

Emissions of climate forcing gases from tropical soils
Ute Skiba, Jan Dick,
Centre of Ecology and Hydrology, Edinburgh,
Bush Estate, Penicuik, EH26 0QB, UK

Introduction

Atmospheric concentrations of naturally occurring greenhouse gases or climate forcing gases like carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and indirectly carbon monoxide (CO) and nitric oxide (NO), are increasing rapidly. The increase is primarily anthropogenic in nature i.e. the result of human intervention. Activities such as combustion of fossil fuels, urbanisation, agricultural activities and deforestation have all contributed to the increase in these gases. Africa is estimated to contribute 1682 Tg CO₂ (6%), 27 Tg CH₄, (9%), 184 Tg CO (21%), 1.4 Tg N₂O (12%) and 11 Tg NO (10%) of the total global anthropogenic emissions (Oliver & Berdowski, 2001).

Both natural and anthropogenic processes are responsible for the emission of greenhouse gases from soil. The contribution of soils to the global greenhouse gas budget is increasing due to intensification of agricultural practices and conversion of natural to agricultural soil ecosystems in developing countries. At the global scale soils are major sources of the two greenhouse gases N₂O and CH₄. Our knowledge of the role of soils, land management and land use change arises mainly from studies in temperate developed countries in Europe and North America. Little is known of the importance of soil emissions from tropical soils (Albrecht and Kandji, 2003). Studies on tropical soils tend to be concentrated in a few countries in Central and South America, such as Costa Rica and Brazil. Soils, however, are very different in tropical parts of the African and American continents. African soils typically are weathered and have very low organic matter content. Consequently, our knowledge on the role of soil in the African greenhouse gas budget is unsatisfactory and does not provide accurate emission and sink inventories. Accurate data is necessary to formulate sensible mitigation and adaptation policy and allow Africa to take advantage of the international funds established to support such policies (Dessai and Schipper, 2003). Before assessing these issues, we need to know the sources and sinks and processes involved in the emissions of greenhouse gases from soils in Africa. The current knowledge is summarised below.

Nitrous oxide

Of the greenhouse gases reviewed here, N₂O is the only one which is predominately produced in soil. It is also the greenhouse gas with the largest uncertainty in its source strength. Microbial processes in soil are responsible for about 57% (10.2 Tg N₂O-N y⁻¹) of the total annual global emission from all anthropogenic and natural sources. Increasing N inputs to agricultural and natural soils by N fertilisation, N fixation and N deposition have greatly increased emissions from this source in the last few decades (Kroeze *et al.* 1999). Increased N fertiliser usage and N deposition are predicted for African Sahel (Batterbury and Warren 2001). This implies that the countries of Africa

will continue to increase their emissions of N_2O . Unfortunately these are also the countries with the least information on N_2O emissions. The soil processes are however common in all soils and therefore we review the information on all soils as an indication of the factors important to African soils.

N_2O is produced by the biological processes of nitrification and denitrification. The principal variables controlling the rate of N_2O emission from all soil ecosystems are N input to soil, soil water content and the temperature. Nitrogen input to soil by fertilisation, atmospheric deposition, animal manure, biological N fixation, and the stimulation of N mineralisation by ploughing, freeze-thaw cycles and first rainfall to a very dry soil (pulsing effect) will all stimulate N_2O production and emission. However, N_2O is produced only in reasonably moist soils, with a water field pore space $> 40\%$ (Davidson, 1991). At present the IPCC methodology only takes into account the relationship between N_2O and N input, using an emission factor approach. It is assumed that 1.25% of the N applied as synthetic fertiliser, manure or crop residues to agricultural land and 1% of the N supplied by atmospheric deposition to natural soils is emitted as N_2O (IPCC, 1997). These emission factors are based on very limited data, mainly from temperate climates and the same soil emission factor is used both for nitrogen fertilised grassland soil in Alaska and the dry lands of Kenya.

Studies have shown that the timing of fertiliser application, the soil water removal by crops and/or the quantities of plant residues incorporated all influence soil N and water dynamics which effect N_2O production and emission rates (i.e. Rees et al. 1996, Veldkamp et al., 1998). The few data on tropical arid savannah ecosystems suggest that N_2O losses are very low. For example, N_2O emissions from Miombo woodlands are less than $0.4 \text{ kg } N_2O\text{-N ha}^{-1} \text{ y}^{-1}$. Scaled up to the total area occupied by Miombo woodlands (2.7 million km^2) they contribute $0.2 \text{ Tg } N_2O \text{ y}^{-1}$ to the annual African budget (Wuta, 2003).

Soil can also be a weak sink for N_2O , which can occasionally be observed in very wet, waterlogged soils.

Nitric oxide

Nitric oxide is not a greenhouse gas, but is involved in reactions leading to tropospheric production of the greenhouse gas ozone (O_3). The global budget of NO is dominated by fossil fuel combustion, with soils estimated to contribute only one third of the total global emissions ($10\text{-}20 \text{ Tg } N \text{ y}^{-1}$). The same microbial processes leading to N_2O production also produce NO. The same controlling environmental variables influence NO production. However NO is only emitted from freely aerated soils whereas N_2O emission is favoured by organic rich, moist soils. Experimental research in semi-arid African soils suggests that African soils are more likely to be a significant source of NO than N_2O (Dick et al. 2001, Scholes et al, 1997). However, the emission inventories suggests that agricultural emissions of N_2O are 10 times larger than for NO (Olivier and Berdowski, 2001). Such discrepancies must be addressed if accurate emissions from African soils are to be estimated.

Soil is also a small sink for NO; the sink capacity is dependent on the atmospheric NO concentration and wet soils are more likely to act as sinks than dry soils.

Methane

Agriculture, predominately CH₄ emissions from ruminants, is the largest source of CH₄ in Africa, but contributes less than 3% of the global total emission. Soil is estimated to be only a very minor net source of CH₄ in African countries (Oliver & Berdowski, 2001).

Soil is both a source and a sink for CH₄. Methane is produced in anaerobic soils during microbial decomposition of organic matter. Waterlogged soils are the largest source of CH₄. Natural wetlands, including the floodplains in Southern Africa, contribute to 20% (115 Tg y⁻¹) and rice paddies to 10% (60 Tg y⁻¹) of the total global methane emission (IPCC, 2001). Much of the methane produced in the anaerobic soil layer will be oxidised in surface, aerobic soil layers. The net CH₄ emission is therefore a delicate balance between rate of methane production and consumption. Processes leading to increased methane consumption can reduce methane emissions as much as reducing methanogenesis. Organic fertilisers have been shown to increase methane emission. Well-drained soils, including the arid organic-poor soils of Africa, are rarely a source for CH₄. However, in such environments soil-feeding termites can be a significant source of CH₄. Globally they have been estimated to produce 20 Tg CH₄ y⁻¹ (3% of the global total emission) (IPCC, 2001).

Soils sequester a small, but significant quantity of atmospheric CH₄. Globally soils are estimated to oxidise 30 ± 15 Tg CH₄ y⁻¹ (about 5% of the total global CH₄ emission rate) (IPCC, 2001). Methane oxidation is carried out by a group of aerobic microorganisms. The main environmental parameters affecting CH₄ oxidation rates are soil disturbance, N additions, changes in the soil bulk density, soil water content, soil diffusion properties and changes in soil temperature. Methane oxidation rates are inhibited by more than 60% when natural soils are disturbed by cultivation. Recovery rates are slow (>100 years) when natural woodlands are reinstated (Prieme *et al*, 1997). The destruction of primary tropical forests was estimated to reduce the sink capacity for methane by 10-35% (MacDonald *et al*. 1998).

The arid soils in the countries of Africa are unlikely to grow into an important source of CH₄, unless flooding of fertile, organic rich soil for rice production or by natural causes increases drastically. The net CH₄ source strength is more likely increased due to destruction of primary forests and savannas and thereby a reduction of CH₄ oxidation.

Carbon dioxide

The burning of fossil fuel accounts for 90% of all anthropogenic CO₂ emissions (249,965 Tg y⁻¹). Fortunately we cannot measure a comparable increase in atmospheric CO₂ concentrations as about half of the emitted CO₂ is re-absorbed by the vegetation and oceans. Our current global carbon stock in the soil is 2,011,000 Tg and in plants 466,000 Tg. Tropical savannas and

grasslands hold 14% of the global C stock each in plants and soil and tropical forests hold 45% in plants and 10% in vegetation (IPCC, 2001). The carbon storage in soil ranges from very transient (several days) to long term (100 years+). It is important to understand and predict the processes that will mobilise the long-term inert carbon pool in the soil. Land use change to managed ecosystems, soil drainage and soil degradation has turned many soils into important carbon producers. These processes can be counterbalanced through the establishment of tree-based agroforestry practices. In degraded pasture, croplands and grasslands C stocks in the vegetation and soil could be increased by 57 Mg C ha⁻¹ over 20-25 years (50 Mg C ha⁻¹ above ground and 7 Mg C ha⁻¹ in soil) (Sanchez, 2000). In a separate study three alternatives to slash-and-burn: commercial cassava cultivation, improved forest conversion, and stratified agroforestry were shown to reduce C losses by 10, 55 and 75 t C ha⁻¹, respectively. In addition these alternatives also have potential to alleviate rural poverty, protect biodiversity and deflect additional deforestation (Kotto-Same et al. 1997).

Carbon monoxide

Carbon monoxide is an important indirect greenhouse gas, influencing the OH-CH₄-O₃ chemistry. The dominant source of carbon monoxide (CO) on the African continent is the burning of biomass (114 Tg y⁻¹) and biofuel (56 Tg y⁻¹), which is 62% and 30% of the total annual anthropogenic CO emissions from Africa.

Soil is a very minor source and sink of CO. The decay of plant matter in the topsoil is estimated to contribute 2 – 8% to the global annual CO budget. CO production is non-biological. High temperatures enhance CO emissions and the production rate is proportional to the organic matter content of the soil. Thermal CO production from the global topsoil non-woody litter pool was estimated at 40 Tg CO y⁻¹ (<5% of the global total) (Schade and Crutzen 1999). CO is also emitted from degrading dry dead vegetation on the soil surface. The photochemical CO source strength from standing dead plant material and litter in grassland ecosystems and deciduous forests ranges from 20 to 65 Tg CO y⁻¹ (5% of the global total) (Schade & Crutzen, 1999).

A number of microorganisms in the soil can oxidise CO to CO₂ under aerobic conditions. The removal of CO from soil is estimated at 70 Tg y⁻¹ in the tropical regions and at 250 Tg y⁻¹ globally (Graedel and Crutzen, 1993). The oxidation rate is increased by high organic matter content, low soil pH and a reasonably high humidity. However the non-biological CO emissions from tropical soils may significantly outweigh the CO sink capacity of tropical soils.

Land management practices that can increase greenhouse gas emissions in semiarid Africa

Biomass burning

Approximately 40% of all savannas are burned towards the end of the dry season (Yienger and Levy 1995). Biomass burning increases the inorganic N

pools by temporarily removing the plant sink for inorganic N and reducing the microbial sink for N by removing litter with high C: N ratios (Davidson 1991). Soil NO, N₂O and CO emissions have been shown to increase significantly following burning. For example, (Levine et al. 1996) showed, that in a dry savannah in Africa, burning followed by wetting increased NO emissions more than burning or wetting alone.

Yienger and Levy (1995) estimated that biomass burning is likely to account for 0.6 Tg yr⁻¹ of the global biogenic NO emission. However, the severity of the burn and timing of the burn in relation to rainfall events will influence subsequent soil trace gas emissions.

Pulsing (first rainfall after a prolonged dry season)

In climates with distinct wet and dry seasons, the first rainfall on to dry soil has been shown to create a large, but short lived, pulse of CO₂, NO and N₂O emissions, which can contribute significantly to the annual total emission.

The rate of NO, N₂O and CO₂ emission was shown to depend on the quantity of rain. Light rainfall resulted in a brief flush of NO up to 96 µg NO-N m⁻² h⁻¹ within 1 day of wetting but N₂O emissions were negligible. In contrast heavy rainfall produced a flush in N₂O emissions up to 2000 µg N₂O-N m⁻² h⁻¹, but little NO (Dick et al, 2001). Light rainfall from a very dry semi-arid savannah increased CO₂ respiration 5 fold, but a heavy rain event increased respiration rate by an order of magnitude (Zepp et al. 1996). Interestingly, the pulse of NO emission was the same for a nutrient poor and a nutrient rich African savannah (Scholes et al. 1997), and the pulse of CO₂ was the same for a burned and wooded savannah (Zepp et al, 1996).

Land use change

Land use change in tropical countries is mediated by slash and burn practices, deforestation of primary or secondary forests and ploughing of grasslands. These processes all remove the competition for nutrients in soil and will change soil structure and increase soil mineralisation rates. Several studies have shown that such activities lead to short-term increased emissions of the greenhouse gases CO₂, N₂O and NO, but reduce the sink activity for CH₄. For example, studies in South and Central America have shown that, in the short-term, conversion of tropical forests to pasture substantially increases emissions of N₂O. In Costa Rica emissions from young pasture (2 - 10 y) (380 - 580 µg N₂O- N m⁻² h⁻¹) greatly exceeded those from the primary forest (50 - 100 µg N₂O- N m⁻² h⁻¹) (Keller et al. 1993). In contrast, an old cattle-grazed pasture emitted only one-fifth as much N₂O as that from the primary forest during the wet season (8 - 12 µg N₂O- N m⁻² h⁻¹ and 50 µg N₂O- N m⁻² h⁻¹, respectively), and during the dry season the older pasture was a small sink for N₂O (Verchot et al. 1999).

Conclusions

Global society must determine priorities on climate forcing gas emissions under the United National Framework Convention in Climate change (UNFCCC). Science can help by providing data that will foster true comparisons across environmental and social ranges.

Obtaining the basic data is a relatively simple and straightforward process. The current method (IPCC, 1997) is only an approximation; more basic gas emission data is required from tropical soils to verify the numbers estimated from temperate regions. The influence of land management strategies including those planned for mitigation and adaptation policies along with the economic and social driving variables needs to be measured and modelled at a regional or country scale. Ideally this information can then be integrated into regional and global policy for example, by using instruments like carbon trading (Beg et al., 2002). An outline of such a project strategy is given in Appendix 1 to foster discussion on this topic.

The semi-arid soils in Africa are presently important sources of NO and N₂O, and a small source of CO₂ and CO, but a small sink for CH₄. Any processes that stimulate natural soil mineralisation and respiration or the input of mineral and organic N fertiliser will increase NO, N₂O and CO₂ emissions. NO emissions prevail in dry soils and N₂O in wetter, organic rich soils. Increase in mulching is likely to increase CO emissions from soil. However, our understanding of the source and sink strength of African soils is based on very few relevant data. This issue needs to be addressed urgently so that sensible local, international and global mitigation and adaptation policies can be formulated.

References

- Albrecht, A. and S.T. Kandji. Carbon sequestration in tropical agroforestry systems. *Agriculture, Ecosystems & Environment*. In Press, Corrected Proof
- Batterbury, S. and A. Warren (2001). The African Sahel 25 years after the great drought: assessing progress and moving towards new agendas and approaches. *Global Environmental Change*. 11:1-8.
- Beg, N., J.C. Morlot, O. Davidson, Y. Afrane-Okesse, L. Tyani, F. Denton, Y. Sokona, J.P. Thomas, E.L. La Rovere and J.K. Parikh (2002). Linkages between climate change and sustainable development. *Climate Policy*. 2:129-144.
- Davidson, E.A. (1991). Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrogen Oxides and Halomethanes* Eds. J.E. Rogers and W.B. Whitman. American Society for Microbiology, Washington, pp. 219-235.
- Dessai, S. and E.L. Schipper (2003). The Marrakech Accords to the Kyoto Protocol: analysis and future prospects. *Global Environmental Change*. In Press
- Dick, J., U. Skiba and J. Wilson (2001). The effect of rainfall on NO and N₂O emissions from Ugandan agroforest soils. *Phyton-Annales Rei Botanicae*. 41:73-80.

Graedel, T.E. and Crutzen, P. (1993) Atmospheric Change: An Earth System Perspective. Freeman & Co., New York. 446 pp.

IPCC (1997). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Eds. J.T. Houghton, L.G. Meira Filho, K. Lim., I. Trennton, I. Mamaty, Y. Bonduki, D.J. Griggs and B.A. Callander, Cambridge University Press, Cambridge.

IPCC (2001). The scientific basis Eds. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, Maskell, K. and C.A. Johnson. Cambridge University Press, Cambridge. 870 pp.

Keller, M., E. Veldkamp, A.M. Weitz and W.A. Reiners (1993). Effect of Pasture Age on Soil Trace-Gas Emissions from a Deforested Area of Costa-Rica. *Nature*. 365:244-246.

Kotto-Same, J., P.L. Woome, M. Appolinaire and Z. Louis (1997). Carbon dynamics in slash-and-burn agriculture and land use alternatives of the humid forest zone in Cameroon. *Agriculture, Ecosystems & Environment*. 65:245-256.

Kroeze, C., A. Mosier and L. Bouwman (1999). Closing the global N₂O budget: A retrospective analysis 1500- 1994. *Global Biogeochemical Cycles*. 13:1-8.

Levine, J.S., E.L. Winstead, D.A.B. Parsons, M.C. Scholes, R.J. Scholes, W.R. Cofer, D.R. Cahoon and D.I. Sebacher (1996). Biogenic soil emissions of nitric oxide (NO) and nitrous oxide (N₂O) from savannas in South Africa: The impact of wetting and burning. *Journal of Geophysical Research- Atmospheres*. 101:23689-23697.

MacDonald, J.A., P. Eggleton, D.E. Bignell, F. Forzi and D. Fowler (1998). Methane emission by termites and oxidation by soils, across a forest disturbance gradient in the Mbalmayo Forest Reserve, Cameroon. *Global Change Biology*. 4:409-418.

Olivier, J.G.J. and J.J.M. Berdowski (2001). Global emissions sources and sinks. In *The Climate System* Eds. R. Guicherit and B.J. Heij. A.A. Balkema Publishers/Swets & Zeitlinger Publishers, s, Lisse, The Netherlands, pp. 33-78.

Prieme, A., Christensen, S., Dobbie, K.E. and Smith, K.A. (1997). Slow increase in the rate of CH₄ oxidation in soils with time, following land use change from arable agriculture to woodland. *Soil Biology Biochemistry* 29:1269 - 1273.

Rees, R.M., K. Castle, J.R.M. Arah and P.A. Furley (1996). Nitrous oxide emissions from a range of soil-plant and drainage conditions in Belize. In *Advances in Hillslope Processes* Ed. M.G. Anderson, Brooks, S. M., Wiley, Chichester, UK, pp. 347 - 365.

Sanchez, P.A. (2000). Linking climate change research with food security and poverty reduction in the tropics. *Agriculture, Ecosystems & Environment*. 82:371-383.

Schade, G.W. and P.J. Crutzen (1999). CO emissions from degrading plant matter (II). Estimate of a global source strength. *Tellus Series B-Chemical and Physical Meteorology*. 51:909-918.

Scholes, M.C., R. Martin, R.J. Scholes, D. Parsons and E. Winstead (1997). NO and N₂O emissions from savanna soils following the first simulated rains of the season. *Nutrient Cycling in Agroecosystems*. 48:115-122.

Veldkamp, E., M. Keller and M. Nunez (1998). Effects of pasture management on N₂O and NO emissions from soils in the humid tropics of Costa Rica. *Global Biogeochemical Cycles*. 12:71-79.

Verchot, L.V., E.A. Davidson, J.H. Cattanio, I.L. Ackerman, H.E. Erickson and M. Keller (1999). Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. *Global Biogeochemical Cycles*. 13:31-46.

Wuta, M. (2003) Nutrient Dynamics in Miombo Woodlands in Zimbabwe, PhD Thesis, University of Edinburgh.

Yienger, J.J. and H. Levy (1995). Empirical-Model of Global Soil-Biogenic Nox Emissions. *Journal of Geophysical Research-Atmospheres*. 100:11447-11464.

Zepp, R.G., W.L. Miller, R.A. Burke, D.A.B. Parsons and M.C. Scholes (1996). Effects of moisture and burning on soil-atmosphere exchange of trace carbon gases in a southern African savanna. *Journal of Geophysical Research-Atmospheres*. 101:23699-23706.

Appendix 1. Project outline to estimate Climate forcing gases from tropical soils formulated by CEH research team

The following project outline is presented as a discussion document for the meeting. In this project the land uses associated with trace gas fluxes will be simultaneously characterised biophysically and socioeconomically so that the impacts of different land use policies on regional and global greenhouse gas budgets and on the livelihoods of the population can be determined. All stakeholders, policy makers, scientists, local communities etc will be involved in the initial stages to ensure that relevant data is collected and each group will be responsible for ensuring dissemination of the results. This project will quantify the emissions from different land uses in a range of representative ecological zones and will determine the possible impacts of climate change by identifying particularly vulnerable eco-zones. Policy options for mitigation and adaptation will be formulated.

The specific objectives and their 'measurable indicators' are:-

- 1. Identify a range of land uses in savanna and drylands forests that represent a wide range of agroecosystems found elsewhere in the tropics.** Descriptions and locations, land uses and cropping systems of the selected sites within humid to semi-arid regions decided at Planning Workshop.
- 2. Evaluation of the relative socio-economic merits of different land uses for the sustainable livelihoods and food security of subsistence farmers and to determine their impacts on the local and extrapolate to the national economy.** Socio-economic descriptions of the sites and land uses and their impacts on the local economy will be presented in reports to local and international stakeholders, vis à vis their acceptability and applicability of land uses that alleviate or reduce poverty.
- 3. Measure the effects of land use in the tropics on soil fluxes of N₂O and CH₄** 1. Land use specific annual fluxes of soil N₂O and CH₄ measured 2. Provision of a very large database of new land-use specific measurements of tropical N₂O and CH₄ fluxes and the impact of seasonal climate changes and soil management on the magnitude of these fluxes for their ability to mitigate climate change.
- 4. Measure the above and below ground carbon inventory.** Land-use specific inventories of standing carbon stock above and below ground, together with net primary productivity and soil respiration. Together with leaf area index, these parameters will also serve to characterise the agroecosystems.
5. Quantification of spatial variability of land use in the rural landscape and its extrapolation to the regional level. *A quantitative description of the land use mosaic at the level of the village, region and nation.*
6. Scale-up N₂O and CH₄ fluxes from different tropical land uses to regional and global levels. *The regional and global distribution of N₂O and CH₄ fluxes from tropical soils will be determined by revising Intergovernmental Panel on Climate Change (IPCC) methodology using country specific emission factors. The sensitivity and vulnerability of each eco-zone will be determined.*
- 7. Hold workshops in Africa and Europe to integrate all the research findings, and working with a wide range of policy makers, development**

agencies and other stakeholders formulate them into mitigation and adaptation policy options. Reports from policy workshops and other policy related publications.

8. **To disseminate research findings** 1. Use of results by policy makers in Africa and Europe, other stakeholders and scientists. 2. Publication of research findings in scientific journals and presentation at workshops and conferences and to the IPCC, UNFCCC and other interested agencies.

In addition to the above a rounded project would have

9. **Rigorous co-ordination of project to ensure effective integration of a wide range of European and Developing Country skills and knowledge within this complex trans-disciplinary project** – Timely achievement of high quality outputs, within budget.

10. **To provide relevant post-graduate training to developing country scientists.** Enhanced capacity (assessed by award of qualifications) in climate change research methods in national research institutes.