4 is reasonably well balanced, while there appears to be an unidentified sink(s) for CO_2 and source(s) of N_2O (see [8] for more discussion of global budgets).

Agriculture and clearing of land for agriculture account for about 25%, 65%, and 90% of total anthropogenic emissions of CO_2, CH_4, and N_2O, respectively [7]. Agriculture is also thought to be responsible for about 55% of the NH_3, 50% of the carbon monoxide (CO) (largely from biomass burning), and probably also makes an important contribution to NO_X released into the atmosphere as a result of human activities [5, 19, 47].

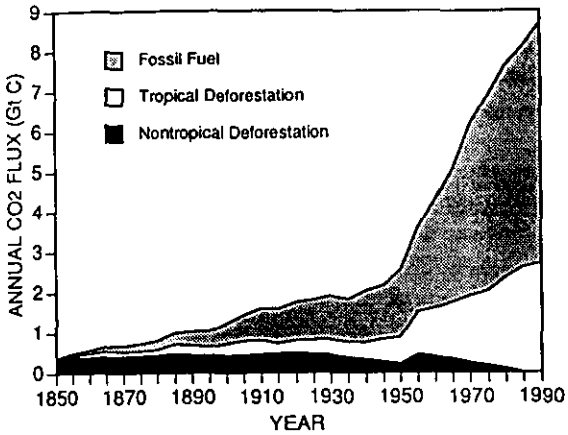

Fig. 1. Carbon dioxide emissions associated with land clearing activities and fossil fuel combustion between 1850 and 1990. Prepared using data from [15, 42, 43, 55]

Carbon dioxide

Combustion of fossil fuels and conversion of land to agriculture are the major anthropogenic sources of CO_2. Conversion of land to agriculture, especially tropical forests, results in loss of stored carbon in tree biomass and soils. The pattern of CO_2 release from these sources between 1850 and 1990 is shown in Figure 1. The most notable feature is the considerable growth in CO_2 release from both fossil fuel combustion and deforestation in the tropics since 1950. Prior to 1920, most conversion of land to agriculture and deforestation occured in the temperate regions of the world [17]. Subsequently, land clearing shifted to tropical Africa, America, and Asia. Current, large scale deforestation is occuring only in the tropics and temperate regions of the world are now small sinks for CO_2 [16].

The data used to construct the deforestation source [15] are considerably less certain (perhaps ± 35%) than the data for fossil fuel sources [42, 43, 55], which are estimated to be accurate to within 10%. The latter data also include a small source for cement manufacture. Using these data, the cumulative release of CO_2 over the last 140 yr from combustion of fossil fuels was 230 Gt C, while that from land conversion to agriculture was 150 Gt C. Two-thirds of the land conversion source 100 Gt C) was associated with deforestation in the tropics. At least 80% of the CO_2 evolved as a result of deforestation is considered to be derived from tree biomass, with no more than 20% due to mineralization of soil organic matter [17].

Carbon dioxide release associated with current deforestation is estimated to be between 1.1 to 3.6 Gt C yr^{-1} [16]. This rather wide range results from uncertainties in rates of forest clearing, the fate of deforested lands (permanent or temporary clearing), and forest carbon stocks. For example, recent studies have shown that deforestation in the Brazilian Amazon in the 1980's was overestimated by a factor of at least 2 [55]. Nevertheless, offsetting factors led the Intergovernmental Panel on Climate change (IPCC) to conclude that its 1990 estimate of 1.6 ± 1.0 Gt C yr^{-1} for CO_2-C release from deforestation was still valid [53, 55]. This quantity is 27% of the 6 Gt C yr^{-1} presently released by combustion of fossil fuels and represents 21% of total anthropogenic CO_2 emissions. It should be noted that the higher estimates of Houghton [15] (presently 2.7 Gt C yr^{-1}; 31% of total anthropogenic emissions and 45% of the fossil fuels source) were used in Figure 1 because these were considered to be the best data.

Although the estimated release of CO_2 to the atmosphere over the last 10 yr is 85 Gt C, the observed increase in atmospheric CO_2 during this time was only 38 Gt C, or 45% of that released. Several hypotheses have been advanced to explain this discrepancy, including overestimation of the deforestation source, underestimation of oceanic uptake, and increased C fixation by natural terrestrial ecosystems [55].

Carbon dioxide emissions associated with the manufacture of agricultural equipment and agrochemicals and with fuel use on farms in developed nations is less than 3% of that generated by other uses of fossil fuel in these countries [3, 19] and therefore is also a minor source compared to conversion of forest lands to agriculture.

Methane

Methane is microbially generated in a variety of anaerobic environments found in agriculture. The estimated 205 Tg CH_4 yr^{-1} (154 Tg C) released to the atmosphere from agricultural sources is derived from enteric fermentation in ruminant animals (80 Tg), paddy rice production (60 Tg), biomass burning (40 Tg), and animal wastes (25 Tg) [55]. Recent research in India [38, 39] caused the IPCC to lower its estimate of CH_4 emissions from paddy rice from 100 to 60 Tg CH_4 yr^{-1} [55], however further measurements under a range of production conditions in Asia are needed to improve estimates of CH_4 emissions from this source.

Atmospheric CH_4, and also CO, are microbially oxidized to CO_2 in aerobic soils. However, constraints

in the physical transport of these gases to the oxidizing organisms [25] limits the contribution of oxidation in soil relative to oxidation in the troposphere by OH radicals. For CH_4, the soil sink strength is estimated to be about 10% of the atmospheric sink strength. Changes in land use, chronic deposition of N from the atmosphere, and alterations in N dynamics of agricultural soils have, however, reduced soil oxidation of CH_4 [22, 36, 46, 51]. It has been estimated that the oxidation of atmospheric CH_4 by soils of temperate forest and grassland ecosystems has been reduced by 30% [37] and recent work showing that snow covered soil continues to oxidize CH_4 suggests that the importance of soil consumption may have been underestimated [53]. Although the soil sink strength is relatively small, it's absence would cause the atmospheric concentration of CH_4 to increase at about 1.5 times the current rate. Effects of agriculture on oxidation of atmospheric CO have not been studied.

Nitrogen oxides and ammonia

Soils are considered to be the the major source of N_2O [55] and NO [56]. Increased emissions of N_2O and NO from soils are associated with fertilizer additions, exploitation of biological N fixation, and enhanced mineralization of soil organic N in agricultural ecosystems. Agricultural emissions of NH_3 (Table 2) largely arise from animal manures [1] and rice paddies fertilized with urea [12]. On a global basis, three quarters of the N_2O emissions are from natural sources, but anthropogenic sources dominate NO and NH_3 emissions (Table 2).

The impact of N_2O on radiative forcing is direct, but the impacts of NO and NH_3 are indirect and more difficult to assess. Nitric oxide participates in a variety of reactions that affect troposopheric levels of ozone (O_3), which is a greenhouse gas, and OH radicals, which initiate oxidative destruction of CH_4 [56]. Volatilization of NO and NH_3 leads to unintended fertilization of landscapes surrounding sources which, together with leaching of NO_3 ions from cropland, undoubtedly cause further anthropogenic emissions of N_2O and also NO. Such effects have not been evaluated, nor are they considered in the IPCC budget for N_2O [55]. This budget is fragmentary since it ignores the grassland biome and major anthropogenic perturbations to the terrestrial N cycle. Significant emissions of N_2O may be ascribed to grasslands [7] which cover a global area almost as great as forest lands 3.1×10^9 ha vs 4.0×10^9 ha). Perturbations to the terrestrial N cycle are largely related to agriculture and are thought, in aggregate, to have increased annual inputs of fixed N by a factor of three (Table 3). By analogy to experience in tropical forests [32], increased N cycling in the terrestrial biosphere would be expected to lead to increased emissions of N_2O and probably also NO.

Measurements of the effect of inputs of fixed N, either fertilizer or organic N, to agricultural lands on anthropogenic N_2O emissions are generally incomplete because the added N is not completely traced through the environment, i.e. off site effects are not considered. Using a dairy farm in the USA as an example, Duxbury *et al.* [7] estimated that only about 20% of the applied N is traced back to the atmosphere although about 80% is estimated to be returned within a decade [33].

Ammonia volatilization from agricultural ecosystems has been estimated to be 40 Tg N yr^{-1} [47], which corresponds to half of the fertilizer N used annually [10]. Volatilization from animal manures is the major source of NH_3 in developed countries because these are the primary N containing product of their agricultures. For example, the annual N budget for agriculture in the USA (Fig. 2) shows that the quantity of animal manure N generated (7.7 Tg N) is equal to the amount of fertilizer N used, while that removed in products for human consumption in the USA is only 1.3 Tg. An additional 2.6 Tg is exported, primarily as grain and animal feed. Although animal manure is recycled to cropland, up to half of the manure N may be volatilized to the atmosphere as NH_3 prior to it's incorporation into soil [1]. In developing countries, the major source of NH_3 is volatilization from rice paddies following application of fertilizer, usually urea. Although the fate of fertilizer N is variable, an overall generalization is that a third of the fertilizer N applied to paddy rice is recovered in the crop, a third is lost as NH_3, and a third is denitrified to N_2 [12].

Perhaps 10% of the NH_3 volatilized to the atmosphere is oxidized to NO [47], while the bulk of the remainder is returned to plant and land surfaces of both agricultural and natural ecosystems. The impact of this large scale fertilization of landscapes on N_2O and NO emissions has not been explicitly addressed. Additionally, the amount of N_2O and NO arising from leached NO_3^- ions, which may average 20–25% of applied N [14], is not known but much may be denitrified in riparian zones and stream beds or cycled through wetland or aquatic vegetation.

Given the incomplete analysis of the impact of N use in agriculture on N_2O emissions, it is probable

Table 2. Estimated global source strengths of ammonia and N oxides. Source [6]

Gas	Global Source Strength		Soil Source Strength		Other Ag.
	Total	Anthropogenic	Total	Anthropogenic	Sources
	——— Tg N yr^{-1} ———				
N_2O[1]	10.2	2.4	7.8	2.1	<0.2
NO[2]	68	40	20	?	?
NH_3[3]	75	50	19	9	32

[1] from [55], using the upper value given for the effect of fertilizer addition;
[2] from [5, 30];
[3] from [47].

Table 3. Estimated annual inputs into the terrestrial N-cycle. Source [6]

Process	Amount
	Tg
Background N fixation	110
New fixation	
Fertilizer manufacture	90
Biological N fixation by legume crops	40
Mobilized by human activities	
Fossil fuel combustion	25
Biomass burning	40
Flux from cleared lands	20
TOTAL	325

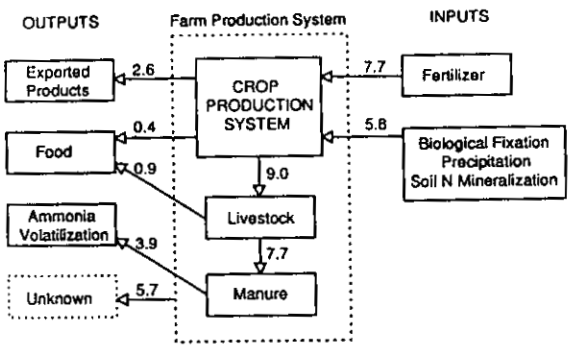

Fig. 2. Annual nitrogen budget (Tg N) for agriculture in the USA. Modified from [1]

that the unidentified source of N_2O, which is equal in magnitude to that already attributed to agriculture [40], is also associated with agriculture. A complete accounting of fertilizer N and N mineralized from soil organic matter, together with assessment of the effects of enhanced biological N fixation, is needed if we are to accurately assess the impact of N use in agricultural ecosystems on radiative forcing of climate.

Sulfur gases

Sulfur containing gases impact the earth's radiative budget through their conversion to sulfate aerosols, which scatter radiation back to space, influence cloud formation, and provide surfaces for chemical reaction [55]. Sulfate aerosols are considered to have a net cooling effect on the earth's climate [18]. A variety of volatile sulfur compounds, including carbonyl sulfide (COS), carbon disulfide (CS_2), and several organic compounds (e.g. methane thiol (CH_3SH), dimethyl sulfide (CH_3SCH_3), and methyl thioacetate (CH_3COSCH_3)) are known to be generated in soils and animal manures, especially under anaerobic conditions [11, 24, 48, 50, 52]. Carbonyl sulfide and CS_2, which is oxidized to COS in the troposphere, are considered to be the most important sulfur containing trace gases because COS migrates to form long-lived sulfate aerosols in the stratosphere. In contrast, sulfur dioxide (SO_2) and other readily oxidized organo-sulfur compounds form tropospheric sulfate aerosols which are quickly washed back to the Earth's surface by rainfall [54].

Biogenic source-sink strengths for COS and CS_2 are not well established but the available evidence indicates that soils are a source of COS and CS_2, while vegetation is a sink for COS [4]. The impacts of agriculture on emissions of these gases are largely unknown, although rice paddies, ruminant animals and animal waste are probable direct agricultural sources. The single report of measurement of COS and CS_2 emissions from rice paddies [21] found similar fluxes

for both gases at levels comparable to those observed for other terrestrial ecosystems [4]. No flux data for emissions of these gases from animals or animal waste handling systems could be found. Indirect effects of agriculture are also likely because nitrogen additions to forest soils have been shown to increase emissions of COS and CS_2 two- to three-fold [34]. Ammonia volatilization from animal manures, rice paddies, and surface placed urea are estimated to add 41 Tg N yr^{-1} to the atmosphere (Table 2), which leads to untargeted fertilization of surrounding natural ecosystems.

Contributions of agriculture to radiative forcing of climate

Relative radiative forcing created by agricultural and non-agricultural activities

The relative impact of additions of different greenhouse gases to the atmosphere on radiative forcing of climate can be assessed by multiplying the global warming potential (GWP) index of a gas by it's source strength [18, 49]. The GWP index combines the radiative capacity and atmospheric residence time of a gas with a time frame of analysis and expresses the result relative to CO_2, which always has a value of 1. Such analyses are limited by uncertainties in both the radiative effects and source strengths of gases and usually only include CO_2, CH_4, N_2O, chlorofluorocarbons (CFC's), and sometimes O_3. The contributions of different activities to global radiative forcing of climate (over a 100 yr time frame) for 1990 anthropogenic emissions of greenhouse gases are shown in Figure 3. Energy use is the dominant contributor to radiative forcing, while agricultural activities account for almost one-quarter of the effect. Roughly two-thirds of the agricultural contribution is attributable to agricultural practices and one-third to clearing of land for agriculture. The contribution of chlorofluorocarbons (CFC's), which are potent and persistent greenhouse gases is also substantial, but future contributions from this source will diminish as use of these chemicals is phased out.

The importance of agriculture as a source of radiative forcing varies amongst countries. In developed countries, with high per capita energy use, agriculture is generally a minor source of greenhouse gases relative to fossil fuel combustion. In contrast, agriculture can be an important source of the radiative forcing generated by less industrialized countries. This situation

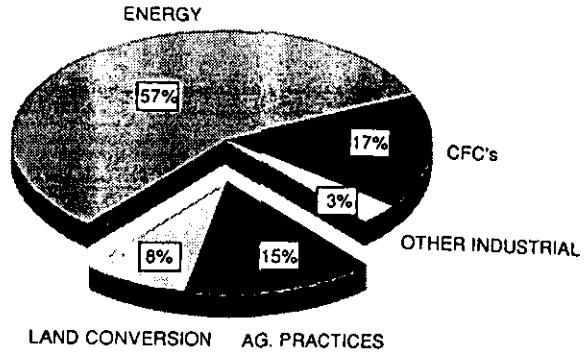

Fig. 3. Relative contributions of different activities to 100yr radiative forcing of climate created by anthropogenic emissions of greenhouse gases in 1990. Calculated using emission and GWP data in [18, 55]

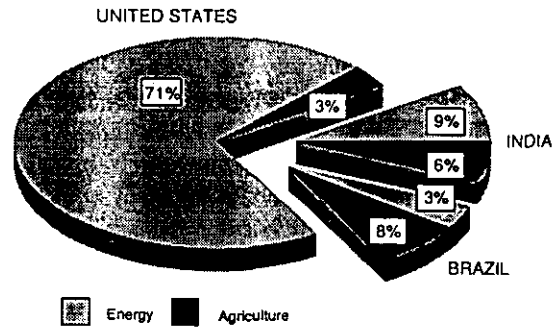

Fig. 4. Relative contributions of agriculture and energy sectors to the combined 100yr radiative forcing created by 1990 anthropogenic emissions of CO_2 and CH_4 in the United States, India, and Brazil. Redrawn from [8]

is illustrated in Figure 4, which shows how the combined radiative forcing generated by the USA, India, and Brazil is distributed by country and how this is further subdivided between each country's agricultural and energy sectors. As a source of radiative forcing, agriculture is a minor contributor in the USA, comparable to the energy sector in India, and the major contributor in Brazil. The radiative forcing created by agriculture in India and Brazil is two and three times, respectively, that created by US agriculture. However, the total radiative forcing generated by the USA is 5 and 7 times that generated by India and Brazil, respectively.

The importance of current emissions of CO_2, CH_4, and N_2O created by agricultural and non-agricultural activities to global radiative forcing over the next 100 yr is shown in Figure 5. These analyses are based on IPCC estimates of source strengths and GWP values [18, 55]. The doubled CH_4 scenario represents the case where the indirect GWP of CH_4 is assumed to be equal

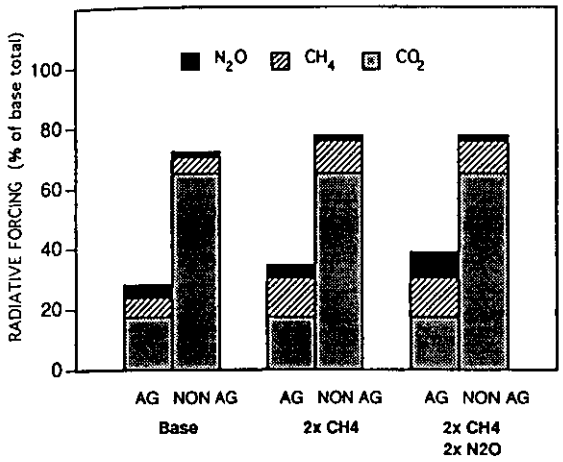

Fig. 5. Relative contributions of anthropogenic emissions of CO_2, CH_4, and N_2O to 100yr radiative forcing created by agricultural and non-agricultural activities. The base case was calculated using emission and GWP data in [18, 55] and the 2x scenarios represent doubled GWP for CH_4 and doubled emissions attributable to agriculture for N_2O

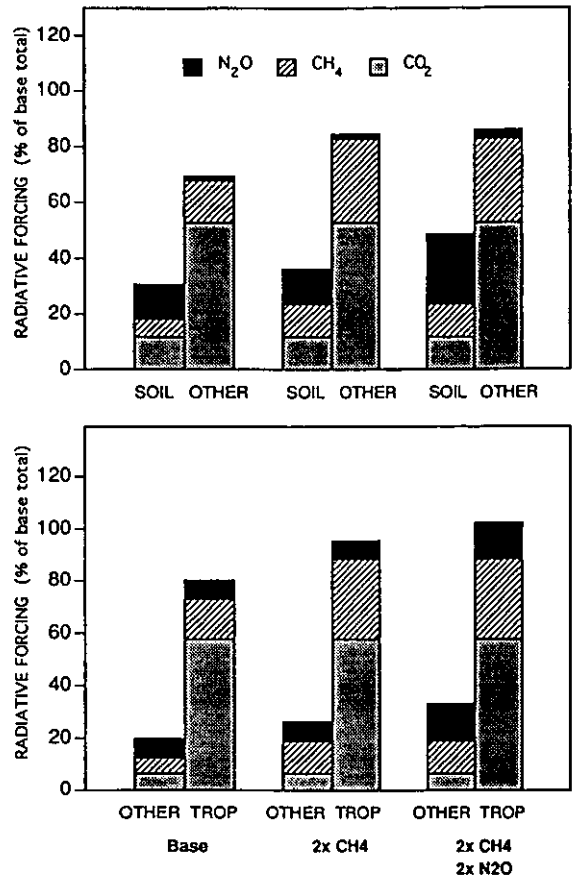

Fig. 6. Distribution of 100yr radiative forcing generative by agriculture in 1990 between soil and non-soil sources and between tropical and non-tropical environments. Scenarios as described in Figure 5. Source [6]

to it's direct GWP. Quantitative evaluation of indirect effects of greenhouse gases is, however, so uncertain that the IPCC withdrew it's earlier estimates of indirect GWP values [18]. It is known that the several indirect effects of CH_4 are positive, i.e. they increase the GWP of this gas, and they may generate a GWP similar to that of the direct effect. Carbon dioxide and N_2O do not have significant indirect effects. The additional radiative forcing created by the doubled CH_4 scenario is roughly equally divided between agricultural and non-agricultural activities. The doubled N_2O scenario assumes that the unknown N_2O source is associated with agriculture and so increases the radiative forcing created by agriculture.

The results of these radiative forcing analyses show that the combined effects of agricultural practices and land clearing contribute between 28–33% of the radiative forcing generated by present emissions of the three gases considered. Neither of the alternative scenarios have a large effect on the importance of agriculture to total radiative forcing. Carbon dioxide emissions from fossil fuel combustion are the dominant source of radiative forcing created by the non-agricultural sector. Emissions of CO_2 associated with conversion of land to agriculture are the most important agricultural contributor in the base case, however both CH_4 and N_2O become important contributors in the doubled CH_4, doubled N_2O scenario which likely represents the upper limit of the agricultural contribution. The latter scenario also causes overall radiative forcing due to agriculture to increase 16% above the base case.

Origins of greenhouse gases associated with agriculture

Table 4 shows 1990 estimated emissions of greenhouse gases from agricultural sources broken down by soil and non-soil sources and by tropical and non-tropical agroecosystems. This data was coupled with GWP indices to compare the relative radiative forcing created by these agricultural categories using the methodology described in the preceding section.

Figure 6a shows that about one-third of the anthropogenic radiative forcing attributable to agriculture is associated with soil sources of greenhouse gases, while two-thirds is from non- soil sources. The principal non-soil sources of greenhouse gases are CO_2 emissions

Table 4. Estimated emissions of greenhouse gases from agricultural sources in 1990. Source [6]

Gas	Total	Temperate	Tropical	Soil	Non-soil
		Tg yr^{-1}			
CO_2	6527	660[1]	5867	1173	5354
CH_4	198	57	141	60	138
N_2O	5.3[2]	2.6[3]	2.6[3]	4.7	0.6

[1] fossil fuel use on farm and for manufacture of farm chemicals;
[2] using the high end of the range given by IPCC for emissions from fertilizer [55];
[3] based on equal use of fertilizer N by countries in temperate and tropical regions.

associated with conversion of tropical forests to agriculture and CH_4 emissions from ruminant animals and animal wastes. Figure 6b shows that 80% of the radiative forcing created by agriculture arises in tropical agroecosystems. Of the three gases considered, CO_2 emissions associated with agricultural development are a major component of radiative forcing attributable to tropical agroecosystems. Methane emissions from ruminant animals and rice paddies are also important, but N_2O emissions are of minor importance, except in the scenario with doubled N_2O. Essentially all of the soil sources of CO_2 and CH_4 are from tropical environments. Given faster N cycling in the tropics and the fact that more than half of global fertilizer N use is in developing countries [10], it is likely that at least half of the N_2O emissions from soils would also come from tropical soils.

Uncertainties

Net effects of agroecosystems

Most studies of greenhouse gas emissions from agricultural ecosystems have concentrated on a single gas, measured only a part of the system, and, as noted earlier, ignored off site effects. Consequently, there is a need for more complete assessment of the effects of various agricultural ecosytems on greenhouse gas emissions and radiative forcing of climate. Such assessments should consider all factors that affect greenhouse gas fluxes, both to and from the atmosphere, to derive a net radiative forcing effect for a particular type of agriculture or agricultural setting. Tradeoffs between different greenhouse gases and establishment of representative baseline fluxes from/to the natural ecosystem(s) that agriculture replaced are two important factors to address.

A rice paddy will be used to illustrate the complexities involved in a comprehensive study. First, a tradeoff between emissions of CH_4 and N_2O may well occur depending upon water management. Strongly reducing conditions and a high proportion of anaerobic soil volume favor CH_4 generation and emission but favor reduction of N_2O to N_2, whereas less reduced conditions and a low proportion of anaerobic soil volume favor oxidation of CH_4 to CO_2 and N_2O escape to the atmosphere, rather than reduction to N_2. Fluxes of both CH_4 and N_2O should therefore be measured under a range of conditions that represent farm water management practices. Particular attention should be paid to times when water status is changing, including the initial flooding and final draining periods. Additional factors that need to be assessed include the effect of soil type on CH_4 and N_2O emissions (acid soils appear to have lower emissions of CH_4 but higher emissions of N_2O), the relative effects of different straw management practices (burning releases a range of greenhouse gases and reactive products while incorporation leads to increased CH_4 emissions), emissions and radiative consequences of emissions of sulfur gases and NH_3, effects on oxidation of atmospheric CO, and the impact of different management practices on storage of carbon in soil.

Global flux, estimates

The agricultural contribution to radiative forcing of climate is composed of three main components, namely CO_2 emissions associated with conversion of land to agriculture, CH_4 emissions from animals and animal wastes, and emissions of various greenhouse gases from soils. The high level of uncertainty in the former [16] has already been mentioned. Global estimates of greenhouse gas emissions from soils are also uncertain because they are extrapolated from measurements

made at small scales (< $1m^2$), where fluxes are highly variable in space and time [35]. The recent development of selective, fast response gas detection systems, such as tuneable diode laser infra-red spectrophotometry, will allow use of micrometeorological methods for field scale measurements. While these measurements will clearly be an improvement over chamber methodologies, they will not supplant the need for flux prediction to be based on an understanding of controlling variables, i.e. they may only help to define the extent of variability amongst sites. Global estimates of greenhouse gas emissions from soils will ultimately have to be made using models, and experimental means of validating these will need to be devised.

Estimates of CH_4 emissions from animal based agricultures are perhaps the most certain of the three agricultural components, although these are also based on extrapolation from small scale studies [29, 44]. Continued efforts are needed to improve estimates of greenhouse gas emissions from all three agricultural components of radiative forcing of climate.

Tropospheric chemistry

Tropospheric chemical processes have a large impact on the Earth's radiative budget, but their effects are much less certain than the direct radiative effects of greenhouse gases. Emissions of CH_4, CO, and NO_x are particularly relevant to the chemistry surrounding tropospheric O_3 and OH radicals. The level of tropospheric O_3 is controlled by a complex set of reactions and feedbacks that are temporally and spatially variable. Ozone is generated in the troposphere by a series of reactions involving photo-oxidation of CO, CH_4, and non-methane hydrocarbons in the presence of NO_x. Reaction outcomes vary with reactant concentrations; at NO_x concentrations < about 10pptv, the net result is a decrease in tropospheric O_3 and OH radicals, whereas production of O_3 and OH radicals occurs at higher NO_x levels. Additionally, feedbacks between O_3, its precursor gases, and OH radicals introduces self-regulation of both O_3 and CH_4. Elevated levels of O_3 and NO_x enhance production of OH radicals, which in turn oxidize CO and CH_4 with consequent reduction in O_3 generation [7]. Current evidence indicates that NO_x emissions, primarily from nitrification in soils are large enough to influence local and regional atmospheric chemistry. Nitrogen fertilized soils appear to be a major source of NO_x and emissions from agricultural fields may dominate NO_x production in agricultural regions during the cropping season [56].

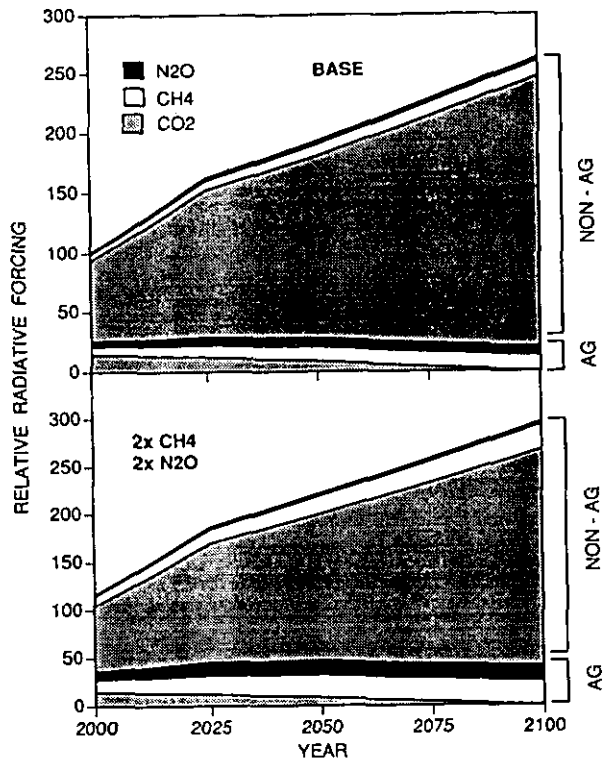

Fig. 7. Relative radiative forcing associated with projected future anthropogenic emissions of CO_2, CH_4, and N_2O under IPCC scenario IS92a [28] for agricultural and non-agricultural sources. The base case was calculated using emission and GWP data in [18, 55] and the 2x scenarios represent doubled GWP for CH_4 and doubled emissions attributable to agriculture for N_2O

Future scenarios

The IPCC has made projections of greenhouse emissions for several future growth patterns [28]. Projections for the IS92a scenario, which is a moderate growth case (2.3 - 2.9% annually) that includes a phase out of CFC's, are shown in Figure 7. In the base case, which is the IS92a scenario, it can be seen that the total radiative forcing created by emissions of CO_2, CH_4, and N_2O from agriculture is expected to drop in the future, while that from the non- agricultural sector is expected to increase sharply. The decline in the agricultural source is due to a decrease in deforestation over time until, in fact, reforestation creates a net sink for atmospheric CO_2. In contrast, fossil fuel use and CO_2 emissions from the non-agricultural sector are expected to increase continuously. Agricultural emissions of CH_4 and N_2O are expected to rise as food production is increased to meet the needs of a popu-

lation that is expected to grow from the present 5.5 billion to 11.3 billion by 2100. Consequently, radiative forcing created by agriculture increases somewhat over time in the doubled CH_4, doubled N_2O scenario. It is clear, however, that the importance of agriculture to future radiative forcing will decline relative to the non-agricultural sector. The contribution of agriculture to projected radiative forcing in 2100 is 7–14% of the total, compared to 28–33% at present.

Mitigation strategies and options

A two-fold approach to mitigation of greenhouse gas emissions is suggested; mitigation efforts should target major sources of radiative forcing and should consider the essentiality of activities creating radiative forcing. These criteria lead to the conclusion that the major mitigation effort should be aimed at reducing use of fossil fuels, but some effort to reduce greenhouse gas emissions from agriculture is justified.

To be effective, efforts to reduce greenhouse gas emissions from agricultural sources will have focus on the tropical environment because 75–80% of present agricultural radiative forcing is attributable to tropical agriculture (Fig. 8b). Analysis by gas gives varying results depending on the scenario used. If the doubled CH_4, doubled N_2O scenario is considered the most appropriate, an argument could be made to address all three gases as their relative contributions to present radiative forcing are 47% for CO_2, 32% for CH_4, and 21% for N_2O.

Although CO_2 release associated with deforestation in the tropics is the largest single source of agricultural radiative forcing, the deforestation issue is largely socio-political and as such is beyond the realm of the agricultural sciences; there is certainly no justification for large scale clearing of humid tropical forests from a food production perspective. Perhaps the best that agroecology can hope to achieve is to stabilize forest clearing as by increasing agricultural production on already cleared lands so that local food needs are met. Such a strategy would require that inputs needed to do so become accessible to resource poor farmers and that limits be placed on new settlement.

Interest is presently being given to the possibility of increasing carbon sequestration in soils. Interest in this approach stems from the knowledge that the organic carbon levels of surface soils generally show substantial decreases after conversion of land to agriculture, and it is estimated that up to 20% of the CO_2 evolved following deforestation may be due to mineralization of soil organic matter. However, this approach is unlikely to be successful because of unfavorable dynamics of organic matter accumulation (see below). Moreover, the extent of soil organic matter mineralization in agricultural lands has probably been greatly overestimated due to inappropriate methodologies used in assessment of soil organic matter loss and failure to consider the impact of soil erosion on carbon storage at the Earth's surface. Fuller discussion of this topic can be found elsewhere [6, 8]. It is sufficient to state here that accelerated erosion of soils from agricultural lands may actually have led to increased storage of carbon at the Earth's surface instead of loss of carbon as is widely assumed.

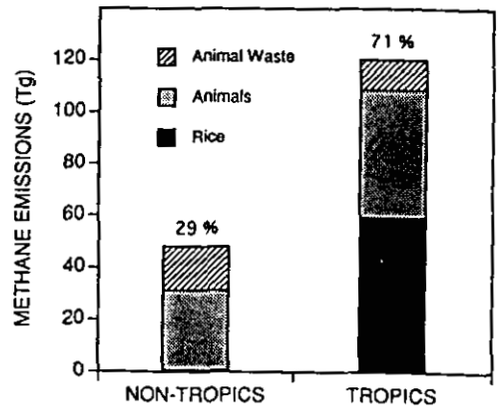

Fig. 8. Distribution of agriculturally derived emissions of CH_4 between tropical and non-tropical environments. Source [6]

Soil organic matter levels in cultivated soils can be increased by adoption of conservation tillage practices, but much of the literature describing such increases suffers from the same methodological inadequacies found with measurement of soil organic matter loss. The few studies that can be used to determine carbon sequestration rates show gains between 0.22–0.5 t C ha^{-1} yr^{-1} [20, 31], which would do little to offset anthropogenic releases of CO_2. A similar conclusion was reached in a study of the carbon sequestration benefits associated with large-scale adoption of no-tillage agriculture in the USA [23].

Mitigation of CH_4 emissions is likely to prove more feasible. About 70% of the agricultural sources of CH_4 are attributable to tropical agriculture (Fig. 8), with half coming from animals and their waste and half from paddy rice. The bulk (70%) of the CH_4 generated by animals is derived from cattle [29]. The amount of CH_4 produced by these animals varies with the qual-

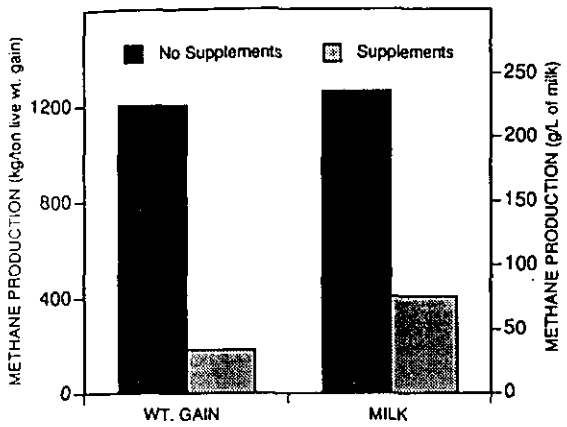

Fig. 9. Effect of dietary supplements (urea, bypass proteins, and minerals) on CH_4 production by cows fed low quality forages. Source [29]

ity of feed, ranging from about 8% of the digestible energy for a high protein diet to 16% of the digestible energy for low quality forage. The effect of diet on CH_4 emissions can, however, essentially be eliminated by the use of dietary supplements, including urea, bypass proteins, and mineral nutrients [29]. Dietary supplements also improve animal growth and health and substantially reduce CH_4 emissions per unit of product, e.g. live weight gain or milk production (Fig. 9). Consequently, both emissions per animal and the numbers of animals needed to sustain a given level of productivity can be reduced [29].

Options identified to reduce methane emissions from rice paddies include cultivar selection and development, and changes in nutrient and water management [2]. Care must be taken to fully evaluate the impact of proposed mitigation practices, as previously noted. Conflicts may also arise as agriculturalists seek to improve the productivity and sustainability of rice based production systems. For example, attempts to improve the soil environment for crop growth by increasing organic residue inputs and practices such as legume green manuring will enhance emissions of CH_4[26, 27] and possibly also COS and CS_2.

Nitrous oxide emissions from agricultural soils can be minimized through improved N management [3] and improved water management in irrigated agriculture. Available technologies for improved N management include soil testing and computer based expert systems to determine fertilizer N requirements, timing of N application to when it is needed by the crop, multiple N applications, use of cover or intercrops to recover residual N, placement of N deep enough to lower the N_2O to N_2 ratio when denitrification does occur, and use of nitrification inhibitors. Fertilizer source may also offer some mitigation possibilities but high variability amongst studies reported in the literature [9] precludes definitive choices at this time. Research is still needed to determine why fertilizer N recovered at harvest is generally no more than 50% of that applied.

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