The role of soils and land use in the greenhouse effect

A. F. BOUWMAN

International Soil Reference and Information Centre, P.O. Box 353, NL 6700 AJ Wageningen, Netherlands

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Abstract

The major greenhouse gases emitted by soils are CO_2 , CH_4 , N_2O , NO and CO. The annual rise of the atmospheric CO_2 concentration is 0.5 %. Different modelling approaches of the biosphere are compared. The biosphere is at present a small sink of CO_2 due to stimulation of growth by CO_2 . Continued global forest clearing will reduce this absorbing capacity. The CH_4 concentration is rising with 1.1 % per year, caused mainly by increasing areas of rice paddies, production of human wastes, numbers of ruminants, biomass burning and increasing nonbiogenic sources. Atmospheric CO is rising at a rate of 2 to 6 % per year. Its major biogenic sources of N_2O and NO are soils (natural and cultivated), oceans and biomass burning. The increase of atmospheric N_2O and NO is probably due to the increasing area of cultivated land and the global upward trend in the use of chemical fertilizers.

Keywords: greenhouse gases, carbon dioxide, methane, carbon monoxide, nitrous oxide, nitric oxide

Introduction

The earth's atmosphere absorbs thermal (infrared) energy which is emitted by the surface. This trapping of energy by radiative absorbers within the atmosphere elevates surface temperatures by several tens of degrees Centigrade above what they would be in the absence of an atmosphere (Dickinson, 1986a). The trapping of energy is commonly called the 'greenhouse effect'.

Atmospheric gases with absorption bands in the infrared region of the electromagnetic spectrum are called 'greenhouse gases'. The most important greenhouse gases emitted from soils and/or their land cover are carbon dioxide (CO₂), methane (CH₄), carbon monoxide (CO), nitrous oxide (N₂O), nitric oxide (NO) and water vapour. The concentration of several of these greenhouse gases is rising. The contribution of a number of gases to the global warming is compared in Table 1. Pessimistic scenarios predict that a doubling of the concentration of CO₂ and other greenhouse gases will be reached towards the year 2050 (Keepin et al., 1986). Dick-

A. F. BOUWMAN

Туре	Residence time (y)	Annual rise (%)	1985 concen- tration	Radiative absorption potential ⁸	Contribution to global warming (%) ⁹
CO ₂	2 ¹	0.5 ²	345 ppm ²	1	45
CO	$2-3^{3}$	$2-6^{3}$	90 ppb ¹	n.a.	?
CH_4	7-84	1.34	1.65 ppm ⁶	+	10
N ₂ O	$100-200^{5}$	0.25^{5}	300 ppb ⁵	++	5
O_{3}^{10}	$0.1 - 0.3^{1}$	2.0^{1}	n.a. ⁷	+++	5
CFC's ¹¹	65-110 ¹	3.0^{1}	$0.18-0.28 \text{ ppb}^1$	++++	25

Table 1. Atmospheric concentrations of the major greenhouse gases, their rise, residence time and contribution to the global warming.

¹ Ramanathan et al. (1985) (data for 1980); ² Bolin (1986); ³ Khalil & Rasmussen (1984); ⁴ Khalil & Rasmussen (1985); ⁵ Crutzen & Graedel (1986); ⁶ Bolle et al. (1986); ⁷ O₃ varies from 25 ppb at surface to 70 ppb at 9 km (Ramanathan et al., 1985); ⁸ Swart (pers. comm.); $CO_2 = 1$, n.a. = not applicable; + = 10-100, + + = 100-1000, +++ = 1000-1000, ++++ = 10000; ⁹ Calculated for period 1980-2030 with data from Ramanathan et al. (1985); ¹⁰ O₃ = ozone; ¹¹ Chlorofluorocarbons; data presented are for the two major CFC's.

inson (1986b) estimated that such an increase will lead to a global warming of between 1.5 to 5.5 $^{\circ}$ C.

Apart from their role in the atmospheric radiative balance, CH_4 , CO, N_2O and NO are known for their interactions with ozone (O_3). The biogenic sources and sinks of the above-mentioned gases will be discussed in the context of their global budgets. The effect of changing land use on the production of water vapour through evapotranspiration and on the surface heat balance is outside the scope of this paper and will not be discussed.

Global biogenic sources and sinks of greenhouse gases

Carbon dioxide (CO_2)

The emissions of CO_2 by terrestrial biota, including soil emissions and clearing and burning of forests, have contributed significantly to the present atmospheric CO_2 concentration. At present, however, the major source of CO_2 is the combustion of fossil fuels. The estimated CO_2 emission for 1980 is 5.3 Gt C y⁻¹ (Gt = gigaton; 1 Gt = 10¹⁵ g) (Marland & Rotty, 1983). In projections for the year 2050, Keepin et al. (1986) give estimates of the CO_2 emission resulting from fossil fuel combustion ranging between 2 and 20 Gt C y⁻¹ depending on the application of various techniques of improving the efficiency of fuel use. For comparison: the size of the atmospheric CO_2 pool is about 700 Gt C (Goudriaan & Ketner, 1984).

There are two approaches to the assessment of the role of terrestrial biota in the CO_2 budget. First, there are bookkeeping models which account for rates of deforestation and forest volumes and yield the CO_2 release. The best known representatives of this approach are Houghton et al. (1983, 1987) and Detwiler & Hall (1988), who report net biospheric release rates of 1.8 Gt C y⁻¹ and 1.0 Gt C y⁻¹ respectively

Reference	Present release caused by forest clearings	Present net release including increased net primary production	
Bookkeeping models			
Houghton et al. (1983)	1.8-4.7		
Houghton et al. (1987)	1.0-2.6		
Detwiler & Hall (1988)	0.3-1.7		
Dynamic biosphere models			
Goudriaan & Ketner (1987)	7	-0.9	
Goudriaan (1987)		0 to -0.5	
Esser (1987)	2.7	-0.1	

Table 2. Comparison of the annual flux of carbon from terrestrial biota by various authors. All figures in Gt C y^{-1} .

(see Table 2). The release of CO_2 from soils due to forest clearing of 0.1 to 0.3 Gt C y^{-1} (Detwiler & Hall, 1988) and 0.2 to 0.4 Gt C y^{-1} (Houghton, pers. comm.) is included in the above figures. In both estimates the formation of charcoal during burning is accounted for.

Secondly, a number of researchers have developed dynamic models of the global carbon cycle including the CO_2 injection into the atmosphere by fossil fuel combustion and forest clearing, the role of oceans as a CO_2 sink, and the stimulation of growth by CO_2 . Examples are Goudriaan & Ketner (1984), who used a simple matrix of conversions of land use and a 12-layer ocean model, and Esser (1987), who used soil, climate and land use data sets and an ocean consisting of 2 layers, all regionalized on a grid of 2.5° latitude \times 2.5° longitude. The results of both dynamic models suggest that at present the biosphere is a net sink of CO_2 (see Table 2). The CO₂-induced increase of net primary production may be greater than the loss of CO_2 caused by deforestation. Goudriaan & Ketner (1984) postulate that charcoal formation in the process of biomass burning is another important sink of carbon. The point in time where the biosphere turned into a sink of CO_2 is around 1970 according to both dynamic models. Further deforestation however, will repress the CO_2 fertilizing effect (Esser, 1987). The ever decreasing vitality of forests caused by acid precipitation in industrialized regions may also become increasingly important.

The data pertaining to land use change are difficult to obtain and exceedingly difficult to verify, particularly data from developing countries. Estimates of forest destruction range between 10 and 20×10^{10} m² y⁻¹, much of it in the Amazonian region (Henderson-Sellers, 1987). Great controversy exists concerning the nature of changes (permanent clearing versus partial destruction or shifting cultivation; the latter process could account for an even greater extent of forest loss than permanent clearing), while definitional differences add to the difficulty of comparing estimates. Brown & Lugo (1982) reported differences between estimates by various authors of tropical forest volumes of over 200 %.

The annual increase of the atmospheric CO₂ is about 0.5 % or 3.5 Gt C y⁻¹. Gou-

Netherlands Journal of Agricultural Science 37 (1989)

driaan (pers. comm.) estimates that in the absence of other disturbances, an injection of CO_2 into the atmosphere will eventually be partitioned over atmosphere, oceans and terrestrial biota in the ratios 0.11, 0.71 and 0.18; due to lack of time for redistribution at present the oceans absorb a fraction of only 0.4. With a CO_2 injection of 5.3 \pm 0.5 Gt C y⁻¹ from fossil fuel combustion (Marland & Rotty, 1983) and 0.3 to 1.7 Gt C y⁻¹ from forest clearing (Detwiler & Hall, 1988), oceans would absorb 2.1 to 3.0 Gt C annually. The two dynamic biosphere models described above predict an absorption rate of 1.8 Gt C y^{-1} by the oceans in 1980. Using a value of 1.8 Gt C y⁻¹ for oceanic uptake and the high estimates of release rates the budget is balanced with an additional sink of 2.2 Gt C y^{-1} . With the high value for oceanic uptake and low release rates, there is need for an additional source of 0.9 Gt C y^{-1} . If these results are attributed to the biosphere, there is an annual change in net primary production of -1.3 to +3.9 Gt C y⁻¹ (or -2.1 to +6.5 % based on net primary production figures given in Goudriaan & Ketner (1984)). This indicates the uncertainties in the global carbon budget. It also indicates that possibly the fertilizing effect of CO₂ is less important than was assumed by Goudriaan & Ketner (1984) and Esser (1987).

Methane (CH₄)

Methane is formed during anaerobic decomposition of organic material. Thus, inundated soils or soils with an impeded drainage and the intestinal tract of ruminants are potential CH₄ sources. The present global release rate of methane is 329 to 654 Tg CH₄ y⁻¹ (Tg = terragram; 1 Tg = 10¹² g) (Bouwman, 1988), while the size of the atmospheric methane reservoir is about 4400 Tg (Bolle et al., 1986). Estimates of the annual increase of atmospheric methane range between 1.1 % (Bolle et al., 1986) and 1.3 % (Khalil & Rasmussen, 1985). Individual sources are rice paddies (70-170), ruminants (66-90), wetlands (25-70), wastes and landfill sites (30-70), oceans/lakes/other biogenic sources (15-35), termites (2-42), exploitation of natural gas and coal mining (65-75), biomass burning (55-100). Methane fluxes show a very great temporal and spatial variability. Currently, measurements of soil emissions are being carried out in inverted closed boxes. Extrapolation of results from such point measurements to smaller scales is fraught with potential errors.

The growth of the human world population and the annual increase of the area of paddy rice cultivation $(1.1 \% y^{-1} \text{ since } 1935)$ correlate well to the CH₄ increase in the atmosphere. This indicates that atmospheric CH₄ is most likely related to an-thropogenic activities. The increase of methane over the past 200 years is probably due to rising emissions (70 %) whereas a smaller part (30 %) is possibly caused by a depletion of OH radicals (Khalil & Rasmussen, 1985). The latter radicals play a role in the oxidation of (amongst other) methane. Their depletion is caused primarily by the ever larger CO emission from various anthropogenic sources (see below).

Major methane sinks are: reaction with OH radicals in the troposphere (260 Tg y^{-1}), transport to the stratosphere (60 Tg y^{-1}) (Bolle et al., 1986) and oxidation in arid soils (32 Tg y^{-1}) (Seiler, 1984). Clearly sources and sinks are not balanced in this budget.

Carbon monoxide (CO)

CO is not capable of absorbing thermal radiation, but it affects concentrations of OH radicals. This in turn has an effect on radiatively important gases such as CH_4 , O_3 and CFC's. The major sources of CO are known, but their magnitudes are still uncertain. The background concentration of CO is increasing at a rate of 2 to 6 % per year (Khalil & Rasmussen, 1984), but estimates are uncertain due to fluctuations of sources and sinks and the relatively short residence time of CO in the atmosphere. Estimates of global CO emission range between 1270 and 5700 Tg CO y⁻¹ with an average of 2920 Tg CO y⁻¹ (Bouwman, 1988). The major sources are biomass burning (800) (Crutzen, 1983), fossil fuel burning (450) (Logan et al., 1981), oxidation of hydrocarbons including methane (680-2380) (Logan et al., 1981). The primary sinks are oxidation to CO₂ and soil uptake (3000 and 450, respectively) (Crutzen, 1983). Estimates of the global sink strength range between 1960 and 4750 Tg CO y⁻¹ averaging 3600 Tg CO y⁻¹. The model is not completely balanced, indicating the uncertainty in the estimates.

Nitrogenous greenhouse gases (N_2O and NO)

Major sources of nitrogenous oxides are nitrification and denitrification processes. N_2O and NO are intermediate products, which under certain conditions may escape from being further reduced (denitrification) or oxidized (nitrification). With the available data, Bouwman (1988) attempted in his review to estimate the global biotic sources of nitrous oxide. The global N_2O emission from cultivated soils (0.3-28 Tg y⁻¹), natural soils (11-27 Tg y⁻¹), emissions due to biomass burning (1-2 Tg N y⁻¹) and oceans and estuaries (1-3 Tg N y⁻¹) yield a likely total global biogenic emission of 13 to 57 Tg N y⁻¹. For comparison: the global N-fertilizer consumption in 1985 was about 74 Tg N. In the above estimate it is assumed that the emission induced by N-fertilization (0.5-2 % of the N-fertilizer consumption) is included in the flux rate given for cultivated fields. The major non-biogenic source is fossil fuel combustion (1-3 Tg N y⁻¹). All N₂O is eventually transferred to the stratosphere where it reacts with ozone.

As for CH_4 , the major problem of giving global estimates of N_2O fluxes is their extreme spatial and temporal variability. The currently used measurement techniques make their extrapolation a difficult task.

The importance of NO and its relation to N_2O production was recognized in recent years. The production ratio of $NO:N_2O$ is a highly uncertain factor in all such calculations as it is very sensitive to abiotic controls such as oxygen pressure (Levine et al., 1984). Recent research indicates that NO production during nitrification of NH₃ in aerobic soils can exceed that of N_2O (Mosier, 1987). The estimated global NO production in soils is 4-16 Tg N y⁻¹ (Logan, 1983). Other global sources of NO + NO₂ are fossil fuel combustion (14-28 Tg N y⁻¹), biomass burning (4-24 Tg N y⁻¹) and lightning (2-20 Tg N y⁻¹); major sinks are precipitation (12-42) and dry deposition (12-22) (Logan, 1983). Nitric oxide is not able to absorb infrared radiation, but it catalyses various atmospheric reactions in which O₃, CH₄ and CO are involved.

Netherlands Journal of Agricultural Science 37 (1989)

A. F. BOUWMAN

Discussion

One of the major conclusions is that the total budgets of greenhouse gases are relatively well known, but the allocation between the various sources needs to be improved. For this purpose the knowledge of the geographic extent of the major soils, soil conditions and ecosystems responsible for these fluxes needs to be improved. At present, there are no global soil and land use maps or digital data sets which are suitable for this purpose. As was discussed above, most of the global geographic information on land use changes is unreliable.

With regard to CO_2 , all the figures presented in this paper are highly uncertain. The combining of bookkeeping methods with dynamic approaches, as was done in this paper in a very unsophisticated way, will prove helpful in reducing the uncertainties in the estimates of present and predictions of future fluxes of CO_2 .

Important biomes for CH_4 are the natural wetlands, which need to be differentiated according to chemical qualities of the water, vegetation type, characteristics of the peat, water height and climatic conditions; and the areas of wet rice, where more data on soil conditions, land and crop management would form the basis for more reliable flux estimates. Especially natural wetlands in northern areas, where the greatest temperature rises are expected, may in future become much more important sources. Concerning N₂O and CO, geographic information on soil-specific and land conditions responsible for their fluxes needs improving.

For all the minor greenhouse gases (CH₄, CO, N_2O and NO) measurement techniques for average fluxes from large ecologically uniform areas need to be developed.

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