1

Keynote speeches on Africa and Global Carbon Cycle

Greenhouse Gas Inventory in West and Central Africa, constraints and perspectives

Khouma M.[1]

ABSTRACT

Most of African people rely on natural resources for food, fiber, medicines and housing material. These resources are seriously threatened by climate change impacts which main driver is greenhouse gas concentration in the atmosphere deriving from human activities. The sectors of agriculture, land use, land use change and forestry are the main sources of emission of African countries. Inventories of these greenhouse gas emissions besides its mandatory aspect resulting from the United Nations Framework Convention on Climate Change allow a better integration of climate change issues in the development planning process by generating quantified data on most emitting sources of greenhouse gas in order to better allocate financial resources devoted to mitigation and adaptation. The paper focused on key findings from the regional project (14 countries) on quality improvement of greenhouse gas inventories in west and central Africa and data gaps still needed to be filled in terms of activities and emission factors for the sake of quality improvement of these inventories.

Keywords: Greenhouse gas, Africa, Climate change, Agriculture, Forestry, Land use

INTRODUCTION

In the context of their commitments as Parties to the United Nations Framework Convention on Climate Change (UNFCCC,1992), all countries should submit to the secretariat of the convention inventories of greenhouse gas not regulated by the 1987 Montreal Protocol to the United Nations Convention on Protection of the Ozone Layer. For non annex I countries, including all African countries, submission of inventories is part of the National Communication. By Article 4.1paragraph (a) of the UNFCCC, all Parties are obliged to develop and periodically update national inventories of anthropogenic emissions by sources and removals by sinks of all GHGs not controlled by the Montreal Protocol, using comparative methodologies.

African countries are hosting large areas of forest, savannah and grass land and many populations are relying on woody formations for fuel wood, charcoal and forest fruits, building materials and medicine.

For the period 2000–2005, the African share of global emissions from land use change was 17% (Canadell *et al.*, 2009). Land use change and forestry sectors are the most emitting

---

[1] United Nations Development Programme GEF Project RAF 02G31 - B.P. 50037 Dakar R.P. Senegal - khoumamamadou@yahoo.fr

sector in African countries. On average, 55% of CO_2 (equivalent) emissions are from the land use change and forestry (LUCF) sector for West and Central African countries, (UNDP/GEF, 2004) and it is where uncertainties and data reliability are the most critical.

LUCF and agriculture are specially cited for challenges regarding representative and historical activity data collection, and need for additional training on Intergovernmental Panel on Climate Change (IPCC, 1997, 2000, 2003) methods and software.

That's why a regional project entitled "Capacity building for Improving the quality of Greenhouse gas inventories in West and Central Francophone Africa" was funded by the Global Environment Facility (GEF), administered by the United Nation Development Programme (UNDP) and executed by the United Nations Office for Project Services (UNOPS). The Project started in November 2004 for four years.

Participating countries are: Benin, Burkina Faso, Burundi, Chad, Côte d'Ivoire, Gabon, The Gambia, Ghana, Guinea, Mali, Niger, Nigeria, Senegal and Togo.

FIGURE 1
Participating countries

OBJECTIVE

The overall objective of the project is to strengthen the capacity of participating countries to improve the quality of their national greenhouse gas inventories (GHGI) for their national communications. The Project is focussed on reducing uncertainties and improving activity data and emission factors in the LUCF and agriculture sectors. Countries will also use Good Practices Guidance (GPG) to strengthen national arrangements so that, as a result of this project, GHG inventories for future National Communications will be compiled in a sustainable manner and the inventories will be of a higher quality than those prepared for the Initial National Communications.

MATERIALS & METHODS

Generally, the inventory should be structured to follow the reporting requirements of the UNFCCC (UNFCCC, 2002) and it is divided into six main sectors:

1. Energy
2. Industrial Processes
3. Solvent and Other Products
4. Agriculture
5. Land Use Change and Forestry
6. Waste

Emissions and removals of the following direct Greenhouse gases (GHGs); Carbon dioxide (CO_2); Nitrous oxide (N_2O); F-gases (hydro-fluorocarbons (HFCs); per-fluorocarbons (PFCs) and sulphur hexa-fluorocarbons (SF_6) as well as the following ozone and aerosol precursor gases; sulphur dioxide(SO_2); nitrogen oxides (NOx); carbon monoxide (CO); and non-methane volatile organic compounds (NMVOCs) are to be estimated. The relative level and impact of the six major gases is compared using their relative global warming potential (GWP). A GWP is the relative effect of a substance in warming the atmosphere over a given period (100 years in the case of the Kyoto Protocol), compared with the value of one for CO_2.

Project activities are organized into two levels: at regional level, training of trainers workshops are organized. At national level, each regional workshop is replicated by the 14 national coordinators who participated at regional workshops. On average, 12 people are trained in each country during each national workshop.

Several studies are also carried out including the followings:

- Study on archiving compilation and management of national inventory system
- Institutional framework for inventory
- Manual of procedures for Greenhouse gas inventories
- Emission factors improvement
- Quality Control/Quality Assurance (QC/QA) Plan
- Stakeholder awareness campaign
- The expected situation at the end of Project is:
- Quality of inventories improved
- Institutional framework for inventories strengthened
- Long-term strategies for inventories improvement elaborated
- Improvement of data collection and management
- Emission Factors/Coefficients improved and disseminated
- International network of information exchange put in place
- Increased trained experts
- Better sensitization of stakeholders
- Technical peer review system of inventories implemented

RESULTS & DISCUSSION

At the end of year 2008 the Project has organized all planned regional workshops as follows:

- Good Practices Guidance (Accra)
- Inventory Process with UNFCCC software (Niamey)
- Emission Factors improvement (Bamako)
- QC/QA (Libreville)
- Agriculture and Land Use (ALU) Software from the Environmental Protection Agency (EPA) of the United States, (Banjul)
- Peer Review (Abidjan)

During all these workshops, with an average of 35 participants including, hands on training were conducted with data of different sectors and countries.

Improvement through the Regional Project

In the sub sector of enteric fermentation (methane emission from animals) the Project yielded more appropriate figures using tier 2 methodology for cattle. Tier 2 is referred to as an estimation methodology using country specific emission factors. Tier 1 is an estimation methodology based on default emission factors.

We found that for the region the non lactating cows emit more than lactating cows. This is opposite to IPCC default factors stated. Using data from participating countries we have the following emission and conversion factors:

➔ Methane emission from cattle
On average for non lactating cows the methane emission factor is 62.11 Kg / CH_4/year and for lactating cows it is 41.61 Kg /CH_4/year. An uncertainty of ± 50 % is associated to the methodology. This result is consistent with the common practice where lactating cows received more digestible feed of better quality leading to less methane emission

➔ Wood density
From 151 samples of wood an average of 0.7 ton/m^3 is found (SIEF, PROGEDE, 2004).

➔ Carbon content
Carbon content of plants can be situated at 39.2% of the dry biomass and Nitrogen content 0.63, from a study (Picard et al. 2006). See Table 1

TABLE 1
Average Carbon content and Nitrogen content of 4 main species[2]

Compartment	State	C%	N%
leafs	Dry biomass	39	1.34
branches	Dry biomass	39.25	0.29
stems	Dry biomass	39.25	0.25

---

[2] Terminalia macroptera, Combretum glutinosum, Combretum geitonophyllum, Piliostigma thonningii (adapted from Picard et al. 2006)

The carbon content could seem to be low but the results are common in the Sahelian regions and are from 160 samples of the four main species.

➔ Root to shoot ratio for crops:
For root to shoot ratio a value of 0.35 is calculated for millet (Ganry &Cisse, 1994).

Rice =1 for non fertilized and 0.83 for fertilized rice (IRAT, 1968).

➔ Nitrogen content of cattle manure:
From six different locations in Upper East Region (Sudan Savannah Zone) of Ghana, an average of 1.34 % for nitrogen content of manure is found (FAO, 2005).

For institutional aspects under financial support of the project, studies were carried out and measures to make GHGI more sustainable are identified in each country. Data collection barriers are identified and data providers also with the type of data provided, the data format and modalities of data release are documented. In this respect, countries have developed long-term national strategies for improving inventories and enhancing sustainability of the institutional framework, and identify or establish a unit responsible for inventory preparation. Data collection harmonization is done. Information systems on GHGI are now widely spread among participating countries. QA/QC is now in most inventories. Sensitization of stakeholders is done at several levels.

A peer review system was established through a regional workshop where the results were shared by all countries. In this respect participants agreed that it is more realistic to have the peer review on cross country basis taking into account lack of expertise that does not allow having enough inventory experts and reviewers in the same country. The objective was to provide countries with the skill of peer reviewing process. They will use it in the future on cross country basis.

Constraints

Main constraints identified through this regional project are:

- Difficulties related to mobility of trained experts that can leave the process for another job.
- Data Format, most data are not directly usable for GHGI (i.e. crop residue should be estimated using yields minus quantities grazed and quantities taken out the fields).
- Seasonal migration of animal making animal census unreliable.
- Biomass estimate from annual growth rate.
- Fraction of total savannah area burnt annually.
- Combustion ratio (available data don’t reflect most of African countries. There is little data originating from African countries.

Most of these constraints can be addressed by:

- Incentives to national experts with better working conditions.
- Use of satellite images, where feasible, to improve accuracy of activity data (LUCF).
- Emission Factor improvement through funding of regional research projects (i.e. burnt areas, methane from rice cultivation, quantity of nitrogen lost by denitrification).

Experience learned from the Regional Project can be summarized as follows:

- It is easier to improve activity data (AD) than emission factors (EF)
- Data harmonization is very important at national level
- Uncertainties from AD seem to be greater than those from EF
- Having a national unit in charge of GHG inventory is a good start for a sustainable inventory system.

Perspectives

Through the regional Project at least 10 experts are trained in GHGI in each participating country. To make the process sustainable a unit of GHGI should be implemented where it does not exist. The network initiated by the Project will be consolidated to a formal African greenhouse gas inventory Network. Trained experts can put to advantage their skills in activities related to Clean Development Mechanism (CDM) and Reduction of Emission from Deforestation and Degradation where GHGI principles are applied in large.

Reducing uncertainties of activity data at national level is a big step toward improving the quality of GHGI but having a regional research project focused on four to five most common emission factors at regional level could also contribute to the overall quality of inventories.

This regional project should be designed around:

- Methane emission from flooded and irrigated rice fields
- Annual growth rate of forests and savannahs
- Biomass Fraction burnt, Biomass Fraction oxidized (collaboration with CarboAfrica is effective on this issue as some African experts are trained in fire related workshops)
- N_2O emission from denitrification

CONCLUSIONS

During the lifetime of the Project quite all data collection barriers are identified in all countries. For each country main data providers are identified with the type of data provided, the data format and modalities of data release are documented. Strategies for long term improvement of the process of GHGI were elaborated in each country. More than 100 regional experts were trained in GPG and methodology of inventories using UNFCCC and EPA software. Basic inventory teams are in place in most of countries with respect to the preparation of the second national communication. Improvements have been made for some emission and transformation factors. The project outputs need to be consolidated through a regional network of African experts. Further improvement can be envisaged in terms of Regional Research Project on most commonly needed emission factors.

REFERENCES

Canadell J., Raupach M., Houghton R., 2009. Anthropogenic CO_2 emissions in Africa. Biogeosciences, 6, 463–468, 2009. www.biogeosciences.net/6/463/2009/

FAO, 2005. Fertilizer use by crop in Ghana. Land and Plant Nutrition Management Service Land and Water Development Division . Food and Agriculture Organization of the United Nations, Rome, 2005. 52 p.

Ganry F., Cisse L., 1994. Bilan hydrique agricole et sécheresse en Afrique tropicale. De François-Noël Reyniers, Laomaibao Netoyo Ed John Libbey Eurotext, Paris, 1994, p. 262-272.

IPCC, 1997. Revised, 1996, IPCC Guidelines for National Greenhouse Inventories. Houghton J.T., Meira Filho L.G., Lim B., Treanton K., Mamaty I, Bonduki Y., Griggs D.J., Callander B. A. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA, Paris, France.

IPCC, 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, Penman J., Kruger D., Galbaly I., Hiraisi T., Nyenzi B., Emmanuel S., Buendia L., Hoppaus R., Martinsen T., Meijer J., Miwa K., Tanabe K. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/OECD/IEA/IGES, Hayam, Japan.

IPCC, 2003. Good Practice Guidance for Land Use, Land- Use Change and Forestry. Penman J., Gytarsky M., Hiraisi T., Krug T., Kruger D., Pipati R., Buendia L., Miwa K., Ngara T., Tanabe K., Wagner F. (Eds). Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayam, Japan.

IRAT, 1968. Un type d'aliment du bétail trop négligé en zone tropicale : les sous produits de récolte. C. Agr. Pr. Pays Chauds 1968 -1. Cultures fourragères p. 75-82.

Picard N., Ballo M., Dembélé F., Gautier D., Kaïré M., Karembé M., Mahamane A, Manlay R., Ngom D., Ntoupka M., Ouattara S., Savadogo P., Sawadogo L., Seghieri J.,Tiveau D. Évaluation de la productivité et de la biomasse des savanes sèches africaines : l'apport du collectif SAVAFOR. Bois et Forêts des Tropiques, 60(288):75-80.

PROGEDE, SIEF, 2004. http://www.sendeveloppementlocal.com/downloads/

UNDP/GEF, 2004. Project document RAF 02/G31 Capacity Building for Improving the Quality of Greenhouse Gas Inventories (West and Francophone Central Africa). UNDP, New York. 76 p.

UNFCCC, 1992. United Nations Framework Convention on Climate Change. FCCC/INFORMAL/84. GE.05-62220 (E) 200705. UNFCCC Secretariat Bonn, Germany.

UNFCCC, 2002. Decision 17/CP.8: Guidelines for the preparation of the National Communications from Parties not included in Annex 1 to the Convention, Conference of Parties (COP 8) of the United Nations Framework Convention on Climate Change (UNFCCC), held in October-November, 2002. UNFCCC Secretariat Bonn, Germany.

2

Terrestrial Carbon Observations in Africa and Ecosystem fluxes

Ankasa flux tower: a new research facility for the study of the carbon cycle in a primary tropical forest in Africa

Belelli Marchesini L., Bombelli A., Chiti T., Consalvo C., Forgione A., Grieco E., Mazzenga F., Papale D., Stefani P., Vittorini E., Zompanti R., and Valentini R.

Department of Forest Environment and Resources (DISAFRI),
University of Tuscia, via S. Camillo de Lellis, 01100 Viterbo, Italy

ABSTRACT

A new station for the monitoring of CO_2 fluxes over a primary tropical forest in Ghana (Ankasa Conservation Area) is operative as part of the CarboAfrica eddy covariance network. Carbon, water and energy fluxes were measured by the eddy covariance technique, and a soil characterization and a survey on biodiversity were carried out. Preliminary observations of CO_2 fluxes (Fc) integrated at daily scale showed a sink activity of the forest, having a comparable magnitude and daily patterns to those measured over Amazonian tropical forests; however the quantification of non turbulent fluxes needs to be addressed to correctly evaluate the carbon exchanges with the atmosphere of such a complex forest canopy. The carbon content of soil is a significant component of the total carbon content in forest. This area shows high biodiversity, among the highest measured in African tropical forests, and with an interesting presence of rare species. Further data are being collected and a breakthrough in the understanding of the carbon cycling in topical forest ecosystems of Africa is expected.

INTRODUCTION

A new station for the monitoring of CO_2 and energy fluxes over a primary tropical forest in Ghana is operative as part of the CarboAfrica eddy covariance network. The facility, located in the Ankasa Conservation Area (05° 16’ 11.2”N; 02° 41’ 41.55” W), includes a 65 m tall steel tower equipped with a system enabling the measurements of fluxes at the top of the structure, of CO_2, air temperature and humidity along a vertical profile and of relevant physical parameters of the forest ecosystem. The Ankasa flux tower is the first in the African continent collecting data on CO_2 exchanges over a tropical primary forest. after most of research of carbon fluxes in tropical forests was so far conducted in Amazonia (Grace et al.,1995; Mahli et al.,1998) and lately in Asia (Takanashi et al., 2005). The activity of the Ankasa flux tower is expected to shed light on carbon cycling in this kind of ecosystems in Africa and more generally on the ecological feedbacks of tropical forests in respect with climate change.

Parellely to the start of carbon fluxes measurements the following field campaigns were been carried out: i) the soil of the summit in the surroundings of the tower was characterized and the budget of the organic carbon in recognized pedogenic horizons was determined; ii) the vegetation biodiversity in the surroundings of the eddy tower was quantified and the ecological factors influencing biological diversity and biomass distribution were assessed.

STUDY AREA

The Ankasa Conservation Area lies in Southwest Ghana on the border with the Ivory Coast. It covers 509 km^2 (Fig. 1) and it hosts an ancient rainforest and the most biodiverse in Ghana. Ankasa represents the only wet evergreen protected area in almost pristine state, being home to over 800 vascular plant species. The topography is characterized by rugged, deeply divided terrain in the north and west with flatter swampy ground associated with the Suhien watershed in the East. Its maximum elevation is 150 m, though most lies below 90 m. The climate of the area is characterized by a distinctive bi-modal rainfall pattern occurring from April to July and September to November. The average annual rainfall is 1700 to 2000 mm. Mean monthly temperatures are typical of tropical lowland forest and range from 24 °C to 28 °C. Relative humidity is generally high throughout the year, being about 90% during the night falling to 75% in early afternoon.

MATERIALS & METHOD

Carbon fluxes

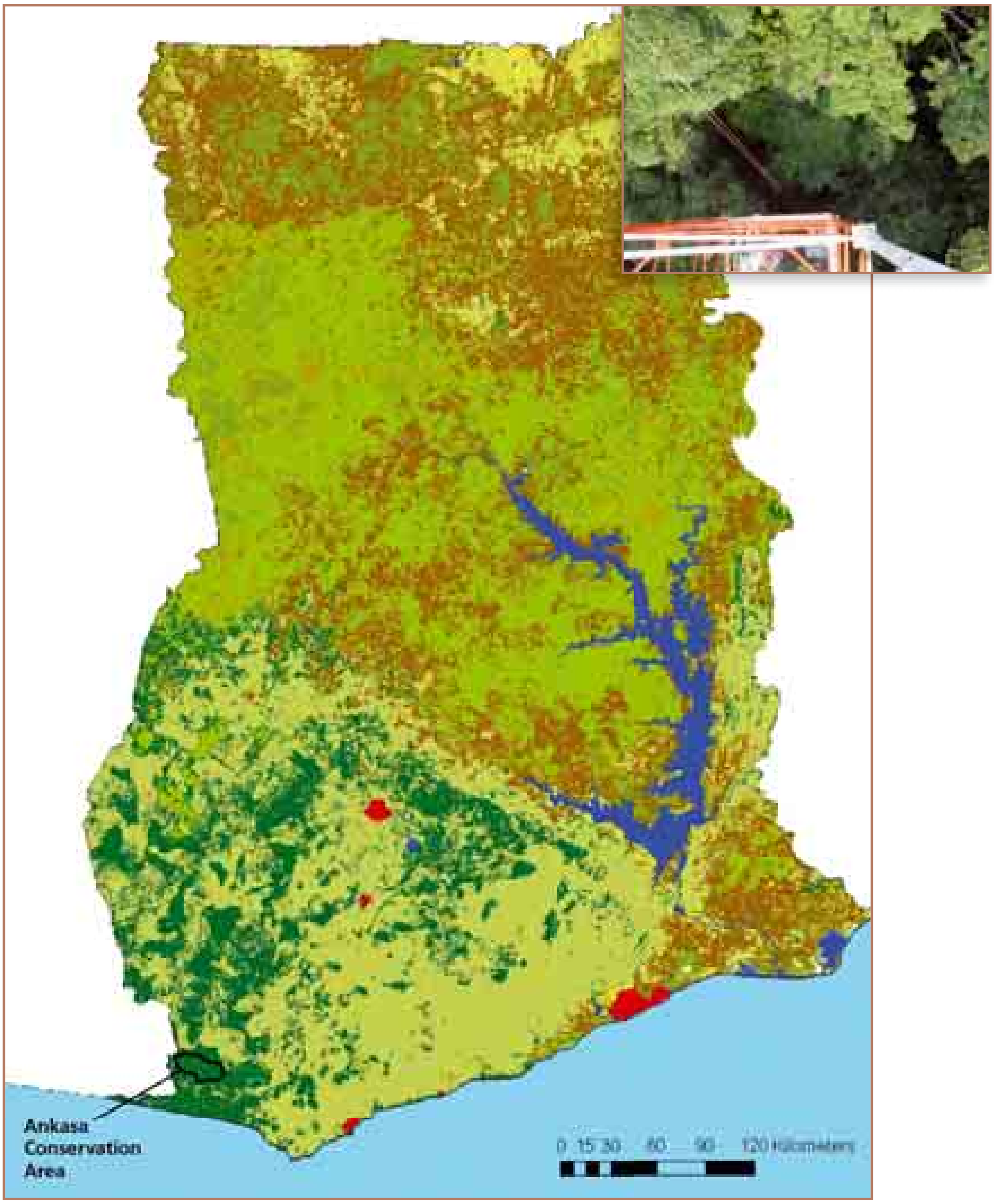
The eddy covariance system consists of a Gill Wind Master sonic anemometer mounted on the top of the tower and a LiCor 7000 closed path CO_2/H_2O analyzer placed at 56 m sucking air samples along a 9 m rilsan tube. Instantaneous data of 3D wind speed, sonic temperature and CO_2/H_2O concentrations are acquired by the EccoCatch software, developed by University of Tuscia, and stored as 30 minutes files for further processing. An additional EGM-CIRAS gas analyzer serves a CO_2 concentration vertical profile system made up of measurements at 6 levels (0.2, 2, 14, 18, 30, 40 m). A Campbell CR1000 logger collects data from the CO_2 profile, and from a number of sensors measuring soil temperature and moisture, solar radiation (global, direct and diffuse photosynthetically active radiation —PAR—), radiative properties of the forest (net radiation, reflected PAR, soil heat flux), and more typical meteorological variables such as air temperature and moisture measured along a vertical profile, precipitation and atmospheric pressure. A set of 9 solar panels, with a power 190 W each, supplies the energy for the system functioning.

Soil

Forty undisturbed soil samples, distributed over the whole selected area, were collected from each horizon (A, Bo1, Bo2), down to 1 m depth. The bulk density was evaluated in 20 random sampling points using a cylinder of known volume (Ø = 8 cm; H = 10 cm) for the Bo1 and Bo2 horizons, while for the A horizon it was obtained collecting all the soil within a frame 20x20 cm so to determine their load on a surface basis. Using the same frame, 20 samples of the litter layer were randomly collected removing by hands all the organic material placed on the mineral soil. The latter was analyzed for particle size distribution (pipette method) and pH in deionized water (1:2.5 ratio soil-solution). Cation exchange capacity (CEC) and

FIGURE 1

The location of the Ankasa Conservation Area (Ghana) with a view of the forest canopy taken from the flux tower.



base saturation (BS) were determined after extraction with NH_4OAc (pH=7) and analysis of cations by atomic absorption spectroscopy. Labile phosphorous (P) was determined as resin extractable phosphate as described by Sibbesen (1977).

Total C and N were determined by dry combustion on finely ground aliquots of mineral soil and to calculate the effective amount of C in the field, each sample was corrected for the original presence of stones and gravel.

Biodiversity

Plant species were identified along two transects and plant height and diameter were measured. The two transects, measuring 1000 m in length and 10 m in width, were perpendicular each other and the tower was at their intersection. The four branches of the two transects were oriented following North, East, South and West, respectively. All species within each sample area were recorded directly on field sheets, or collected as specimens wherever any doubt about identity arose. Plant diameters were measured at breast height (1.30 m, from the ground) considering all trees ≥ 5 cm diameter; diameters of buttressed trees and trees with stilt roots were measured at 50 cm above the point of convergence of these elements. This measurement was taken from the upper side of the tree if the tree was growing on a slope. The height of the tree was measured with Vertex V1.6. Trees with fork above the 1.30 m were taken as one tree. Dead trees were measured without identification and recorded as dead. Regeneration was counted and identified in two permanent sub plots 100 m in length and 10 m in width.

RESULTS & DISCUSSION

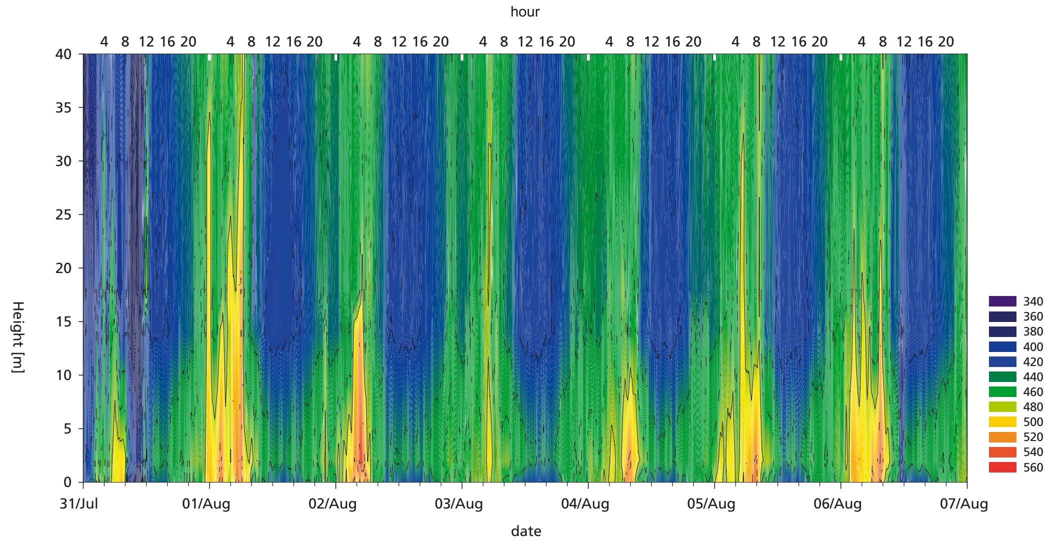
Carbon fluxes

As a preliminary analysis, we present a set of data collected in the first week of August 2008. These data (Fig. 2) show a daily uptake of 1.33±0.73 g C m^{-2} d^{-1} (mean±s.e.) with the CO_2 flux measured above the canopies at 65 m (Fc) ranging from a night efflux of 2.3 to a day-time uptake of -14.8 µmol m^{-2} s^{-1}. The build up of the CO_2 concentration in the closed canopy space at night determines an underestimation of the ecosystem respiration measured on top of the tower on average by a factor 2-2.5 and by a maximum of 4. The CO_2 stored below-canopy is released towards the atmosphere in the early morning once the turbulent motions in the surface layer are activated, as denoted by a positive peak in Fc occurring around 8 a.m although the net ecosystem exchange (NEE), which includes the contribution of the CO_2 stored below the measured flux on the top of the tower, denotes an assimilation activity of CO_2 starting just after the dawn at 6 a.m. Changes in the storage term at night and in the early morning however are generally not compensated by corresponding inverse changes in Fc suggesting that non turbulent fluxes, due to the presence of vertical and horizontal CO_2 concentration gradients, are likely to represent a significant term in the net ecosystem exchange or that the storage term is not , as witnessed by studies in complex forest structures and topography in the tropics (de Araùjo et al., 2008). These preliminary observations in Ankasa forest, confirm patterns and magnitudes of Fc and NEE (Fig. 3) typically observed in tropical forest ecosystems, particularly in the Amazonian basin (Grace et al., 1995). At the same time they highlight the crucial importance of characterizing the magnitude and sign of the night-time storage and CO_2 gradients to correctly evaluate the carbon exchanges with the atmosphere and ultimately the sensitivity of tropical forest carbon pools to climate change (Saleska et al., 2003).

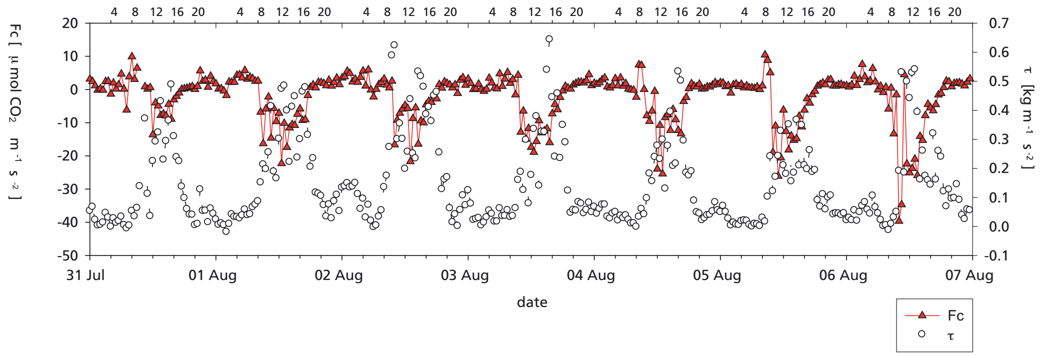
FIGURE 2

Daily pattern of the mean CO_2 vertical profile in the canopy space from 0.2 to 40 m in the period 31 July – 7 August 2008; b) Trend of carbon dioxide flux (Fc) and momentum flux (τ) measured at the tower top; c) Diurnal evolution of the vertical profile of air temperature from 2 to 48 m height.

(a) CO_2 vertical profile within the canopy space



(b) CO_2 and momentum flux measured at 65 m



(c) Air temperature vertical profile

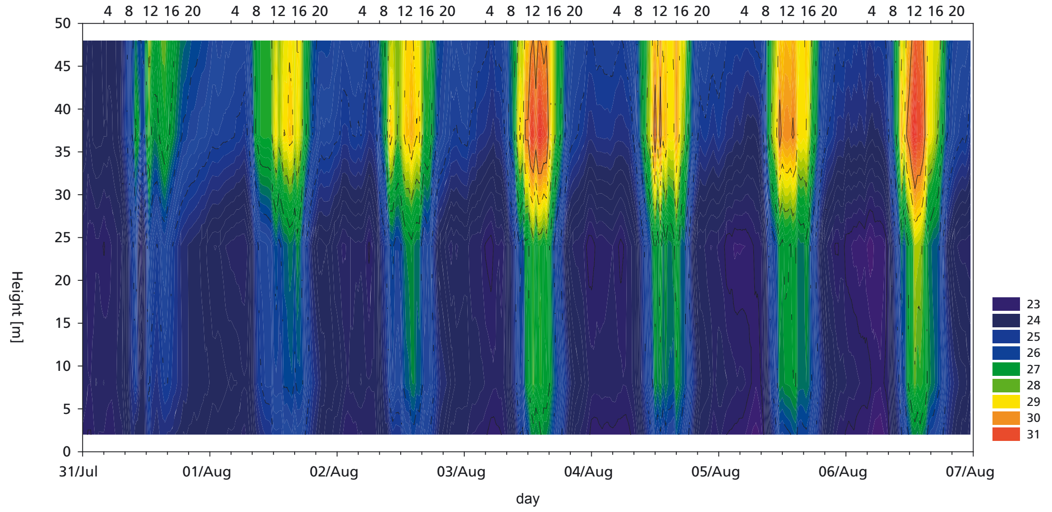
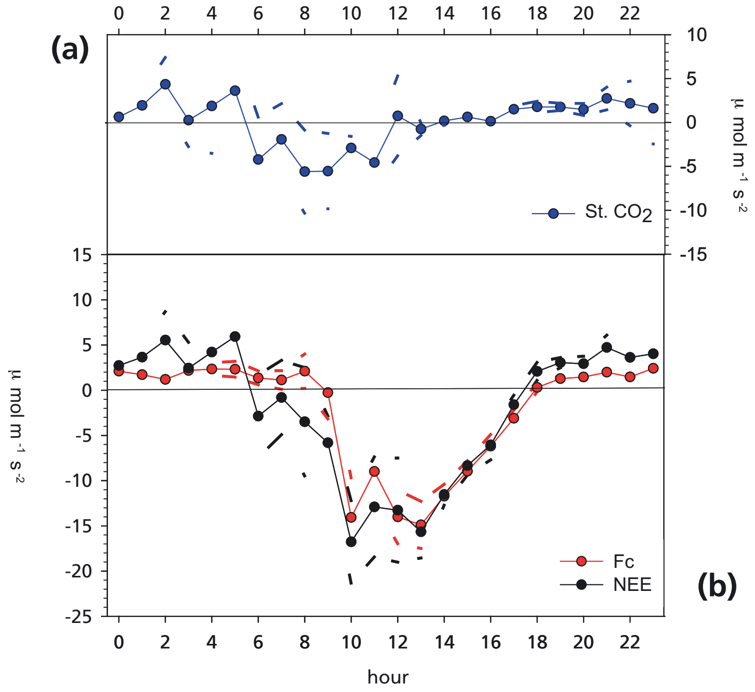


FIGURE 3

Daily trends of storage carbon dioxide flux ($St.CO_2$) (a), of carbon dioxide flux (Fc) measured at the tower top and of the net ecosystem exchange (NEE = Fc+St. CO_2) (b) averaged at hourly time step for the period 31 July – 7 August. Dashed lines delimit the interval of the mean± standard error.



Soil

The results of the soil analysis are showed in table 1, 2 and 3 below. The soil, classified as a Typic Hapludox (Soil Survey Staff, 2006), is very acid, as showed by the measured pH. The observed decrease in CEC with depth, at the same time of an increase in clay content and a decrease of organic matter, is in agreement with the behavior of other tropical soils in Nigeria (Ekwoanya and Ojanuga, 2002), and leads to hypothesize the presence of Caolinite or Illite. Such low to moderate CEC values indicate limited capacity of soil in retaining nutrient cations against leaching. The extracted P that is closely related to the exchangeable P and, therefore, with the P pool that is in equilibrium with the soil solution is low throughout the profile as often observed in natural ecosystems of the tropics (Tiessen, 1993). The variability of the samples resulted to be very low for the measured physical and chemical soil features, sustaining our primary hypothesis of working on an homogeneous area for the main soil characteristics. In spite of the low fertility, this soil store a not negligible amount of organic C (166 Mg C ha^{-1}), 90% of which in the mineral soil down to 1 m depth. This amount of SOC is higher than the average ones estimated for a series of Oxisols sustaining tropical rain forests in the Amazonian basin (102 Mg C ha^{-1}) and Central Africa (129 Mg C ha^{-1}) by Batjies and Dijkshoorn (1999) and Batjes (2008), respectively, using the Soil and Terrain database (SOTER) for Latin America and Africa. Taking into account estimates of the aboveground C stock measured in a close natural wet evergreen forest ranging from 138 to 170 Mg ha^{-1} (Gineste *et al.*, 2008), we can assume that the C budget in the soil of the studied forest in practice corresponds to aboveground C. In conclusion, the not negligible amount of C found in the soil, and not only in the aboveground biomass, focus the attention on the importance of reliable estimates of SOC budget for tropical soils, in most of the cases underestimated.

TABLE 1

Stoniness, bulk density and particle size distribution of the different horizons.

Horizon	Stones-gravel	Db	Sand	Silt	Clay
	%	Mg m^{-3}	g kg^{-1}		
A	11 (14)	1.39 (0.12)	667 (21)	183 (12)	150 (15)
Bo1	26 (16)	1.33 (0.04)	590 (20)	186 (12)	224 (31)
Bo2	35 (5.0)	1.28 (0.09)	564 (63)	176 (20)	260 (78)

TABLE 2

pH, cation exchange capacity (CEC), base cations, base saturation (BS), and available phosphorus (n=40).

Horizon	pH	CEC	Ca	Mg	K	Na	BS	P exch.
		cmol kg^{-1}	cmol kg^{-1}	cmol kg^{-1}	cmol kg^{-1}	cmol kg^{-1}	%	mg kg^{-1}
A	3.7 (0.3)	13.9 (0.6)	2.9 (0.4)	0.8 (0.1)	0.2 (0.03)	0.2 (0.2)	30.2	6.7 (1.5)
Bo1	4.4 (0.2)	11.0 (0.4)	2.5 (0.3)	0.2 (0.04)	0.1 (0.02)	0.2 (0.2)	27.3	4.0 (1.6)
Bo2	4.7 (0.2)	10.5 (0.3)	2.5 (0.3)	0.6 (0.1)	0.1 (0.02)	0.2 (0.2)	30.5	3.4 (1.4)

TABLE 3

Soil organic carbon and total nitrogen on weight and volume bases to 1 m depth (n=40).

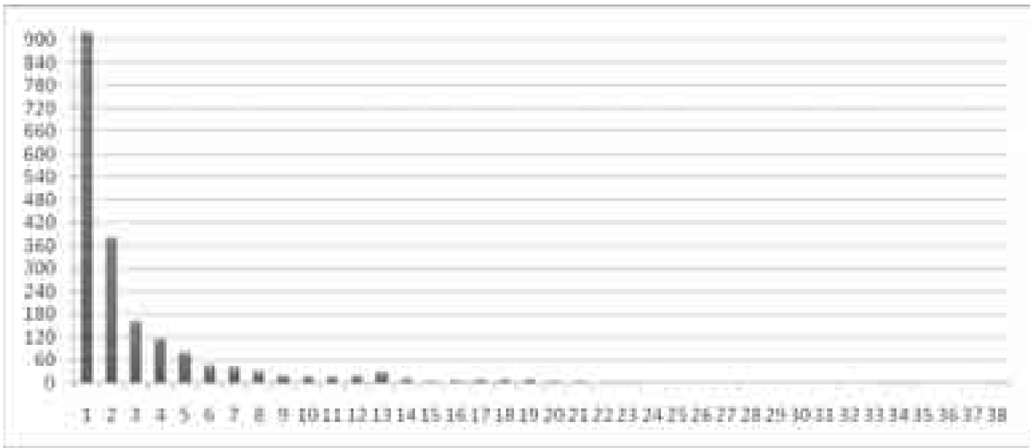
Horizon	C org.	N	C/N	C org.	N
	g kg^{-1}	g kg^{-1}		Mg ha^{-1}	Mg ha^{-1}
Oi-Oe	406.2 (32.1)	15.1 (2.6)	32.1	15.3 (8.6)	0.5 (0.2)
A	60.6 (19.3)	4.4 (1.4)	13.8	30.3 (11.8)	2.2 (0.8)
Bo1	15.8 (3.5)	1.3 (0.3)	12.2	67.6 (15.5)	5.5 (1.6)
Bo2	12.2 (1.2)	0.8 (0.2)	15.3	52.7 (6.3)	3.5 (0.9)
				165.9 (11.2)	11.7 (1.1)

Biodiversity

In the two transects, 1898 individual trees with diameter at breast height (DBH) ≥5 cm were sampled. A total of 39 families, 115 genera, and 175 tree species were determined. In transect A, 146 species, 106 genera, and 38 families; while in transect B 125 species, 88 genera, and 36 families were found. The distribution of forest-types is largely determined by a complex of interacting environmental factors of which climate, geology and soils are the most important. Rainfall has direct effects on moisture availability and indirect effects on soil nutrient levels (Hall and Swaine, 1981). From the first analysis, overlaying the Digital Elevation Model to the Shannon biodiversity index calculated for the two transects, it is evident that biodiversity increases following the gradient of moisture, which is higher in depressions and lower along the slopes. Tree size distribution, represented by DBH, showed a negative exponential curve typical for uneven-aged forests (Figure 4). In terms of volume, species that contribute most to the total volume into the total sample area are reported in table 4.

FIGURE 4

Distribution of trees according to size class based on DBH at 1.3 m from the ground (size class 5 cm, starting from 5-10 cm).



X = diameter classes; Y = number of trees.

TABLE 4

Volume and frequency of plant species.

Species name	V (m^3)	Frequency
Cynometra ananta	313,4	50
Heritiera utilis	195,5	36
Gluema ivorensis	173,8	22
Parkia bicolor	115,7	8
Lophira alata	111,5	7
Strephonema pseudocola	110,8	48
Uapaca guiinensis	98,2	14
Total N. of species	1898	
Total volume	2164.23	

CONCLUSIONS

Measured CO_2 fluxes integrated at daily scale showed a sink activity of the forest. Magnitude and daily patterns of fluxes are comparable to those measured over Amazonian tropical forests; however the night-time inconsistency of the Fc and NEE trends underlines the importance of characterizing the magnitude and sign of non turbulent fluxes to correctly evaluate the carbon exchanges with the atmosphere. The carbon content of soil is a significant component of the total carbon content in forest; this area shows high levels of biodiversity, among the highest measured in African tropical forests, and with an interesting presence of rare species. Research activities carried out in the primary tropical rainforest forest of the Ankasa Conservation Area highlight the need to better characterize tropical forest ecosystems; further studies are ongoing for this purpose.

ACKNOWLEDGEMENTS

The research activities in the Ankasa Conservation Area site are supported by the European Commission through the project CarboAfrica (FP6) and are carried out with the collaboration of the Forestry Commission of Ghana and the Wildlife Division. We acknowledge the support of the Italian Ministry of Environment Land and Sea for the fruitful support and collaboration. We gratefully acknowledge also the help of Mr. Justice John Mensah in the field work and maintenance of the flux tower, and of Mr. Abdul Kareem, park manager of the Ankasa Conservation Area, and the all the park rangers.

REFERENCES

Batjes N.H., 2008. Mapping soil carbon stocks of Central Africa using SOTER. Geoderma 146:58–65.

Batjes N.H., Dijkshoorn J.A., 1999. Carbon and nitrogen stocks in the soils of the Amazon Region. Geoderma 89:273–286.

de Araùjo, A.C., Kruijt, B., Nobre, A.D., Dolman, A.J., Waterloo, M.J., Moors, E.J., de Souza, J.S., 2008. Nocturnal accumulation of CO2 underneath a tropical forest canopy along a topographical gradient. Ecological Applications 18:1406–1419.

de Oliveira A.A., Mori S.A., 1999. A central Amazonian terra firme forest. High tree species richness on poor soils. Biodiversity and Conservation 8:1247–1259.

Ekwoanya M.A., Ojanuga A.G., 2002. Productivity assessment of upland and foodplain soils at Makurdy, Nigeria. Geoderma 108:19–29.

Gineste M., Martel S., Henry M., Adu-Bredu S., Saint-Andre L., 2008. Estimating the impact of selective logging on aboveground carbon stocks in Boi Tano forest reserve. Carboafrica annual meeting Accra 25-27 November 2008, http://www.carboafrica.net/c_outputs_en.asp

Grace, J., Lloyd, J., McIntyre, J., Miranda, A., Meir, P., Miranda, H., Moncrieff, J., Massheder, J., Wright, I., Gash, J., 1995. Fluxes of carbon-dioxide and watervapor over an undisturbed tropical forest in south-west Amazonia. Global Change Biology 1:1–12.

Hall J.B., Swaine M D., 1981. Distribution and ecology of vascular plants in a tropical rain forest. Forest vegetation in Ghana, Geobotany 1.

International Tropical Timber Organization. Status of Tropical Forest Management 2005. ITTO Technical Series No. 24, 2006.

Malhi, Y., Nobre, A.D., Grace, G., Kruijt, B., Pereira, M.G., Culf, A., *et al.* 1998. Carbon dioxide transfer over a central Amazonian rain forest. J. Geophis. Res. 103.

PADP – Ankasa Conservation Area Management Plan 2000. Saleska, S.R.,. Miller, S.D.,. Matross, D.M., Goulden, M.L., Wofsy, S.C.,. da Rocha, H.R., de Camargo, P. B., Crill, P., Daube, B.C., de Freitas, H.C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M., Munger, J.W., Pyle, E.H., Rice, A.H., Silva, H., 2003. Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance induced Losses, Science, 28 November 2003. 302:1554–1557.

Sibbesen E., 1977. A simple ion exchange resin procedure for extracting plant available elements from soil. Plant and available elements from soil. Plant and Soil 46:665–669.

Soil Survey Staff 2006. Keys to soil taxonomy, Tenth edition. United States Department of Agriculture, Natural Resources Conservation Service. US. Government Printing Office, Washington, DC. Pp 325.

Takanashi, S., Kosugi, Y., Tani, M., Matsuo, N., Mitani, T., & Nik, A. 2005. Caracteristic of the gas exchange of a tropical rain forest in peninsular Malaysia. Phyton.Ann. (REI Bot.45), 61–66.

Tiessen H., 1993. The study of phosphorus cycles in ecosystems. In: Anderson JM, Ingram JSI (Eds), Tropical Soil Biology and Fertility: a handbook of methods, pp. 179–188.

Estimation of net ecosystem exchange at the Skukuza flux site, Kruger National Park, South Africa

Nickless A.[1], Archibald S.A.[1], van der Merwe M.[1], Scholes R.J.[1],
Williams C.A.[2], Hanan N.[3]

ABSTRACT

Annual estimates of gross primary production (GPP) and ecosystem respiration (R_{eco}) were obtained for the Skukuza flux site, Kruger Park, South Africa, based on the eddy covariance flux data. A new method of extrapolating night-time respiration to the entire day and filling gaps in eddy-covariance data in semi-arid systems was developed. The purpose for developing this method was to better account for the manner in which net ecosystem exchange (NEE) in drylan systems occurs as pulses driven by rainfall events, compared to current standard interpolation procedures developed primarily for temperate flux sites. The standard techniques furthermore do not take into account the decrease in respiration at very high soil temperatures. An artificial neural network (ANN) model was used to model GPP and R_{eco} by incorporating fraction absorbed photosynthetically active radiation (fAPAR), the timing and magnitude of rainfall events, and temperature. The ANN predicted measured fluxes accurately (MAE 0.42 gC/m2/day), and was able to represent the seasonal patterns of photosynthesis and respiration at the site. The annual integral of the filled NEE data was found to range from -138 to +155 g C/m^2/y over the five years eddy covariance measurement period. A full explanation of the methods and a full analysis of the data can be found in Archibald *et al.* (2009).

Keywords: Eddy Covariance, Interpolation, Partitioning, Gap-Filling, Net Ecosystem Exchange

INTRODUCTION

It is common practise when using the eddy covariance method to accumulate the fluxes into half-hourly measurements. But accumulating these half-hourly measurements into longer period summaries is not a simple matter of adding the half-hourly values together. Even the best run eddy flux tower will have some missing data, which then needs to be filled in by means of modelling techniques in order to derive annual estimates of net ecosystem exchange (NEE). Ecologists are also interested in the components of NEE: gross primary production (GPP) and ecosystem respiration (R_{eco}). Observing the convention that fluxes from the atmosphere to the ground are given a negative sign, NEE can be expressed as NEE = GPP + R_{eco}.

---

1 CSIR, Natural Resources and the Environment, PO BOX 395, Pretoria, 0001, South Africa
2 School of Geography, Clark University, Worcester, MA 01610-1477, USA
3 Natural Resources Ecology Lab, Colorado State University, Fort Collins, CO 80523, USA

A large body of work exists on different gap-filling techniques, and standard methodologies have been developed (Falge *et al.* 2001; Papale and Valentini 2003; Moffat *et al.* 2007). These methods have largely been developed in moist temperate systems, and therefore are not always appropriate for tropical wet-dry systems. This is because the majority of these models, particularly the more popular models, assume that the major controls on flux processes to be solar radiation and temperature, whereas temperatures in the semi-arid tropics are almost always warm enough to permit physiological activity, and insolation is sufficient, at least during non-cloudy days, for light saturation of part or all of the typically-sparse canopy. In arid and semi-arid systems, the main control on the rate and duration of many ecosystem processes is soil moisture.

As a further complication, in low-rain, high-evaporation ecosystems, where the soils dry out between successive rainfall events (so-called pulse-driven systems), the various terms in the carbon budget are highly dependent on the recent history of the system (Huxman *et al.* 2004). For example, following a rainfall event, respiration increases rapidly whereas it takes several days for the ecosystem to reach maximum photosynthesis (Huxman *et al.* 2004; Xu *et al.* 2004). Similarly, the magnitude of the system response depends not only on the size of the current rainfall event, but on the amount and timing of preceding events: after a long drought the response to a rain event is larger than to a similar-sized event during the middle of the rainy season, but the time taken to reach the peak response is longer (Veenendaal *et al.* 2004). Therefore, it is not possible to use instantaneous measures such as the soil moisture content as a sole proxy for the state of the system. Gap-filling therefore requires consideration of indices that have ‘memory’: for instance, accumulators of water deficit.

Moreover, ‘phenomenological’ models will only be appropriate when they truly represent the underlying responses (Falge *et al.* 2001). Most current respiration models, used for interpolating day-time respiration from night-time respiration, define the relationship between respiration and temperature using an exponential- or logistic-shaped function; i.e. functions that either continually increase, or level off at a maximum value (Moffat *et al.* 2007). These models were developed in systems where temperature ranges are generally below 30 °C (Fang and Moncrieff 2001; Lloyd and Taylor 1994). Physiologically, respiration is expected to decrease once temperature exceeds the optimum for microbial activity (Yamano and Takahashi 1983). In tropical dry systems, the soil temperature in the top centimetres often exceeds 40 °C.

This paper demonstrates a simplified technique of interpolating day-time respiration. New variables related to the hydrological condition of the system are explored, in addition to the variables more commonly used in gap-filling techniques, and these variables are then used in an artificial neural network (ANN) to gap-fill the five year eddy covariance data set. This is used to obtain annual estimates of NEE.

MATERIALS AND METHODS

A flux tower situated in a semi-arid savannah near Skukuza, in the Kruger National Park has been collecting data since February 2000. The site has a mean annual rainfall of 550 ±160 mm, which is strongly seasonal, occurring between November and April (summer). The landscape is gently undulating, consisting of broad-leaved *Combretum apiculatum*-dominated savannah on the coarse sand crests and fine-leaved *Acacia nigrescens* savannah on sandy clay loam in the valleys (Scholes *et al.* 2001). Further details about this site and the instrumentation used at the site can be found in Scholes *et al.* (2001) and Archibald *et al.* (2009).

Flux measurements were summarised into half-hourly values, excluding fluxes with a u-star value less than 0.25 ms^{-1} (Kutsch *et al.* 2008). In order to separate out day-time NEE into R_{eco} and GPP, a novel interpolation procedure was developed. As with other interpolation methods in general use, day-time R_{eco} interpolation was based on a temperature response function. To describe this response function the Generalised Poisson Distribution (GPD) was used, instead of the more commonly-applied Arrhenius or Lloyd-Taylor functions. This function has been shown to more accurately model nitrification rates in soils over a wide range of temperatures compared to the Arrhenius or Lloyd-Taylor functions (Stark 1996) as it allows response values to decrease after a threshold temperature, and we therefore believe that this function will also be more suited to modelling respiration in hot semi-arid savannah systems (Kirton, unpublished data). The GPD can be expressed as:

$$R_{eco}= M\left(\frac{b-Soil\ temperature}{b-a}\right)^{c} \exp\left\{\left(\frac{c}{d}\right)\left[1-\left(\frac{b-Soil\ temperature}{b-a}\right)^{d}\right]\right\}$$

where a is the temperature at which maximum respiration takes place, b is the temperature below which no respiration will take place, and c and d control the steepness and shape of the curve.

To estimate the parameters of this function, the maximum night-time R_{eco} value in each degree of temperature was obtained from the complete dataset, and the function was then fitted to these values by means of non-linear least squares using the Levenberg-Marquardt algorithm. This curve represented the temperature response of R_{eco} when all other factors were at an optimum level. The half-hourly night-time respiration values and soil temperatures were then extracted for each day and set to calculate the scaling term, $\frac{1}{n_i}\sum\frac{y_i}{\hat{y}_i}$, where n_i is the number of night-time respiration values available for that day, y_i is the respiration value, and $\hat{y}_i$ is the predicted respiration value at the temperature at which the corresponding y_i took place. To obtain the day-time R_{eco} values for a particular day, the soil temperature values were used to calculate R_{eco}, and these values were then multiplied by the day's scaling term, which reduced the estimated respiration values to be within a range determined by the observed night-time respiration values for that day. Therefore, the interpolated day-time respiration values are limited by prevailing environmental factors such as fAPAR (fraction of absorbed photosynthetically active radiation) and soil moisture, achieved by the scaling term. For example, on a winter's day the day-time temperature can often exceed 20°C, whereas the fAPAR and soil moisture values are generally low. On such a day the night-time respiration values are expected to be low, and the scaling parameter calculated from the observed night-time values would act to shrink the temperature response curve. This method therefore produces small estimates for day-time respiration during the dry season, which are in keeping with our understanding of seasonal patterns of respiration and photosynthesis in this system.

Once the day-time respiration values were calculated and night-time respiration filled where possible, the half-hourly GPP values were obtained by subtracting R_{eco} from NEE. The half-hourly NEE, GPP and R_{eco} values were accumulated to a daily (24 hours) time step. This resulted in a dataset with 372 valid records for R_{eco}, 529 for GPP and 698 for NEE available over the full five year period. Gap-filling was carried out at a daily time step, because we wish to use the model in future for retrospective analyses driven by standard daily meteorological data. We used artificial neural networks (ANN) as our gap-filling approach, as this method accommodates non-linear relationships between variables but requires few a priori assumptions on the relative importance of different variables or their functional relationships. The usefulness of ANNs is very dependent on the appropriate selection of input variables – and we hoped to improve on standard methods available by choosing variables which would reflect the pulsed response to soil moisture in arid systems. One ANN was used to gap-fill the five year flux record, due to the large amount of missing data. In order to obtain the best model possible in order to accurately gap-fill the data, all the available data was used to fit the ANN model. Future studies will concentrate on comparing the performance if this ANN model against other models available from the literature.

The drivers considered for GPP and R_{eco} include PAR, fAPAR, the mean temperature during the day (for GPP) and the soil temperature (for R_{eco}). In addition, three derived variables describing the hydrological history of the system were used. These variables were Relative Plant Available Water (θ_{rel}: calculated as soil moisture (θ) scaled between field capacity and wilting point: (θ-WP)/(FC-WP)); water deficit (a function which accumulates the deficit for all days of water stress $\theta < \theta$ crit until rewetting occurs); and time since wetting (the time since the last big wetting event – i.e. time since θ increased above θ_{crit}).

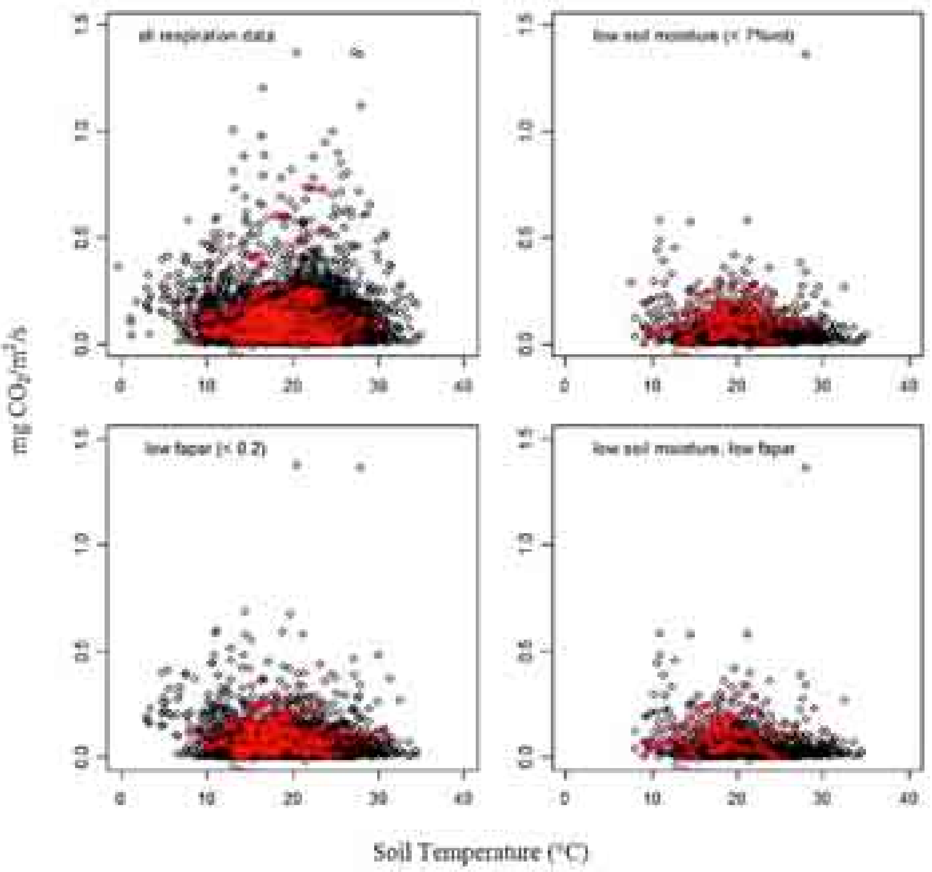
RESULTS & DISCUSSION

In order to asses how well the interpolation method for day-time R_{eco} performed, a plot was generated of the observed night-time respiration against temperature, categorised by fAPAR and soil moisture. A plot of the predicted night-time respiration against temperature for the missing cases, categorised by the same criteria, was then superimposed over the first plot (Fig. 1). The range of values predicted for R_{eco} under different levels of fAPAR and soil moisture appears to be in the same range as that of the observed values, supporting the interpolation method.

The draw-back of this interpolation method is that it depends not only on available soil temperature values, but also on observed night-time respiration values. If either of these values is missing, then interpolated values cannot be obtained for that day. The advantage of this method is that each day has its own data-driven scaling parameter, and therefore will not result in unrealistic estimates for respiration. A second advantage of this method is that in the case where at least three night-time respiration values are available, the missing night-time respiration can also be filled provided the soil temperature values are available.

FIGURE 1

Distribution of observed (black) and interpolated (red) half-hourly night-time respiration values over temperature



Data are presented for all conditions, for periods of low soil moisture, for periods with little leaf material (low fAPAR), and for conditions of low soil moisture and fAPAR. Interpolated values lie well within the distribution of observed values for all conditions. It is also clear that respiration drops off at high temperatures, and that temperature-response functions need to include this reduction at high temperatures if they are to be appropriate for this site.

The ANN identified fAPAR to be the most important predictor of both R_{eco} and GPP, but fAPAR was relatively more important for predicting GPP than for predicting R_{eco}, as would be expected (Tab. 1). We interpret the role of fAPAR in driving R_{eco} as reflecting the availability of readily-respired substrate. For GPP, the time since wetting event was the next most important predictor, which corroborates findings of Williams *et al.* (in press) that there is a delay in the pulse of photosynthetic activity after a rainfall event. In terms of water relations, soil moisture content (θ_{rel}) was the best predictor for R_{eco}, but water deficit and time since wetting were also identified as important. Interestingly, temperature did not prove to be important in predicting either respiration or photosynthesis. This could reflect the daily time-step at which we did the analysis – in this sub-tropical system temperature variation between days and over the growth season is much less important than variation in leaf dynamics and soil moisture in driving NEE. The lowest MAE value (i.e., the best estimate) was obtained when modelling NEE (MAE 0.42 gC/m2/day), and therefore gap-filling was carried out with the ANN model predicting NEE with the purpose of calculating the annual NEE estimates.

TABLE 1

Relative importance (percentage) of the different variables used to predict ecosystem respiration, gross primary productivity, and net ecosystem exchange using an artificial neural network (ANN)

R_{eco}		GPP		NEE	
fAPAR	36%	fAPAR	46%	fAPAR	27%
θ_{rel}	19%	time since wetting	19%	θ_{rel}	26%
PAR	18%	PAR	14%	time since wetting	14%
time since wetting	14%	θ_{rel}	12%	water deficit	14%
water deficit	13%	water deficit	5%	T_{pn}	10%
T_{re}	0%	T_{pn}	4%	T_{re}	6%
				PAR	3%

where fAPAR is fractional interception of photosynthetically active radiation, obtained from the JRC; θ_{rel} is the relative plant available water, which is a scaled version of θ (soil water content); PAR is photosynthetic active radiation; time since wetting is the time since θ increased above θcrit; water deficit is an accumulation of the deficit for all days of water stress $\theta < \theta$crit until rewetting occurs; T_{re} is the average soil temperature; and T_{pn} is the average temperature during the day.

Annually-integrated net ecosystem exchange varied from -138 to +155 gC/m^2/y over the 5 year period for which there were flux data (Tab. 2). In drought years limited carbon uptake occurs even during the height of summer, but in years with above average rainfall the site can be a sink of carbon for several months of the year (Fig. 2).

Only two of the five years had negative NEE (in other words, were net carbon sinks at the annual timescale). It is possible that our gap filling methods overestimate the amount of respiration occurring at this site: there was comparatively little data available during the summer months, due to the repeated failure of the system following lightning strikes (Fig. 3), so the model was probably not well trained to identify days of maximum GPP in this system.

To test this we will need to acquire a more extensive summer dataset for this site. Estimates of random error, calculated using the approach described in Richardson *et al.* (2008), suggest that years where predicted annual NEE was within ±20 gC/m2/y should effectively be considered to be carbon-neutral. Details of the error estimation can be found in Archibald *et al.* (2009).

TABLE 2

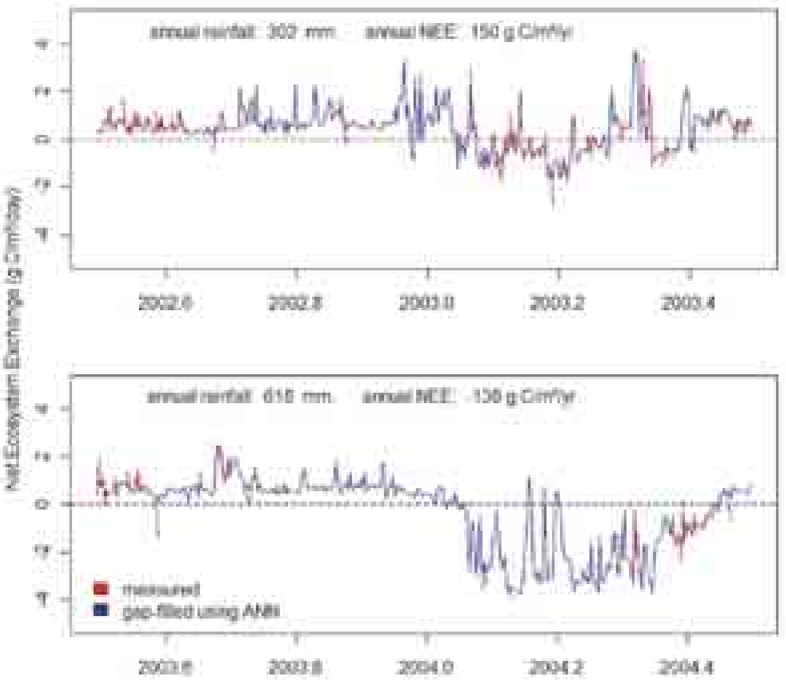
Summary of net ecosystem exchange (NEE) over the 5 year period of flux data

Rainfall year (July to June)	Annual NEE (gC/m^2)	95% confidence interval	Annual rainfall (mm)	Annual PAR (MJ/m^2)	Growing season length (days)	Number of growth days
00_01	42	(17; 67)	659	662	244	245
01_02	155	(130; 180)	572	523	191	169
02_03	150	(125; 175)	303	406	156	166
03_04	-138	(-163; -113)	618	555	188	81
04_05	-83	(-108; -58)	760	665	197	186

Negative values represent an overall sink of carbon. Data gaps were filled using an ANN and predictors fAPAR, water deficit, relative plant available water, mean day-time temperature, time since wetting, and mean soil temperature, in that order of importance. Also reported are annual summaries of rainfall, available photosynthetically active radiation, length of the growing season, and number of growth days (days when soil moisture content is greater than θcrit (7% by volume). The 95% confidence interval for annual NEE was calculated using the estimated random error obtained using an approach based on model residuals described by Richardson *et al.* (2008). The details of the random error estimation approach applied can be found in Archibald *et al.* (2009).

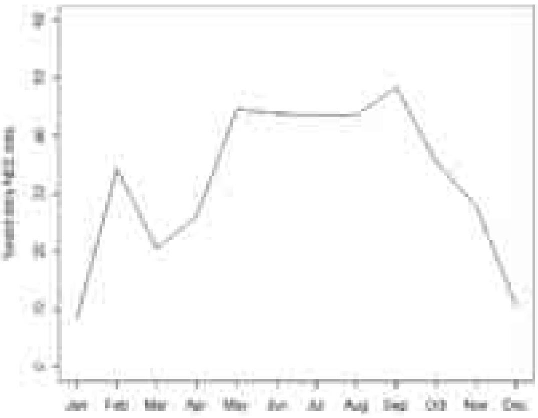
FIGURE 2

Annual time course of NEE for two consecutive years, where the first year was dry and the second year had near average rainfall, at the Skukuza flux tower to show the difference in carbon uptake between these two years



Red line represents measured daily NEE, blue is modelled using an artificial neural network and inputs of fAPAR, soil moisture, temperature, time since wetting, and water deficit.

FIGURE 3
Seasonal distribution of valid NEE data points from a six-year long dataset at the Skukuza flux tower



CONCLUSIONS

The Generalised Poisson Distribution function used here to fit an optimum temperature response curve is an effective method for extrapolating day-time respiration in systems where temperatures often exceed 30°C – provided a scaling factor is used to control for the co-limiting factors such as fAPAR or soil moisture. At a daily to seasonal level, however, temperature was shown to be less important than other factors in influencing NEE.

For the Skukuza flux site, and potentially other hot semi-arid savannah systems, the flux-partitioning and gap-filling procedures developed in this paper are an improvement on standard methodologies largely because they use more appropriate temperature-response functions and explicitly include a soil moisture control, including an index of the wetting history. The accuracy of estimates of annual CO_2 flux we obtained through gap-filling using an ANN at this site is constrained by the paucity of peak growing season flux data.

Results of the ANN gap-filling procedure indicate a large degree of interaction between driver variables and lend support for the development of a process-driven model for this system. Such a model would need to include explicit measures of leaf mass, soil moisture and temperature.

ACKNOWLEDGEMENTS

The authors would like to acknowledge CarboAfrica, the Department of Science and Technology (DST, South Africa), and the CSIR (South Africa), for funding this research. The authors would like to thank Dario Papale for his useful comments on how to improve this paper.

REFERENCES

Archibald S.A., Kirton A., van der Merwe M.R., Scholes R.J., Williams C.A., Hanan N., 2009. Drivers of inter-annual variability in Net Ecosystem Exchange in a semi-arid savanna ecosystem, South Africa. Biogeosciences, 6, 1-16.

Falge E., Baldocchi D., Olson R., Anthoni P., Aubinet M., Bernhofer C., Burba G., Ceulemans R., Clement R., Dolman H., Granier A., Gross P., Grunwald T., Hollinger D., Jensen N., Katul G., Keronen P., Kowalski A., Lai C.T., Law B., Meyers T., Moncrieff J., Moors E., Munger W., Pilegaard K., Rannik U., Rebmann C., Suyker

A., Tenhunen J., Tu K., Verma S., Vesala T., Wilson K., Wofsy S., 2001. Gap-filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107, 43-69.

Fang C., Moncrieff J.B., 2001. The dependence of soil CO2 efflux on temperature. Soil Biology and Biochemistry, 33, 155-165.

Huxman T.E., Snyder K.A., Tissue D., Leffler A.J., Ogle K., Pockman W.T., Sandquist D.R., Potts D.L., Schwinning S., 2004. Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. Oecologia, 141, 254-268.

Kutsch W.L., Hanan N., Scholes B., McHugh I., Kubheka W., Eckhardt H., Williams C. 2008. Response of carbon fluxes to water relations in a savanna ecosystem in South Africa, Biogeosciences, 5, 1797-1808.

Lloyd J., Taylor J.A., 1994. On the temperature dependence of soil respiration. Functional Ecology, 8, 315-323.

Moffat A.M., Papale D., Reichstein M., Hollinger D., Richardson A.D., Barr A.G., Beckstein C., Braswell B.H., Churkina G., Desai A.R., Falge E., Gove J.H., Heimann M., Hui D., Jarvis A.J., Kattge J., Noormets A., Stauch V.J., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. Agricultural and Forest Meteorology, 147, 209-232.

Papale D., Valentini R., 2003. A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatialization. Global Change Biology, 9, 525-535.

Richardson A.D., Mahecha M.D., Falge E., Kattge J., Moffat A.M., Papale D., Reichstein M., Stauch V.J., Braswell B.H., Churkina G., Kruijt B., Hollinger D.Y., 2008. Statistical properties of random CO_2 flux measurements inferred from model residuals. Agricultural and Forest Meteorology, 148, 38-50.

Scholes R.J., Gureja N., Giannecchinni M., Dovie D., Wilson B., Davidson N., Piggott K., McLoughlin C., van der Velde K., Freeman A., Bradley S., Smart R., Ndala S., 2001. The environment and vegetation of the flux measurement site near Skukuza, Kruger National Park. Koedoe, 44, 73-83.

Stark J.M., 1996. Modeling the temperature response of nitrification. Biogeochemistry, 35, 433-445.

Veenendaal E.M., Kolle O., Lloyd J., 2004. Seasonal variation in energy fluxes and carbon dioxide exchange for a broad-leaved semi-arid savanna (Mopane woodland) in Southern Africa. Global Change Biology, 10, 318-328.

Williams C.A., Hanan N., Scholes R.J., submitted. On the complexity appropriate for modeling observed variation of water and carbon dioxide flux responses to rainfall pulses in an African savanna. Oecologia.

Yamano H., Takahashi K., 1983. Temperature effect on the activity of soil microbes measured from heat evolution during the degradation of several carbon sources. Agricultural and Biological Chemistry, 47, 1493-1499.

Xu L., Baldocchi D.D., Tang J., 2004. How soil moisture, rain pulses, and growth alter the response of ecosystem respiration to temperature. Global Biogeochemical Cycles, 18, GB4002, doi: 10.1029/2005GB002281.

Vegetation dynamics in a littoral savannah in Congo

de Grandcourt A.[1, 2], Thongo Mbou A.[1], Kinana A.[1], Ngoyi S.[1], Minzele C.[1], Nouvellon, Y.[2], Saint-André L.[2]

INTRODUCTION

Grasslands occupy a significant part of the land surface in the world (52.5 millions of km^2 i.e. 40.5% of the Earth surface area, excluding Greenland and Antarctica, World Resources Institute, 2000, based on IGBP data). In Africa, grasslands occupy 5 millions of km^2, i.e. 17 % of the surface area of Africa. This biome is directly affected by climate change that we are facing, in particular through changes in seasonal distribution of rainfall and the increase in temperature (Ojima *et al.* 1993).

In the tropics, grasslands experience one or two dry seasons each year and they are frequently burnt (at least once a year) by the farmers. These high constraints have an impact on the dynamic of the vegetation of the grassland. For the grasslands that grow on poor soils, such as the sandy soil of the littoral region in Congo, the constraints are even higher.

There are numerous studies on the vegetation dynamic in temperate prairies (Dhillion and Anderson 1994; Fay *et al.* 2003) and in some tropical grasslands (Guenni *et al.* 2002; Abbadie *et al.* 2005; Collins 1977). Abbadie *et al.* (2005) presented the work undertaken at Lamto in Ivory Coast (West Africa) since 1962. The savannahs observed in Lamto and in the Republic of Congo are both of Guinean type. But at Lamto, the savannah is mainly constrained by the precipitation pattern, whereas the savannahs in the coastal area of the Republic of Congo are constrained both by water limitations and poor soil conditions (sandy soils, low cation exchange capacity, low water retention). However, little is known about these Central African savannahs (Laclau *et al.* 2002). An eddy-covariance station was installed in July 2006 in the littoral region of the Republic of Congo to quantify the carbon budget of the pristine ecosystem, before afforestation with eucalyptus. In order to understand and cross-validate the flux data, and to parameterize and validate grassland ecosystem processed-based models, we decided to study the vegetation dynamic of this grassland. We wanted to test the effect of the season and of the fire on the vegetation dynamic. We present in this article the results on the aboveground and belowground biomass and the measures of the root production and the effect of water availability and fire on these parameters.

---

[1] UR2PI, BP 1291, Pointe Noire, République du Congo

[2] UPR 80, CIRAD PERSYST, Campus de Baillarguet, TA B-80/D, 34398 Montpellier cedex 5, France

MATERIALS AND METHODS:

Site description

The site of Tchizalamou is a grassland in the littoral region of Kouilou, in the Republic of Congo, situated at 4°17’21.0” S and11°39’23.1”E. It is located on a plateau at an elevation of 82 m. The ocean is at 12 km. The soils are Ferralic Arenosols (WRB, FAO, 1998) with a sand content higher than 85%, chemically poor, poor water retention and very deep. These soils are lying on a detritic formation of continental origin, formed during the plio-pleistocene.

An eddy-covariance system was installed at the site in July 2006 to measure CO_2, H_2O and energy fluxes. Precipitation, soil and air temperatures, radiation, wind speed and direction are measured continuously at the site since July 2006. The mean values of the meteorological parameters are calculated each half-hour. The soil water content (from 10 cm to 200 cm) is measured once a week with a TDR (Time Domain Reflectrometry) system in two soil profiles separated by 2 m (SoilMoisture, Santa Barbara,USA). In the system, the speed of travel of a microwave pulse of electricity in a parallel transmission line varies in function of the water content of the soil.

The mean annual rainfall at Pointe Noire over the last 50 years was 1200 mm, with a marked dry season between May and September. The site of Tchizalamou (at 70 km of Pointe Noire) seems to be wetter, probably due to an increasing rain gradient from Pointe Noire to the north east (L’Hôte et Mahé 1996). The mean temperature was 25°C with low seasonal variations (+/- 5°C).

The vegetation observed in the site is a grassland savannah with very scarce bushes of *Annona senegalensis* Pers. (less than 5 shrubs.ha^{-1}). The main species is *Loudetia simplex*, followed by *Ctenium newtonii* and *Loudetia arundinacea* (Nees) C.E. Hubbard. These three species accounted for more than 50% of the total biomass at any moment of the year. All these species are perennial. The maximum height of the herbaceous vegetation is about 1.5 m.

Experimental design

The experimental site for biomass measurements was delimited as one hectare with the flux tower in the middle. Sixteen 7m x 7m plots were selected randomly in the experimental site. Each plot contained 49 sub-plots of 1m^2. Only 16 sub-plots were chosen to study the biomass, the other ones were used to walk inside the plot without trample on the vegetation of the 16 sub-plots. In the 16 sub-plots, biomass was measured alternatively (one subplot is selected randomly at each sampling date). A total of 15 field campaigns were done from September 2006 to July 2008 (every 6 weeks) corresponding to 3 and 6 measurement points in the dry and wet seasons, respectively.

The aboveground phytomass was cut on 1m^2 for each subplot, separating the species. At the lab, the biomass and the necromass were separated during the week following the harvest. Organs were also separated (leaves, stems or stubbles, flowers or ears).

Belowground biomass was assessed from 4 auger cores for each sub-plot (8 cm diameter). Soil samples were taken down to 0.7 m deep, dividing the depth into 4 layers; 0-10 cm, 10-30 cm, 30-50cm and 50-70 cm. The 4 cores were bulked and picked at the lab, roots were sorted first by hand and then in the water. Species were not considered independently for belowground biomass.

Root production was assessed from the in-growth core method from December 2007 to January 2009. Five plots were installed in the experimental site (1' to 5') at the beginning of the study in order to sample the entire 11-month period covered by the study. This can not be done on the plots of 7m x 7m as the aboveground biomass is cut before the installation of the ingrowth-cores. 4 initial cores were sampled with the auger in each plot in three soil horizons (0-10, 10-30 and 30-50 cm). Roots of each sample were removed from the soil and the hole was refilled with the root-free soil of the same horizon. 6 weeks later, the ingrowth cores were harvested and a new cohort of ingrowth cores was installed on an other sub-plot, randomly chosen. Twenty in-growth cores were then sampled in each soil horizons at the same time as the biomass campaigns from December 2007 to July 2008. 4 other campaigns were done after the end of the 2-years biomass survey.

All the samples were dried at 65°C until constant mass was achieved and weighted.

Productivity calculation

Aboveground net primary productivity was calculated as

$ANPP=\Delta C_B+\Delta C_N+L+H$

Where

ΔC_B is the difference of biomass

ΔC_N is the difference of standing necromass

L is the quantity of litter

H is the quantity of grass grazed

In our savannah, the necromass stayed erected and do not become litter and there was no grazing. Under these conditions, L and H are both equal to zero on the equation above. So ANPP can be estimated with the maximum of vegetation (biomass and necromass) (Singh *et al.* 1975; Long *et al.* 1989; Long *et al.* 1992; Sala and Austin 2000).

Belowground productivity was calculated as the annual sum of the root biomass in the ingrowth-cores stayed in the soil during 45 days.

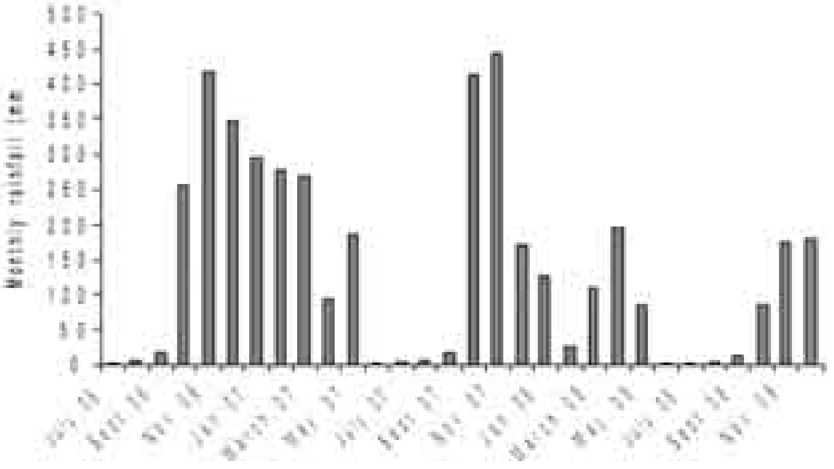
RESULTS AND DISCUSSION

We present the results as the mean value ± the standard error.

Rainfall and soil humidity

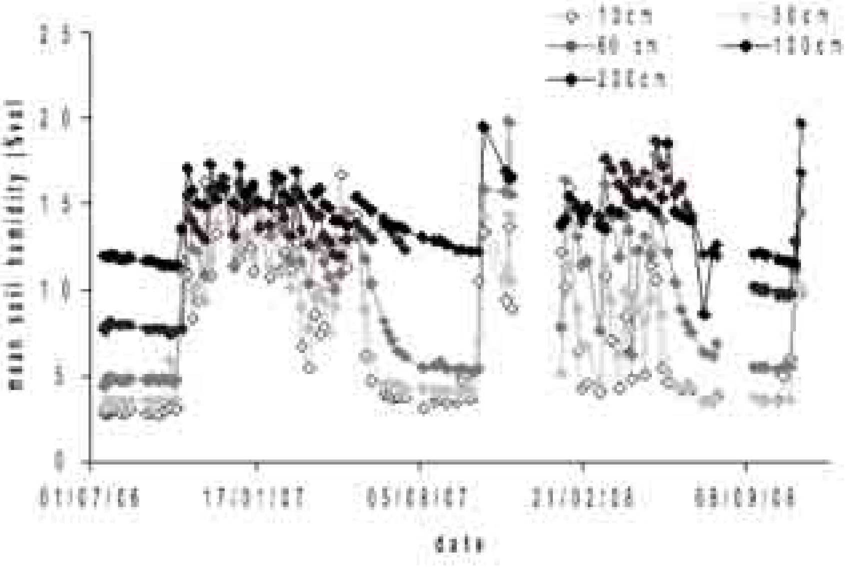
The rainfall presented an interannual variation (fig 1). To study the effect of the rainfall on the vegetation growth, we choose the annual fire as the start point of year of study. During the period July 2006-fire 2007 (June 16, 2007), the rainfall was 2172 mm whereas the rainfall was only 1608 mm between the period fire 2007-fire 2008 (July 2, 2008). The main difference between the two years was linked to the existence of a marked “short dry season” between December 2007 and April 2008, whereas this short dry season did not exist in 2006-2007.

FIGURE 1
Monthly rainfall (in mm) at Tchizalamou site



The soil moisture varied with the soil depth (fig. 2). Only the superficial layers (from 10 cm to 60 cm) presented a large variation of the soil moisture between seasons. During the dry season, the soil humidity was as low as 3 % (vol) at 10 cm and 30 cm depth. During the rainy season, near the rain event, the soil moisture raised to 16 % but in average it was around 10 %. Below 1m depth, a small decrease in soil moisture was observed during the dry season (7 % at 1m depth and 11 % at 2m depth). During the rainy season, the soil moisture raised 17 %. These variations in the top layers and the relative stability in the deep layers are linked to the root front that stops at 65 cm depth.

FIGURE 2
Mean soil volumic humidity (in %) at the different depths : 10 cm, 30 cm, 60 cm, 100 cm and 200 cm depth



Missing values are due to a failure of the measure system. n=2

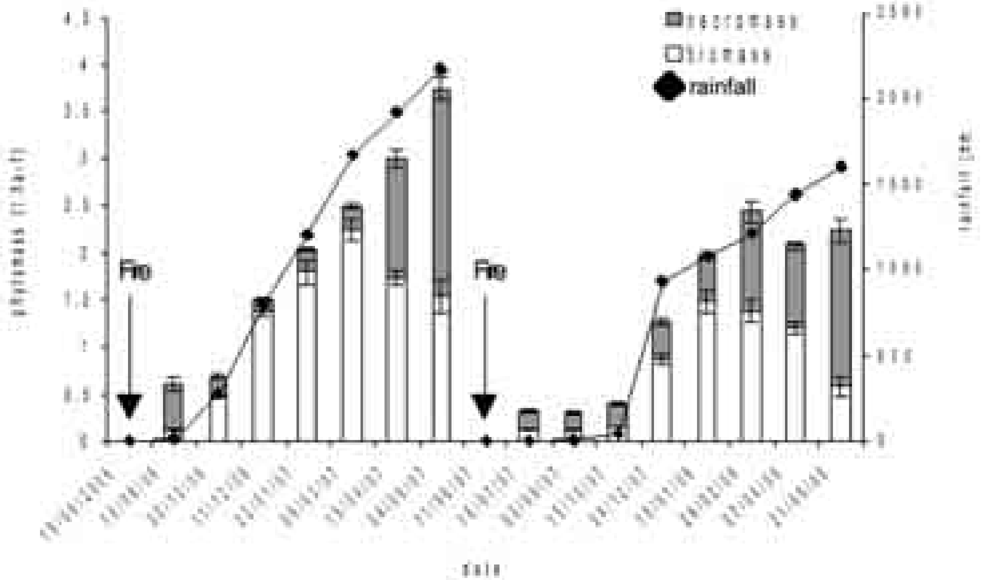
The sandy texture of the soil (more than 90 % of sand, less than 5 % of clay) explains the low values of soil moisture during the dry season and the low water retention capacity of the soil (Laclau *et al* . 2000).

Aboveground Biomass

Aboveground biomass dynamic was linked to the rainfall, especially during the dry season and at the beginning of the rainy season (fig. 3). However, the biomass stagnated and then decreased from March in 2007 and from January in 2008. The maximum of the biomass was 2.2 t.ha-1 (± 0.1 t.ha^{-1}) in March 2007. During this transition, the aerial necromass grew and reached its maximum at the beginning of the dry season (June 2007). In 2008, the necromass appeared earlier than in 2007, due to an exceptionally long "short dry season" (stretching from December 2007 to April 2008). The evolution of biomass and necromass is linked to the type of vegetation, made of 90% of grass. Once the ears were mature, the vegetation stagnated and dried out.

FIGURE 3

Mean aboveground phytomass



Biomass in white and necromass in grey (histogram, in t.ha-1, first X axis) and rainfall (curve, in mm, second X axis) at each biomass harvest. Errors bars represent the standard errors. n=16.

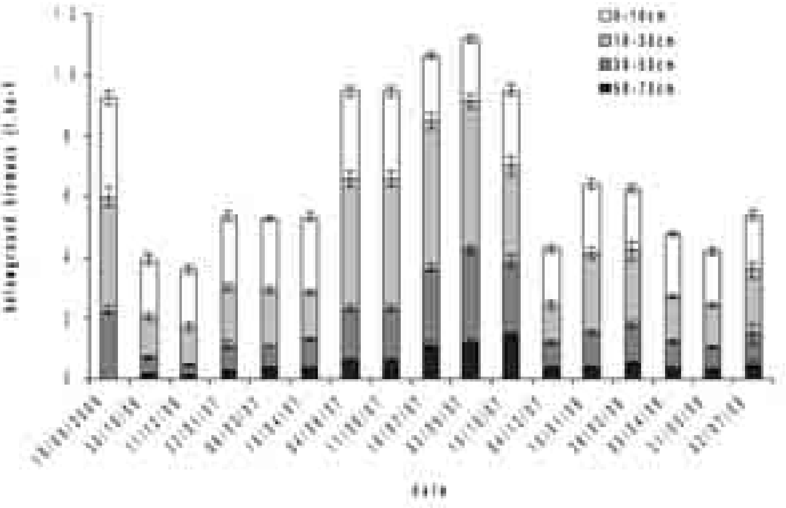
The maximum of the aboveground phytomass (biomass and necromass) was observed in June 2007 with 3.8 t.ha^{-1} (± 0.2 t.ha^{-1}).These results are lower than those of Laclau *et al.* (2002) who obtained a maximum aboveground phytomass (biomass and necromass) of 5.3 t.ha^{-1} (± 0.7 t.ha^{-1}) in June. Nevertheless, the general dynamic was the same in this study, made at 50 km of our site, in the same type of savannah. At Lamto, in Ivory Coast, Gignoux *et al.* (2005) found a maximum aboveground phytomass (biomass and necromass) of 4 to 8 t.ha^{-1}, depending on climate for the grass. As in our case, the necromass appeared in Lamto after 1 to 4 months of growth.

Root Biomass

The root biomass varied from 3.6 t.ha^{-1} ± 0.2 t.ha^{-1} in December 2006 to 11.2 t.ha^{-1} ± 0.4 t.ha^{-1} in September 2007 (fig. 4). The variations were not significant in the layer 0-10 cm but were significant in the layers 10-30 cm and 30-50 cm.

FIGURE 4

Mean belowground phytomass (in t.ha-1) at each biomass harvest



Error bars represent the standard errors. n=16.

The increase in root biomass seems to be related to the drying of the aboveground biomass. It appears that roots are used as carbon storage during the long dry season. In a less evident way, the same relations can be observed between December 2007 and April 2008. When the rains return, the root biomass decreases. This might be due to a transfer of carbon from the root to the aerial part, in order to produce new leaves (Hanson *et al.* 1988; Lambers *et al.* 1998).

At Kondi, Laclau *et al.* (2002) observed a maximum value of the root phytomass of 8.7 t.ha^{-1} in April and a minimum value of 6.3 t.ha^{-1} in July, before the fire. The process does not seem to be the same at Tchizalamou. This might be due to a difference of dominant species.

At Kissoko, at 60 km of the site, Nouvellon *et al.* (2008) measured a root phytomass of 6.3 t.ha^{-1} in March.

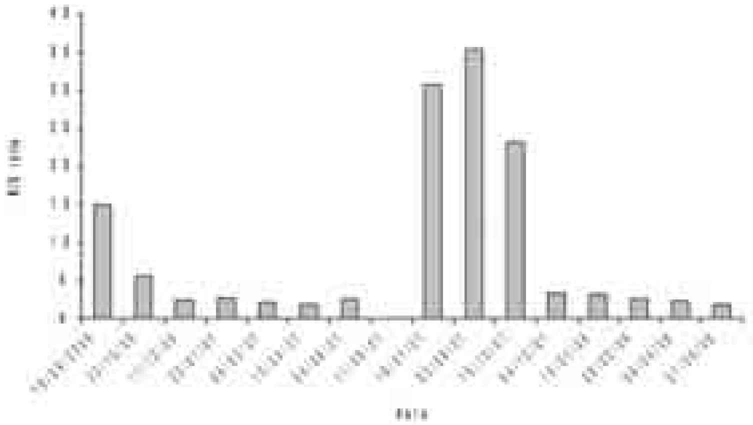
At Kondi, the biomass of roots found in the top 50 cm represented about 80 % of the belowground biomass, regardless of the season (Laclau *et al.* 2002). At Kissoko, about 77 % of the root biomass was found in the first 30 cm (Nouvellon *et al.* 2008). Based on theses observations made on the same ecosystem as ours, our sampling up to 70 cm deep seems to be enough to have a good estimation of the root phytomass.

Root/Shoot Ratio

The roots are the most important part of the total biomass (fig 5). The Root/Shoot ratio ranges from 1.7 at the maximum vegetation (in April) to nearly 40 after the destruction by the fire of the aerial part. At the maximum of vegetation, the value obtained is higher than the Root/Shoot ratio measured at Kondi (1.4 in June). This might indicate that Tchizalamou is a less fertile site than Kondi.

FIGURE 5

Mean Root/Shoot ratio at each biomass harvest calculated from mean aboveground and mean belowground biomass

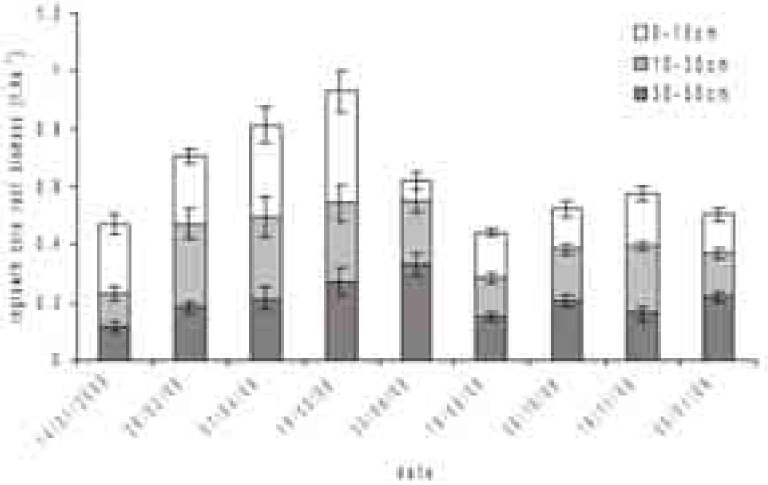


Ingrowth Cores

Ingrowth-core root biomass was higher from January to May 2008 corresponding to the maximum of the aboveground biomass (fig 6). During the dry season (June- September), root biomass remained high in the deep horizons, while it decreased in the shallow horizon. The further rain resumption from October corresponds to the root biomass increase.

FIGURE 6

Mean root biomass (t.ha-1) in the ingrowth cores at 0-10cm, 10-30cm and 30-50 cm depth



Errors bars represent the standard errors. n=20.

During the dry season, the growth of the roots below 10cm-depth is probably due to the carbon storage in the depth horizons. It can also be explained by a roots seeking water at greater depths. However, the humidity probes showed that the water is deeper than 60 cm depth.

The transfer of carbon from old roots to shoots seems to occur simultaneously with a production of new roots (the only ones observed on the ingrowth cores) that should absorbed water and nutrients.

Aboveground an belowground Productions

As the aboveground biomass stays standing and falls on the soil, the maximum-minimum method gives a good approximation of the aboveground production. The mean aboveground production was 3.8 t.ha^{-1}.year^{-1} (± 0.2 t.ha^{-1}.year^{-1}). At Lamto, the aboveground production in the *Loudetia* grass savannahs varied from 4.7 to 7.8 t.ha^{-1}.year^{-1} (Gignoux *et al.* 2005). This production was 5.3 t.ha^{-1}.year^{-1} (± 0.7 t.ha^{-1}.year^{-1}) at Kondi (Laclau *et al.* 2002).

At Tchizalamou, total root production during all the experiment was almost identical for the three soils horizons (1.7, 1.7 and 1.8 t ha^{-1}.year^{-1} respectively for 0-10, 10-30 and 30-50 cm, leading to a total of 5.2 t.ha^{-1}.year^{-1}).

In the *Loudetia* grass savannah in Lamto, the root production estimated with sequential cores varied from 6.5 to 18.6 t.ha^{-1}.year^{-1}, depending on the year for a necromass proportion of 10 % (Gignoux *et al.* 2005). These values are much higher than those observed in our site. This might be due to the method we used- however, methods based on sequential cores (as in Lamto) usually give lower estimations of production than methods based on ingrowth cores (for the comparison of the methods, see Hendricks *et al.* 2006) .However, the difference of method should not be the only explanation as the aboveground production is also higher at Lamto than at Tchizalamou.

CONCLUSIONS

The savannah at Tchizalamou seems to be rather unfertile with belowground and aboveground phytomass lower than the phytomass found in Kondi (Republic of Congo) or in Lamto (Ivory Coast). As in the other savannahs, roots are concentrated in the superficial layers of the soil. We highlight a strong effect of the season and of the fire on the biomass production. The savannah seems to face the constraints by a stocking of the carbon in the deep roots (10-50 cm) during the long dry season. A part of this carbon is transferred to the aboveground biomass at the beginning of the rainy season to allow a quick start of the vegetation when the soil water content allows again the physiological activity of the plants.

Even through the root production and the aboveground production are not calculated during the same period, we can estimate that the total NPP of the grassland at Tchizalamou is 9 t(DM).ha^{-1}.year^{-1}, or 450 gC.m^{-2}.year^{-1} before the fire. These results have to be compared with the NPP obtained by the eddy-covariance method.

ACKNOWLEDGMENTS

We would like to thank CarboAfrica for their support and the chief and the guardians of the site, coming from the village of Tchizalamou, who did a great job to protect the site from the grassland fires. In particular, thanks to the guardians (Jean Jacques Makosso and Evariste Banguissa) who helped for the roots survey.

REFERENCES

Abbadie L., Gignoux J., Le Roux X., Lepage M. (Eds.), 2005. Lamto: Structure, Functioning, and Dynamic of a Savanna Ecosystem. Ecological Studies 179, Springer, New York, USA.

Collins N.M., 1977. Vegetation and litter production in southern guinea savanna, Nigeria. Oecologia 28: 163-175.

Dhillion S.S., Anderson R.C., 1994. Production on burned and unburned sand prairies during drought and non-drought years. Vegetatio 115: 51-59.

Fay P.A., Carlisle J.D., Knapp A.K., Blair J.M., Collins S.L., 2003. Productivity responses to altered rainfall patterns in a C4-dominated grassland. Oecologia 137:245–251.

Gignoux J., Mordelet P., Menaut JC., 2005. Biomass Cycle and Primary Production In Lamto: Structure, Functioning, and Dynamic of a Savanna Ecosystem. In: Abbadie L., Gignoux J., Le Roux X., Lepage M. (Eds.), Ecological Studies 179. Springer, New York, USA.

Guenni O., Marỉn D., Baruch Z., 2002. Responses to drought of five Brachiaria species. I. Biomass production, leaf growth, root distribution, water use and forage quality. Plant and Soil 243: 229–241.

Hanson J.D., Skiles J.W., Parton W.J.,1988. A multi-species model for rangeland plant communities, Ecological Modelling 44 : 89-123.

Hendricks J.J., Hendrick R.L., Wilson C.A.,Mitchell R.J., Pecot S.D., Guo D., 2006. Assessing the patterns and controls of fine root dynamics: an empirical test and methodological review. Journal of Ecology 94: 40-57.

Laclau J.P., Bouillet J.P., Ranger J., 2000. Dynamics of biomass and nutrient accumulation in a clonal plantation of Eucalyptus in Congo. Forest Ecology and Management 128: 181-196.

Laclau JP., Sama-Poumba W., Nzila J.d.D., Bouillet JP., Ranger J., 2002. Nutrient accumulation dynamics in a littoral savanna subjected to annual fires in Congo. Acta oecologica, 23:41-50.

Lambers H., Chapin III FS., Pons TL., 1998. Plant physiological Ecology. Springer, New York, USA.

L'Hôte Y., Mahé G., 1996. West and Central Africa mean annual rainfall (1951-1989), map 1:6 000 000. ORSTOM editions, Laboratoire de Cartographie appliquée.

Long S.P., Garcia Moya E., Imbamba S.K., Kamnalrut A., Piedade M.T.F, Scurlock J.M.O., Shen Y.K., Hall D.O., 1989. Primary productivity of natural grass ecosystems of the tropics: a reappraisal. Plant and Soil 115: 155-166.

Long S.P., Jones M.B., Roberts M.J. (Eds), 1992. Primary Productivity of Grass Ecosystems of the Tropics and Sub-Tropics. Chapman & Hall, London, UK.

Nouvellon Y., Epron D., Kinana A., Hamel O., Mabiala A., D'Annunzio R., Deleporte P., Saint-André L., Marsden C.,Roupsard O., Bouillet J.P., Laclau J.P., 2008 Soil CO_2 effluxes, soil carbon balance, and early tree growth following savannah afforestation in Congo: Comparison of two site preparation treatments. Forest Ecology and Management 255 : 1926-1936.

Ojima D.S., Dirks BOM., Glenn E.P., Owensby C.E., Scurlock J.O., 1993. Assessment of C budget for grasslands and drylands of the world. Water, Air, and Soil Pollution 70: 95-109.

Sala O.E., Austin A.T., 2000. Methods of estimating aboveground net primary productivity. In: Methods in Ecosystem Science, Sala O.E.,Jackson R.B., Mooney H.A., Howarth R.W. (Eds.). Springer, New York, USA.

Singh J.S., Lauenroth W.K., Sernhorst R.K. , 1975. Review and assessment of various techniques for estimating net aerial primary production in grasslands from harvest data. Botanical Review 41, 181-232.

Ground-based remote sensing of atmospheric trace gases in the tropics using FTIR-spectroscopy

Amekudzi L. K.[1], Messerschmidt J.[2], Preko K.1, Warneke T.[2], Notholt J.[2]

ABSTRACT

The tropics play a central role in global climate change. Emissions within the tropics, especially from biomass burning and plants contribute substantially to the global budgets of many important trace gases. Currently large uncertainties in the budgets of many trace gases in the tropics exist mainly due to lack of measurements in the tropics. The first FTIR-spectrometer for solar absorption measurements is being operated at Paramaribo, Suriname. From these observations, 20 different trace gases could be retrieved. The first measurements at the Paramaribo station showed excellent result of CO and C_2H_6. In collaboration with the Kwame Nkrumah University of Science and Technology (KNUST) in Ghana, we have planned to perform solar absorption measurements in Kumasi, Ghana. The location, which is a transition zone between the tropical rain forest and the savannah grassland, is well suited for the study of the composition of emissions from biomass burning and their impact in the upper troposphere. With the start of high precision measurements of greenhouse gases from space, the solar absorption measurements have become increasingly important for the validation of the space-borne measurements. Solar absorption FTIR-spectroscopy technique has been accepted as the most convenient ground-based remote sensing method for the validation of satellite measurements. Currently, the planned instrument for the KNUST, Kumasi project is being prepared at the IUP, University of Bremen, Germany. In this paper, some results from ship cruise from South Africa through West Africa will be presented, as well as some results from Paramaribo in Suriname.

Keywords: FTIR-Spectroscopy, Climate change, Biomass burning, CO, CH_4

INTRODUCTION

The Earth's atmosphere is undergoing rapid changes, mainly due to human activities. The results of deforestation, overgrazing, land degradation, biomass burning and industrialization have profoundly modified the composition of the atmospheric air and climate of the Earth (Scholes *et al.*, 2008). The consequences of these man-made activities include: depletion of stratospheric ozone, increase in

---

[1] Meteorology and Climate Science unit, Department of Physics, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana

[2] Institute of Environmental Physics and Remote Sensing (IUP/IFE), University of Bremen, Germany - Email: leoamekudzi@yahoo.com

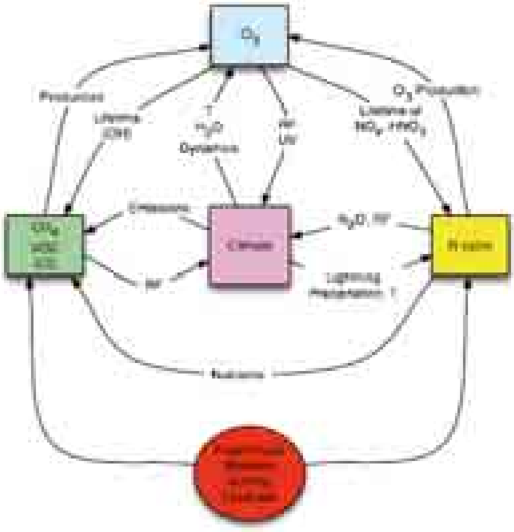
green house gas emission, large scale pollution, amongst others. Followed by the environmental and economic issues arising from these developments,

International agreements such as the Montreal protocol and the Kyoto protocol have emerged, which were also partially pushed forward by many global awareness and civic action of numerous non-governmental organizations. It came as no surprise when the Inter non-governmental Panel on Climate Change was awarded with the 2007 Nobel Prize for peace for their contributions over the last decade on these very important issues.

The primary product of biomass burning is Carbon monoxide (CO). Other sources of CO are oxidation of CH_4 and other biogenic hydrocarbons and fossil fuel combustion. The lifetime of CO ranges from weeks to a few months and it is an effective indicator of transport processes that distribute atmospheric pollutants from biomass and fossil fuel burning on a global scale. The main sink of CO is oxidation by OH. It has been reported in Crutzen and Zimmermann (1991) that atmospheric CO is responsible for more than half of the total turnover of OH. In addition, biomass burning provides an abundant source of green house gases (henceforth GHG) and other chemically active gases such as non-methane hydrocarbons and nitric oxide. These gases, along with methane, lead to the chemical production of tropospheric ozone, another GHG and tropospheric pollutant. Significant proportion of biomass burning activities and their related emissions come from the tropics. In the tropics, CO from biomass burning events can be effectively transported upwards by deep convection and can reach high altitudes in the tropical troposphere (Krishnamurti et *al.*, 1996; Sherwood *et al.*, 2000; Notholt, *et al.*, 2003).

FIGURE 1

Interactions between tropospheric chemical processes, biogeochemical cycles and the climate system



(adapted from IPCC, 2007).

To understand clearly the link between the chemical processes, biogeochemical cycles and the climate system shown in Figure 1 and the anthropogenic impact on climate, a number of scientific missions have been initiated. These missions include satellite observations, aircraft measurements, ground based measurements and modeling of atmosphere processes. In-situ measurements and remote sensing measurement from ground based instruments although limited in spatial coverage, provide a high quality and detailed information about localized events in the atmosphere.

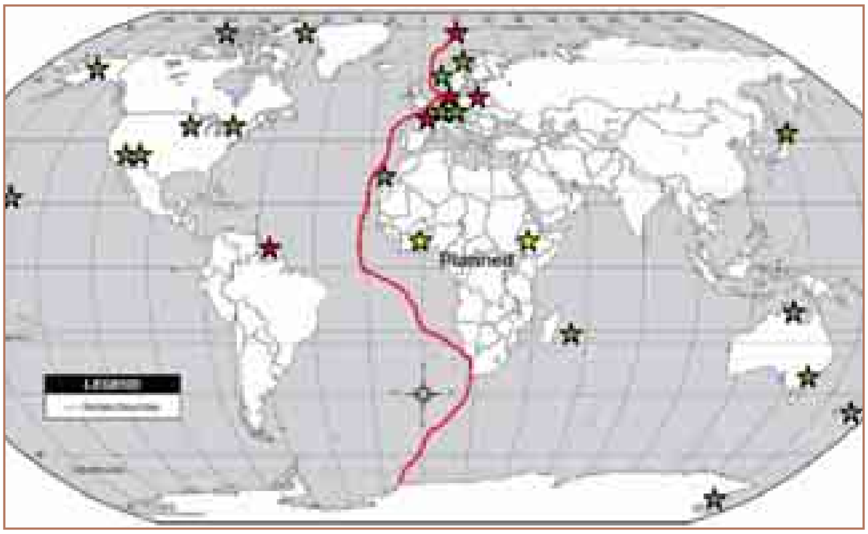
This paper will present results of CO from ship cruise from South Africa through West Africa, as well as results from a ground based observation from Paramaribo in Suriname. In addition, a planned ground based station, which is collaboration between institute of Environment Physics (IUP), University of Bremen in Germany and the Meteorology and Climate Science Unit (henceforth MCSU) in the Physics department of Kwame Nkrumah University of Science and Technology (KNUST) in Ghana will be discussed. Finally, on-going climate scientific research activities in MCSU as well as future research plans of our new institute will be discussed.

EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

Solar absorption Fourier-transform (FT) measurements aboard the research vessel Polarstern have been performed during a cruise on the Atlantic, starting from Cape town (33.9° S, 18.4° E) on 25 January 2003, through the West Africa and ending in Bremerhaven (53.5°N, 8.6° E) on 17 February 2003 (see Figure 2). Details about the cruise (ANTXX/3) as well as meteorological data can be obtained via the internet from the Alfred-Wegener-Institute (http:15//www.awi-bremerhaven.de/MET/Polarstern/GraphInter.html). The experimental setup is described elsewhere (Notholt *et al.*, 2000).

FIGURE 2

The ship cruise (red curve), ground based FTIR stations operated IUP Bremen (red star), other ground based FTIR (green star) and planned FTIR (yellow star)



The spectra were analysed using the line-by-line codes GFIT, developed at NASA/JPL (e.g. Toon *et al.*, 1992), the spectral line information of CO taken from the HITRAN-2000 database and other a-priori profiles (e.g. pressure, temperature, ozone and relative humidity) up to 30 km are taken from ozonesondes. The micro-windows were chosen and optimized according to the measurement site, the type of instrument and the line list database. A list of the target gases with the corresponding micro-windows, interfering species and the information content in terms of the degrees of freedom for signal is outlined in Table 1.

TABLE 1

Best micro-window for retrieving trace gases by infrared remote sensing

Retrieved Species	Microwindow(s) (cm^{-1})	Interfering species	DoF/Alt_{max} (km)
O_3	1000.0 – 1005.0 1110.0 – 1113.0 1117.3 – 1117.9 1120.1 – 1122.0	H_2O, N_2O, CH_4	5/35
CO	2481.70 – 2482.91 2069.55 – 2069.72 2157.40 – 2159.35	H_2O, N_2O, O_3, Solar lines	4/18
C_2H_6	2976.50 – 2977.20	H_2O, O_3, CH_4	2/30

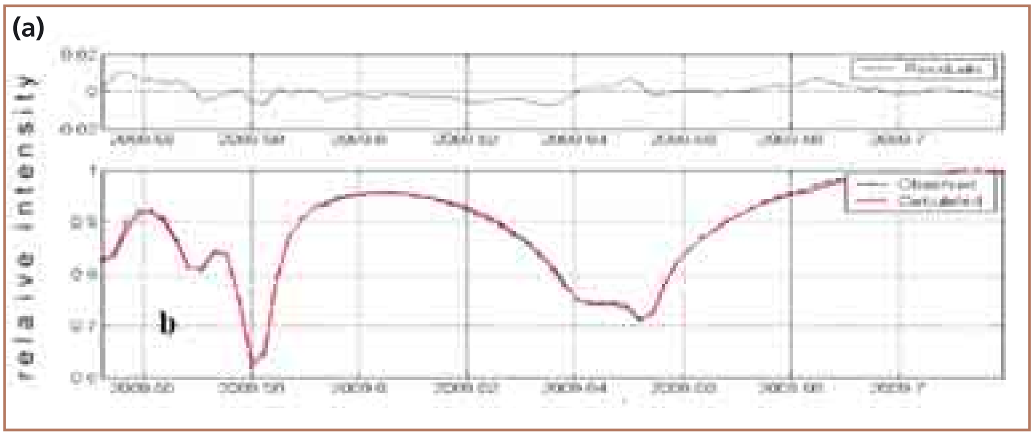
(Velazco 2006)

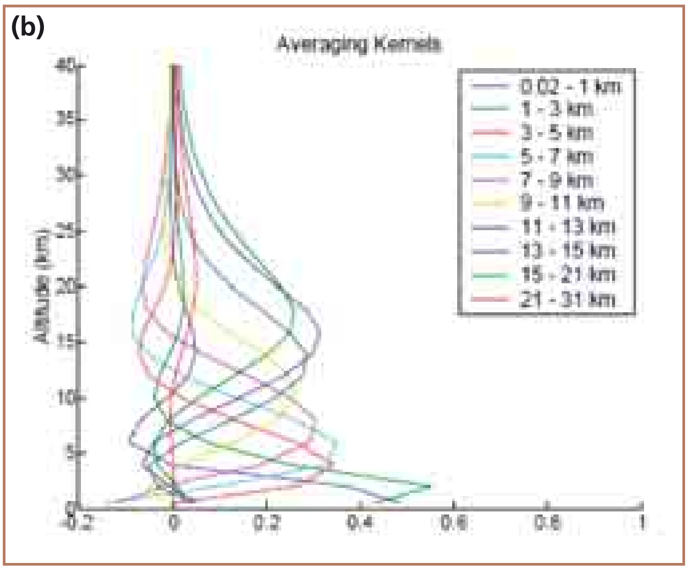
The choice of an appropriate a-priori profile for the retrieval process is very crucial to the optimal estimation retrieval approach employed for retrieving the CO and C_2H_6. For CO retrievals, the a-priori profile used has been adapted from the a-priori profile employed in the MOPITT retrievals (Bremer et *al.*, 2004) and C_2H_6 a-priori were taken from the average of balloon measurements done in the Arctic region (Velazco 2006).

Figure 3a shows the spectral fits of CO for the selected micro-windows, the spectral fits are good as strong CO absorption lines are mainly seen. Above the spectral fit in Figure 3a is the corresponding spectral residual, i.e., the difference between the measured and the modeled differential optical depth. The averaging kernels of the retrieval provide information on the vertical resolution and sensitivity (information content) of measurements for different altitudes. the CO averaging kernels for an optical path difference (OPD) of 90 cm, Solar Zenith Angle (SZA) of 51° and a signal to noise ratio of 500 from altitude range of less than 5 km up to about 35 km is shown in Figure 3b.

FIGURE 3

(a) Example of the spectral fits for the retrieval of CO profiles using the micro-window in Table 1 and (b) the averaging kernels for an optical path difference (OPD) of 90 cm, Solar Zenith Angle (SZA) of 51° and a signal to noise ratio of 500





RESULTS AND DISCUSSION

This section presents the results inferred using FTIR spectrometry method. We will show results of CO measured in the Atlantic on board the research vessel Polarstern. The ship track is shown in Figure 2. Thereafter results from Paramaribo, Suriname (5.8° N, 55.2° W) will be presented.

Measurement of CO and comparison results

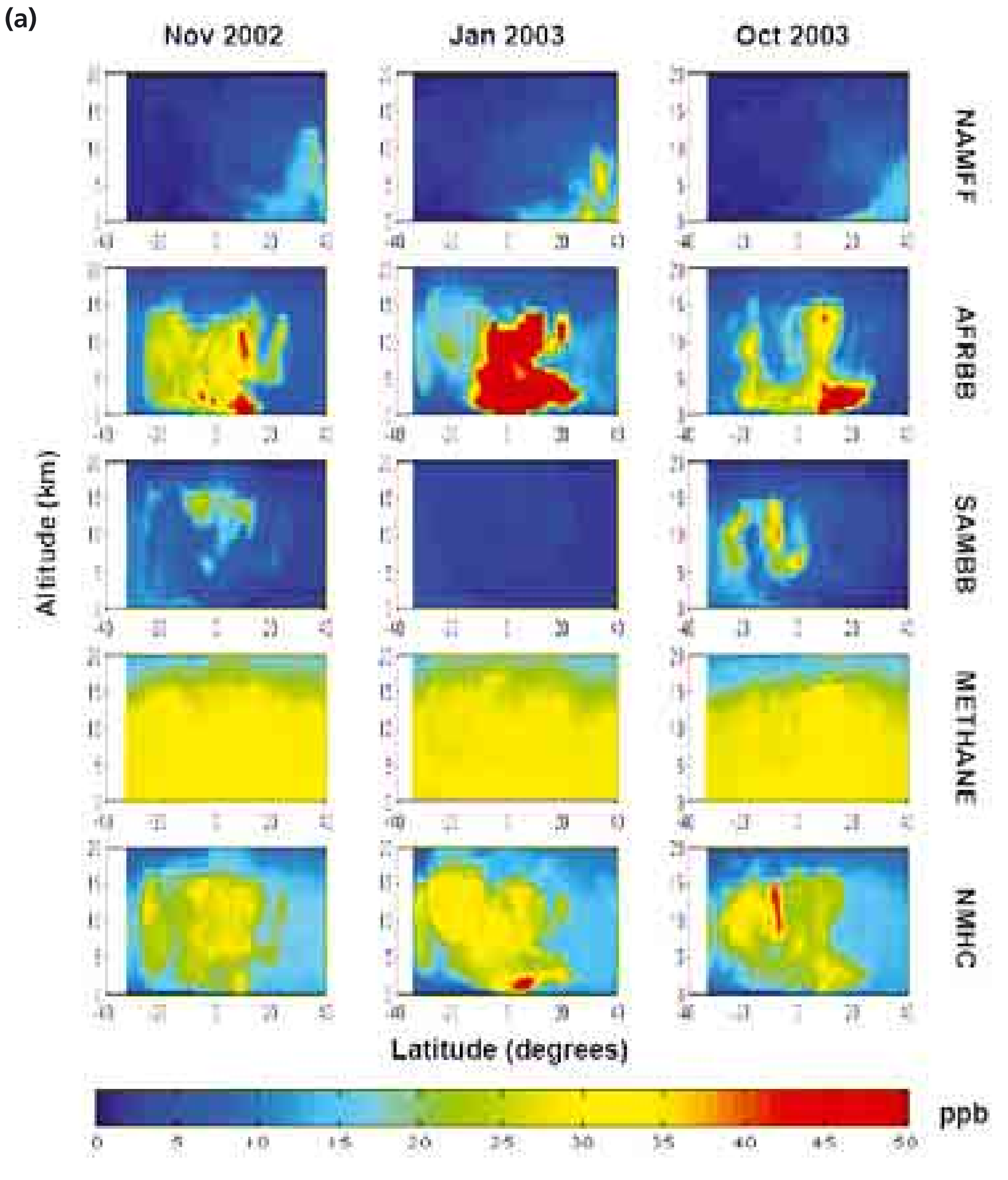
In order to assess the origins of the CO enhancements, the contributions of regional tracer fields from the MATCH-MPIC model were calculated. A selection of the most significant sources for the three cruises and their absolute contributions are shown in Figure 4a. Most of the CO in the equatorial regions come from African biomass burning (AFRBB), with more than 40% contribution during the cruise in Jan. 2003. Oxidation of non-methane hydrocarbons (NMHC) gives about 20-30% contribution to the enhancements in the upper troposphere in the southern hemisphere with the largest contribution during the cruise in Jan. 2003, where air parcels seem to have been entrained in vertical circulations. South American biomass burning (SAMBB) also contributes to the enhancements in the upper troposphere in the southern hemisphere especially for the cruise in Nov. 2002 and Oct. 2003 but SAMBB for the same region is almost absent during the cruise in Jan. 2003. Fossil fuel combustion from the North American continent (NAMFF) has a relatively stable contribution (up to about 20-25%) to the northern hemisphere CO measured in all three cruises. The most dominant source of the background CO is the oxidation of methane (see Figure 4a), which has contribution well above 30% and covers both the northern and southern hemispheres. Details of these results are given in Velazco (2006).

Volume mixing ratio of CO profiles from the MATCH-MPIC model, the FTIR on Polarstern cruise and MOPITT on the Terra satellite are shown in Figure 4b. The data are shown for the three cruises in Nov. 2002 (see Figure.4b, A-C), Jan. - Feb. 2003 (see Figure. 4b, G-I), and Oct-Nov. 2003 (see Figure 4b, J-L). All the three independent observations show similar structures regarding the CO profiles near the equator below 5 km and for most of the measurements in the lower troposphere in the northern hemisphere. The detail of this observation is given in Velazco *et al.*, (2005).

Satellite measurement of CO over the Atlantic and Africa show high values of CO over west and central Africa (see Figure 5). The observed column density values in these regions are in the range of (3.0 – 3.5) ×10^{18} molec./cm^2. As indicated earlier, the high values of CO in these regions are mainly due to biomass burning activities. A ground based FTIR observation station at Kumasi to be monitored by scientist from MCSU will provide a means to validate the satellite observation as well as providing information on detailed local biomass burning events.

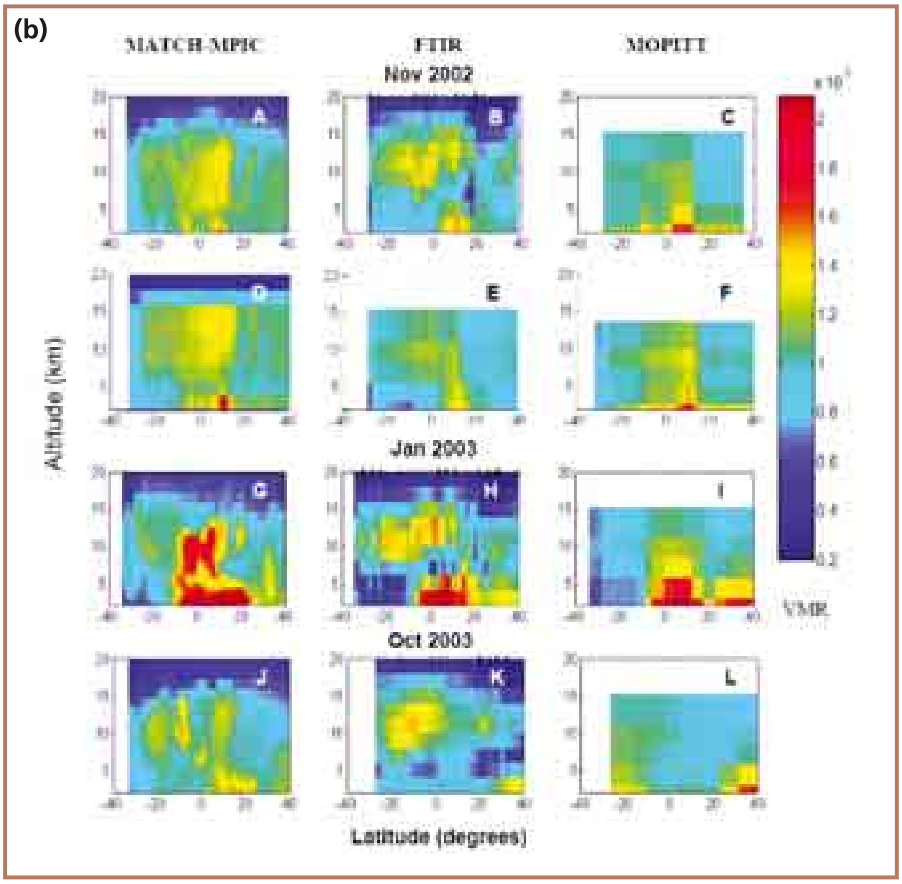
FIGURE 4

(a) Absolute contributions of each regional tracer field to the CO budget for the three cruises calculated from MATCH-MPIC (in ppb)[3]. (b) Comparison of CO volume mixing ratio data from MATCH-MPIC (left column), the FTIR on Polarstern (middle column) and MOPITT on the Terra satellite (right column)



---

[3] The CO tracer fields are; North American Fossil Fuel (NAMFF), South American Fossil Fuel (SAMFF), African Biomass Burning (AFRBB). There are also tracer fields of CO from methane oxidation (METHANE) and from NMHC oxidation (NMHC).

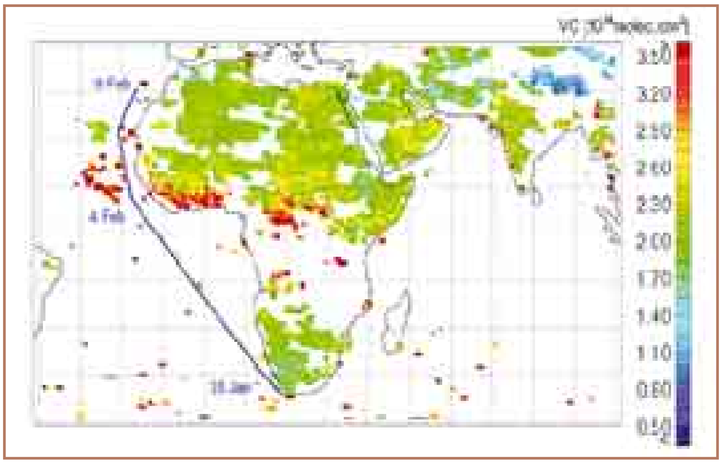


FTIR measurement at Paramaribo

The IUP FTIR has already been operated in a tropical station at Paramaribo in Suriname (lat 5.8°N, Long. 58.2°W). Retrieval results from this station are shown in Figure 6. The Paramaribo station is on similar latitude as the location of the new station in Kumasi, Ghana. Like Kumasi, the major source of CO and its related gases shown in Figure 6 are from biomass burning activities. Details about this result are reported in Petersen *et al.*, (2008). It has been shown elsewhere that these activities are seasonal (Velazco 2006 and references therein).

FIGURE 5

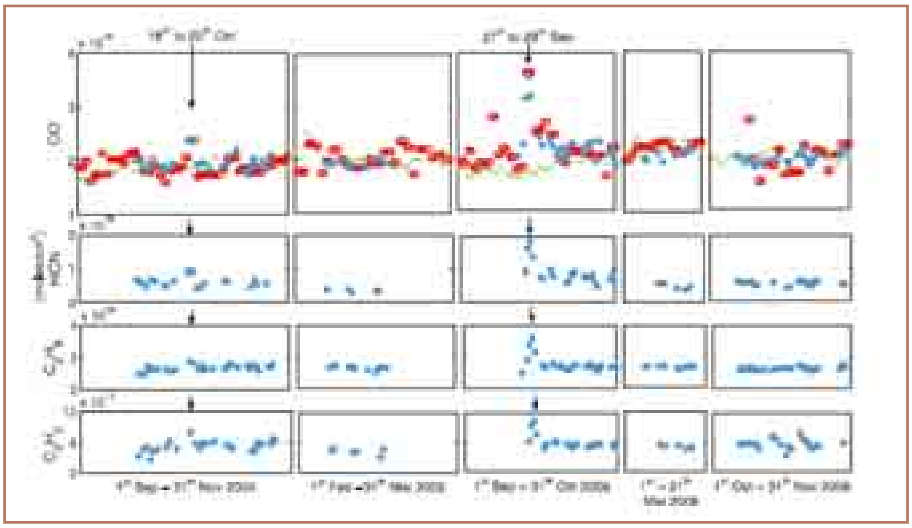
CO vertical columns from SCIAMACHY WFM-DOAS-retrievals (Version 0.4)



The plot includes all available WFM-DOAS data for the duration of the cruise (24, 27, 30, 31 January 2003 and 3, 4, 8 February 2003). Only cloudfree measurements with an error <60% were used (adapted from Warneke 2005).

FIGURE 6

CO (top), HCN, C_2H_6 (in middle) and C_2H_2 (down) are traces gases simultaneously retrieved from FTIR data measured at Paramaribo in Suriname (lat 5.8°N, Long. 58.2°W)



Blue is CO from FTIR, MOPITT in red and MPIC model in green.

CONCLUSIONS

Ground based solar absorption FTIR-spectrometry is a vital component of the global observing system for atmospheric trace gases. The use of ground based FTIR to remotely measure trace gases in Africa will complement the effort of satellite observation over the continent, in addition to provide detailed local information on biomass burning and emissions from other human activities. The FTIR spectrometer is well suited for the measurements of trace gases related to biomass burning and greenhouse gases.

Furthermore, ground based station in Africa will provide very useful data source for validation of satellite overpass. At present there are virtually no FTIR stations operating in Africa (see Figure 2). The planned FTIR site to be located in Kumasi, Ghana will be an important station for capacity building of African scientists in remote sensing observation and will provide very important data for satellite validation over the continent. At present funding is not available (i.e., not yet secured) for establishment of FTIR measurement site at Kumasi, Ghana.

The meteorology and climate science program established in the Physics Department of KNUST is preparing to carry out observation of O_3, NO_2 and aerosol particles using the Sun-photometer. Other experiments currently running include measurement of precipitation and evaporation using the pluvio range donated by University of Cologne in Germany. Other planned activities include crop/vegetation, hydrological, climate, and chemical modeling to investigate climate change and related contributions. We are therefore willing to collaborate with any institutions to prepare a common proposal leading to fulfilling the dreams of our institute in forming a very strong local research group.

ACKNOWLEDGEMENT

We are thankful to the German Ministry for Research and Education (BMBF) for funding the Polarstern cruises via the DLR-Bonn (Grants 50EE0013 and 50EE0014) and the team from Meteorological Service of Suriname and the Anton-de-Kom-University of Suriname for their cooperation. We are also grateful to Dr. Andreas Fink of University of

Cologne for donating pluvio rain gauges to KNUST, Ghana and the Dean of Faculty of Physical sciences KNUST, Ghana for supporting the FTIR-Ghana project.

REFERENCES

Bremer H., Kar J., Drummond J., Nichitu F., Zou J., Liu J., Gille G.C., Deeter M. N., Francis G., Ziskin D., Warner J., 2004. Spatial and temporal variation of MOPITT CO. In Africa and South America: A comparison with SHADOZ ozone and MODIS aerosol, J. Geophys. Res.,109, D12304.

Crutzen P., Zimmermann P.H., 1991. The changing photochemistry in the troposphere, Tellus, 43, 136-151.

Krishnamurti T. N., Sinha M. C., Kanamitsu M., Oosterhof D., Fuelberg H., Chatfield R., Jacob D. J., Logan J., 1996. Passive tracer transport relative to the TRACE A experiment. J. Geophys. Res., 101, 23,889-23,907.

IPCC: IPCC forth Accessment: Climate Change 2007, The Scientific Basis, Intergovernmental Panel of climate change.

Notholt J., Toon G.C., Rinsland C.P., Pougatchev N.S., Jones N.B., Connor B.J., Weller R., Gautrois M., Schrems O., 2000. Latitudinal variations of trace gas concentrations in the free troposphere measured by solar absorption spectroscopy during a ship cruise, J. Geophys. Res., 105, No. D1, 1337-1349.

Notholt J., Kuang Z., Rinsland C.P., Toon G.C., Rex M., Jones N., Albrecht T., Deckelmann H., Krieg J., Weinzierl C., Bingemer H., Weller R., Schrems O., 2003. Enhanced upper tropical tropospheric COS: Impact on the stratospheric aerosol layer, Science, 300, 307-310.

Petersen A. K., Warmeke T, Lawrence M. G., Notholt J., Schrems O., 2008. First ground-based FTIR observations of the seasonal variation of carbon monoxide in the tropics, Geophys. Res. Lett., 35, L03813.

Sherwood S., Dessler A., 2000. On the control of stratospheric humidity. Geophys. Res. Lett., 27, 2513-2516.

Scholes B., Ajavon A., Nyong T., Tabo R., Vogel C., Ansorge I, 2008. Global Environmental change (including climate change and adaptation) in Sub-Saharan Africa, ICSU regional office for Africa Science plan.

Velazco V., Notholt J., Warneke T., Lawrence M., Bremer H., Drummond J., Schulz A., Krieg J., Schrems O., 2005. Latitude and Altitude Variability of Carbon Monoxide in the Atlantic Detected from Ship-borne Fourier Transform Spectrometry, Model and Satellite Data. J. Geophys. Res. 110, D09306, doi: 10.1029/2004JD005351.

Velazco V., 2006. Studies on the Transport of CO and Related Biomass Burning Emissions Using Ground-based Fourier Transform Infrared Spectrometry, Ph.D Dissertation, Unversity of Bremen Germany.

Warneke T., de Beek R, Buchwitz M., Notholt J., Schutz A., V. Velazco, Schrems O., 2005. Shipborne solar absorption measurements of CO_2, CH_4, N_2O and CO and comparison with SCIAMACHY WFM-DOAS retrievals.

Soil and Vegetation: Carbon and GHGs emissions in Africa

3

West Africa´s savannahs under change: integrated view on positive and negative effects of agriculture and land cover changes on carbon cycling and trace gas emission.

Nacro H. B.[1], Struwe S.[2], Abbadie L.[3], Abekoe K. M.[4], Andersson M.[2], Attua E. M.[4], Badiane A.[5], Bilbao B.[6], Bonzi M.[7], Danso S. K. A.[4], Gignoux J.[3], Lensi R.[8], Khouma M.[5], Kjøller A.[2], Konaté S.[9], Manlay M.[10], Neill C.[3], Ouattara B.[7], Tondoh E. J.[9]

ABSTRACT

The WASAC project (West Africa´s SAvannahs under Change) was EU funded from 2002 to 2005 with the purpose of locating and analyzing data on carbon balance and carbon sequestration in the savannah region of West Africa. The project has focused on carbon and nitrogen pools in the savannah zone, aggregating data on plant cover, primary production, soil carbon, CO_2 fluxes and gas emission from soil. Emissions from fires are included and the fire effect on productivity as well as the use and effects of fallows. Results from the cultivation of common crops are considered with reference to different fertilization patterns.

The WASAC project has created a comprehensive database as tool for the analyses of carbon storage in different natural and cultivated ecosystems of the savannah zone.

In the analyses of the results collected it has been the aim to identify relationships that may cause variations in the carbon pools and their turnover under changing environmental conditions and different types of management.

---

1 Université Polytechnique de Bobo 01 BP 1091, Bobo-Dioulasso, BURKINA FASO

2 Department of general microbiology, University of Copenhagen, Solvgade 83 H, 1307 Copenhagen K, DENMARK

3 BIOEMCO, 46, rue d'Ulm 75230 Paris Cedex 05, FRANCE

4 Dept of Soil Science University of Ghana, P.O. Box LG 59, Legon-Accra, GHANA

5 ISRA – DG, Route des Hydrocarbures - Bel Air, BP 3120 – Dakar, SENEGAL

6 Departamento de Estudios Ambientales, Universidad Simón Bolívar, Apartado 89000 Valle de Sartenejas, Caracas 1060 Edo. Miranda, VENEZUELA

7 INERA 01 BP 476 Ouagadougou, BURKINA FASO

8 Centre d'Ecologie Fonctionnelle et Evolutive, 1919 Route de Mende, 34000 Montpellier, FRANCE

9 Université d'Abobo Adjamé, 23 BP 4727 Abidjan 23, COTE D'IVOIRE

10 ENGREF, DFRT/MOST, 648 Rue Jean-Francois Breton, BP 4494, 34093 Montpellier Cedex 05, FRANCE

Some interesting relations are:

- NPP correlates with precipitation and with other environmental variables;
- there are relatively high amounts of carbon in deeper soil layers;
- emissions of N_2O from the savannah region have been found to be lower than the figures quoted by IPCC.

The CENTURY model shows predictions of a moderate loss of soil carbon in different Global Change scenarios like increasing temperatures but also selective sensitivity to changes in moisture by photosynthesis and respiration. Many of the existing results from Africa have been published by few groups and originate from campaigns while a more substantial and systematic data collection seems to be missing. It is therefore the recommendation to establish:

- baseline studies to survey carbon cycle better for sinks and sources;
- long periods of observation – 5-10 years – to allow calibration of useful modeling of SOM and other carbon and nitrogen pools and fluxes;
- analysis of integrated management for food production and carbon sequestration;
- increased awareness of the connectivity between climate, environment, and land-use for food production;
- implementation of large scale projects to assist stakeholders in the region to enter into the carbon trade system under the clean development mechanism.

Keywords: Savannah, Carbon, Nitrogen, Precipitation, Clay, GHG

INTRODUCTION

The WASAC project has been funded by EU from 1 October 2002 to 30 September 2005 with the purpose of locating and analyzing data on carbon balance and carbon sequestration in the savannah region of West Africa. Though identifying and collecting carbon data were the main focus of the project several parallel themes on nitrogen, greenhouse gas emissions and soil productivity have been investigated.

The main end product from the project would be a book synthesizing existing results.

The scientific background and inspiration for the project is primarily found in the research which has taken place at the Lamto station in Côte d´Ivoire and the experience gathered from several decades of work over a broad field. The close interaction between African and French scientists was a focal point for formulating the WASAC project. Along with that other African – European partnerships have given the impetus to develop a larger project investigating the savannah region, the potential for carbon storage, the options for sustainable cultivation with minimized emissions and losses of nutrients. The Danish DANIDA funded FITES project on effects of fires is one of these larger projects but in addition several bilateral projects have created the fundament for WASAC.

One important reason for analyzing the development of the productivity of ecosystems in West Africa is the current demographic situation where populations are growing with an annual rate of 2-3%. These changes in population size and structure lead to a demand for increased food production ranging from basic corn and starch products, vegetables and fruits to animal products – unrefined or processed. In order only to provide the increasing population with food the increase in food production should increase proportional with the population development and if an improved nutritional value and a more varied output should be offered, the production increase needs to be higher. In all regions different cash-crops are important sources of income for the farmers/villagers and also the demand for areas necessary for these crops will increase considerably with an increasing population.

Issues to be considered:

- use of manures: do we know enough on collection, storage and distribution?
- are there other biodiversity considerations to be considered in view of this intensification of farming, both in relation to plants and to wildlife?? If cattle breeding is further marginalized it may have consequences for wildlife conditions.
- is there a solid relationship between soil carbon pools and flows of carbon?
- is there a clear relation between soil carbon content and mineral content (fertility!) – or may such a relationship be established for soil types or for regions?

MATERIALS AND METHODS

The WASAC project aims to provide a holistic synthesis considering the short, mid and long term positive and negative effects of West African agriculture and land cover changes on carbon cycling and trace gas emission. The project will collect the available data (time series when possible) in West Africa on carbon accumulation in soils and trace gas emissions. Results from natural savannah and forest, grazing land, fallows and crop fields will be analyzed. Special attention will be paid to different types of existing agricultural systems; fertilized or unfertilized crop fields, monocultures or mixed cultures and grasslands, in order to reach a complete view of the available knowledge on agricultural practices and Global Change issues and to identify the gaps where more research is needed.

RESULTS AND DISCUSSION

Net primary production in West African savannahs

The maximum aboveground grass biomass (MAGB) at the end of the growing season is used as an estimate of net primary production (NPP). The analysis of factors regulating NPP in savannahs of West Africa revealed that:

- mean annual precipitation explained 64% of the variation in MAGB.
- only 30% of the variation in MAGB was explained by the annual precipitation measured in the same year as determination of NPP (Fig. 1). This suggests that local factors are important for the size of MAGB.
- a fair relationship between MAGB and soil carbon (SOC) was found (R^2 =35%) (Fig. 2).
- no relationship was found between clay content and MAGB.

The higher correlation between MAGB and SOC compared to clay content implies that SOC is more important than clay for the retention of minerals, which serves as nutrients for plant growth.

There was a clear relationship between net root production and MAGB (Fig. 3). The distinct slopes representing the root-shoot ratio of two sub data sets shows that for perennials 66% of the total production is belowground, while for annuals the same proportion of net production occurs above- and belowground (Fig. 3).

FIGURE 1

Relationship between maximum aboveground grass biomass (g DM m^{-2}) and mean annual precipitation (mm)

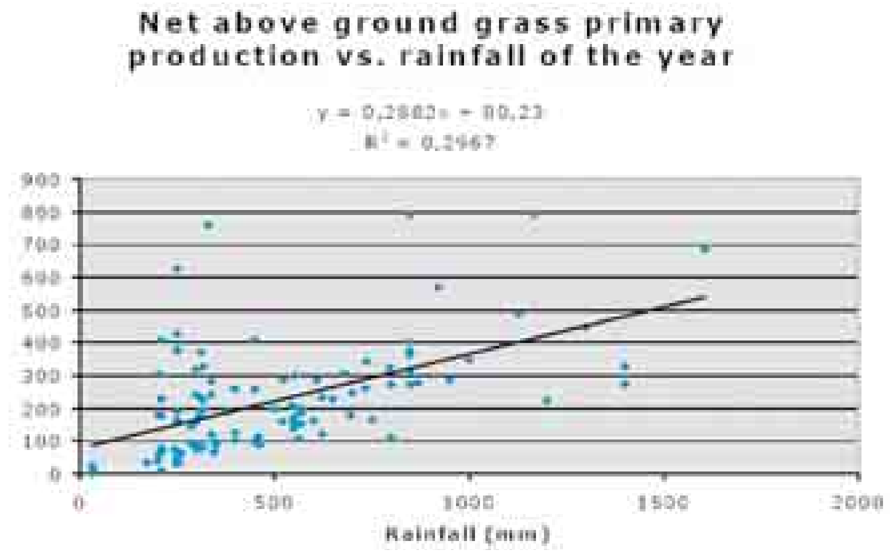


FIGURE 2

Relationship between maximum aboveground grass biomass and soil carbon

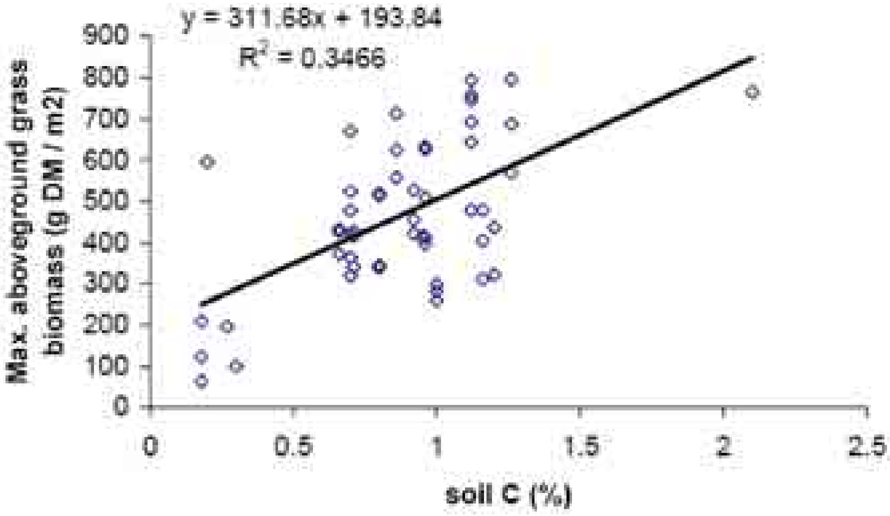
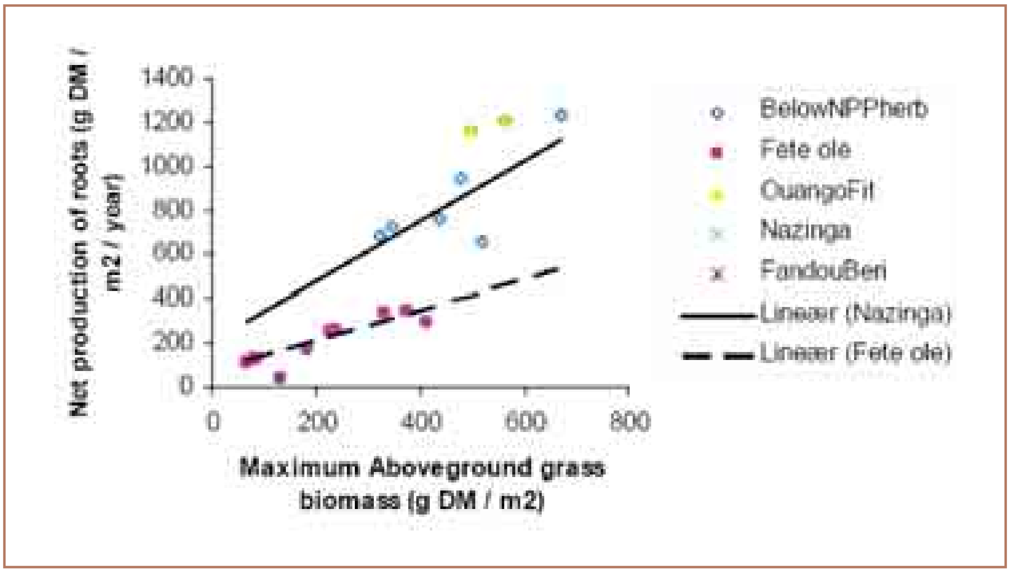


FIGURE 3
Relationship between net production of roots and maximum aboveground grass biomass



Solid line represents vegetation with perennial grasses (root : shoot ratio = 2:1) and broken line represents vegetation with annual grasses (root : shoot ratio = 1:1).

Soil organic matter

Climate, soil type and vegetation usually act together to influence the soil content of organic carbon. Primary production in many savannahs is low, due to low rainfall and poor soil fertility, which leads to a low soil organic matter content (Scholes and Hall, 1996). Indeed, in the Sudanian zone of West Africa, soils are characterized by their low organic carbon content. There are several reasons for the low level of soil organic matter (SOM) and why soils quickly become infertile:

- the quantity of organic matter entering the soil system is reduced by annual vegetation burning, where most of the standing biomass is burned, and by grazing.;
- continuous cropping leading to a progressive decline of organic matter content (Piéri 1989, Kang 1997, Shepherd and Soule 1998);
- the very low storage capacity of sandy soils (Jenny, 1941; Feller, 1994);
- the dominant clay fraction kaolinite in West African soils has a weak capacity for cation exchange and low capacity for physical binding with organic matter;
- the high maximum temperatures and the alternating wetting and drying conditions favor decomposition over production and large soil respiration losses;
- the lack of synchronization between the nutrient demand of plants and nutrient availability.

Soil carbon stock is controlled by climate, vegetation, topography, parent material, time and management (Jenny 1941; Casanova 1991; Trumbore 1997). Most of the traditional carbon models explain soil carbon content as a function of vegetation residues returned to soil (Parton 1987), although recently the soil carbon saturation concept emphasizes the importance of soil physico-chemical properties to stabilize carbon in soil (Six *et al.*, 2002). Physical stabilization or microaggregation and chemical stabilization by means of organo-mineral complex formed with clay and silts are considered as the principal physico-chemical mechanism by which soil carbon is protected against decomposition and leaching (Six *et al.* 2002). Thus, a statistically significant relationship was observed between SOC and the soil clay content. The low SOC and clay contents seem to limit the potential capacity to store soil organic matter in West African savannahs, the sandy soils present a low carbon saturation level due to low clay content (Six *et al.*, 2002). Furthermore the SOC associated with sand is essentially particulate consisting of fine roots and plant fragments, being more labile than clay or silt bound SOC.

Land Management applications

In West African savannahs, cropping systems are characterized by intermittent cultivation with short periods of cropping alternating with shorter or longer periods of fallow (5 to 30 or more years). A progressive decrease of organic matter content was observed during the cropping period, and the soils become quickly infertile. Although there are low contents of SOC in soils of West African savannahs relative high values of pH and cation exchange capacity seem to allow the establishment of local cropping systems. However, the rapid decline of fertility seems to be related to the more labile SOC associated with sandy soils of these savannahs, conferring a low resilience to the conservation of SOC of the cropping systems.

Although it is commonly accepted that fallow will increase soil C content, and influence soil physical and biological properties in a favourable way for plant production and crop growth, many authors found no significant changes of soil carbon content after cultivation. Many different approaches have been used to understand the changing soil processes during the fallow period, soil structure, clay content and clay type (i.e. 2:1 versus 1:1), cropping history (land management), microbial biomass, and climatic characteristics (amount, distribution and intensity of rainfall, temperature). The low clay content reported indicates the low potential capacity to store soil organic matter in West African savannahs thus limiting the effectiveness of the fallow periods in the recovery of the soil fertility.

CONCLUSION

The texture of West African savannah soils dominated by sand with a clay content lower than 40% is a serious limitation. These characteristics restrict capacity of the soil to retain SOC making it more labile to the degradation process than clay or silt bound SOC. Positive characteristics are the pH values near neutrality that compensates the low clay and soil organic matter contents to sustain moderate levels of cation exchange capacity under these conditions. Recovery of natural vegetation seems to be the unique way to restore soil fertility. In comparison, South American savannah soils have pH limitations associated with Al toxicity that inhibit growth of crop species and reduce the soil cation (Ca, K and Mg) and P availability. This emphasizes the need for adequate liming as the first management practice for cultivating species that are not acid tolerant.

In order to be able to designate better management more insight into the processes determining SOC accumulation and cation storage under different cultivation practices seems needed to select systems providing at the same time stable productivity and reduced nutrient losses and emissions.

REFERENCES

Casanova E., 1991. Introducción a la ciencia del suelo. Edit. Litopar, CA. de Artes Gráficas. Caracas, Venenezuela. 393 pp.

Feller C., 1994. La matière organique dans les sols tropicaux à argile 1:1. Recherche de compartiments organiques fonctionnels. Une approche granulométrique. Doct. Sci. Nat., Univ. Louis Pasteur. Strasbourg, pp. 393.

Jenny H., 1941. Factors of soil formation. McGraw–Hill, NewYork. 281 pp.

Kang B.T., 1997. Alley cropping – soil productivity and nutrient recycling. Forest Ecology and Management 91, 75-82.

Parton W J, Schimel D S, Cole C V, Ojima D S, 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sciences Society American Journal. 51, 1173–1179.

Pieri C., 1989. Fertilité des terres de savane. Bilan de trente ans de recherche et de développement agricoles au Sud du Sahara. Ministère de la Coopération. CIRAD. Paris, 444 pp.

Scholes R.J., Hall D.O., 1996. The carbon budget of tropical savannas, woodlands and grasslands. In: Breymeyer A.I., Hall D.O., Melillo J.M., Ågren G.I. (Eds.), Global change: Efects on coniferous forests and grasslands, SCOPE 56, John Wiley & Sons, Chichester, UK. pp. 69-100.

Shepherd K.D., Soule M.J., 1998. Soil fertility management in west Kenya: dynamicsimulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture Ecosystems & Environment 71, 131-145.

Six J., Conant R. T., Paul E. A., Paustian. K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant and Soil 241, 155– 176.

Trumbore S.E., 1997. Potential responses of soil organic carbon to global environmental change. Proceedings of the National Academy of Science. 94, 8284-8291.

Estimates of CO_2 emissions from soil organic carbon for different land uses.

Bonsu M.[1], Adukpo D. C.[2], Adjei – Gyapong T.[1]

ABSTRACT

The study was carried out on acid soils (Ferralsols) at Ainyinasi in the High Rain Forest Agro-ecological Zone of Ghana in 1997. Samples were taken from the 0 – 15 cm depth in a virgin, one-year old cassava farm, recent maize farm, a fully established rubber plantation and a fallowed secondary forest. The organic carbon content of the soils was determined on air- dried samples sieved through 2 mm mesh using the wet oxidation method (Walkley and Black, 1934). Using the average bulk density of 1.4 Mg m^{-3} and soil depth of 0.15 m, the soil organic carbon was converted to kg ha^{-1} and the soil organic carbon (SOC) sequestered by the different land use types was converted to CO_2 by multiplying by 3.67 (Molar ratio of $^{44}/_{12}$).

The study showed that SOC sequestered was highest in the virgin forest soil, followed by one year old cassava farm, recent maize farm (slash and burnt), rubber plantation and fallowed secondary forest, in that decreasing order. Using the virgin forest as the standard of comparison, the one-year old cassava had emitted 13,860 kg ha^{-1} CO_2, the recent maize farm (Slash and burnt) had emitted 77,770 kg ha^{-1} CO_2, the fully established rubber plantation had emitted 88,550 kg ha^{-1} CO_2, while the fallowed secondary forest had emitted 94,710 kg ha^{-1} CO_2.

The study confirms that whenever the virgin forest is intact, the potential to sequester organic carbon is always high. Once the forest is converted to different land uses through vegetation removal decarboxylation processes set in to reduce soil organic carbon with accompanying CO_2 emissions.

Keywords: Estimates, CO_2 emissions, Soil Organic Carbon, High Rain Forest, Agro-ecological Zone of Ghana

INTRODUCTION

It is without doubt to recognize the fact that the evolution of the earth's atmospheric composition has been intimately linked with the development of life on earth. In recent times, it is becoming evidently clear that in addition to

---

[1] Department of Crop and Soil Sciences, Kwame Nkrumah University of Science and Technology (KNUST), Kumasi, Ghana

[2] Department of Physics, University of Cape Coast (UCC), Cape Coast, Ghana

biological and geochemical processes involved in maintaining the composition of the atmosphere, human activities have contributed significantly in shifting the composition of the earth's atmosphere from its natural equilibrium (Bonsu, 2007). Consequently, since 1991, estimates indicate that the global atmospheric concentration of CO^2 has been increasing at a rate of about 1.8 parts per million (ppm) or 0.0018% per year (Rosenzweig and Hillel, 1998).

In the course of the present century, the world population has increased from less than two thousand million to over five and a half thousand million. In the course of the next twenty-five years, a further two thousand million people will be added to the global population (FAO, 1994).

Increase in world population calls for increase in world food demand and consequently increase in food production. In Africa and most developing countries increases in food production will be achieved through cultivation of new lands, such as opening new forest lands through intensification of production on a non-sustainable basis.

Non-sustainable agricultural practices involving deforestation lead to partial oxidation of soil organic carbon and the release of CO_2 into the atmosphere. Also, the burning of forests for the purpose of land clearing and the oxidation of carbon compound in the vegetation are additional sources of emissions of CO_2 through land use into the atmosphere (Parker, 2009).

Further, deforestation consequently leads to soil erosion which exposes organic carbon in the soil to rapid oxidation resulting in CO_2 release into the atmosphere. Serious soil erosion with its attendant nutrient losses means that as the forest is left to regenerate, (as one of the common practices in Africa), the original carbon density will not be achieved because the original forest cut may not be re-established. Consequently, a scrub or shrub with less carbon density may be formed instead. Therefore, soil carbon content of bush fallows scarcely reaches that of the original forest (Nye and Greenland, 1960).

Estimates of carbon release by some developed countries from industrial sources and those released through land use changes in some developing countries are presented in Table 1 (Rosenzweig and Hille, 1998). The Data depict that carbon released from industrial sources far exceeds carbon released from land use changes.

TABLE 1

Carbon released by some countries from industrial sources and land use changes

Country	Carbon from industrial sources (million tones)	Country	Carbon from land use changes (million tonnes)
U.S.A	1135	Brazil	454
Russia	901	Indonesia	124
China	413	Burma	83
Japan	226	Mexico	64
Germany	181	Thailand	62
U.K	141	Colombia	59
Poland	112	Nigeria	57
France	111	Zaire	57
Italy	88	Malaysia	50
India	78	India	41

The aim of this paper is to attempt to estimate carbon dioxide emissions from soil organic carbon under different agricultural land use systems. The carbon dioxide emissions from the different land use systems will be compared with emissions from intact virgin forest in the same vicinity.

MATERIALS AND METHODS

This study was carried out in 1997 as part of sustainable land use study in the High Rainforest Ecological Zone of Ghana. The soils in this ecozone are basically acid, with low nutrient reserves, high aluminium fixation and low effective cation exchange capacity. In spite of these fertility constraints, natural virgin forests abound on these acid soils because of effective nutrient cycling mechanism resulting from organic matter (Nye and Greenland, 1960). This Ecozone has mean annual rainfall of 2200 mm per year. The rainfall is bimodal. The major rainy season starts in April and ends in August, while the minor rainy season begins from September to November.

Sampling and soil preparation

The soils from the High Rainforest Zone at Aiyinasi in the Western Region of Ghana were used for the study. The soils are Ferralsols (FAO) or Oxisols (USDA). The soils in this ecozone have been rendered acid because the excessive rainfall in the area has helped leaching of the basic cations and the replacement of these by Al and H ions on the exchange complex (Bonsu, 1991).

Bulk soil samples were taken from the top 0 – 15 cm depth with the help of a spade in an intact virgin forest, a one-year old cassava Farm, recent maize farm (slashed and burnt) an established rubber plantation and a bush fallow. The soils were air-dried and passed through a 2 mm sieve. The soil separates that passed through the 2 mm sieve were used for the study.

Some physical and chemical analyses of the soils

The particle size distribution of the soils was determined by the hydrometer method (Bouyoucos, 1951) after digesting the organic matter with hydrogen peroxide and dispersing the soils in sodium hexametaphosphate (calgon).

The organic carbon content of the soils was determined by wet oxidation with potassium dichromate followed by titration with ammonium ferrous sulphate using diphenylamine as an indicator (Walkley and Black, 1934).

The pH of the samples was determined in water using soil: water ratio of 1:1 by a standard pH meter in the laboratory.

Conversion of soil organic carbon to CO2

To convert soil organic carbon to CO2, the fraction of soil organic carbon relative to the amount of soil was multiplied by the bulk density of the soil and the depth from which the samples were taken and converted to kilogram per hectare. The final result was multiplied by a factor of 44/12 (i.e. molecular weight of CO_2/ atomic mass of C) to convert the carbon to carbon dioxide.

RESULTS AND DISCUSSIONS

The texture of the soils (Table 2) shows very slight variations and ranges from sandy loam to sandy clay loam. As expected for these soils, the PH values are low indicating acid reaction. As expected, the organic carbon content is highest in the virgin forest and lowest in the bush fallow. Generally, the organic carbon content is not very high, even in the virgin forest, because the acid nature of the soils precludes organic carbon accumulation. However, comparison of the different land uses with the virgin forest indicates significant decrease in soil organic carbon when the intact virgin forest is cut and used for agricultural purposes (Table 3).

Using the virgin forest as the standard for comparison, the one-year old cassava farm has emitted about 1387 kg/ha CO_2 or 7.3% of carbon sequestered in the forest. The recent maize farm has emitted 7784 kg/ha CO_2 or 40.7% of carbon sequestered in the virgin forest. The fully-grown rubber plantation has emitted 8863. kg/ha CO_2 or 46.4% of carbon sequestered in the virgin forest, while the bush fallow has emitted 9479.61 kg/ha CO_2 or 49.6% of the carbon sequestered in the virgin forest (Table 4).

TABLE 2

The texture of the acid soils

Land Use	Sand (%) 2-0.02mm	Silt (%) (0.02 – 0.002mm)	Clay (%) 10.002mm)	Texture Class
Virgin forest	77.9	5.5	16.6	SL
One year old Cassava farm	72.4	7.7	19.9	SL
Recent maize farm	72.6	5.7	21.7	SCL
Rubber plantation	71.7	5.9	22.4	SCL
Bush fallow	70.2	6.8	23.0	SCL

SL = Sandy Loam; SCL = Sandy Clay Loam

TABLE 3

Some properties of the soils, soil organic carbon and converted carbon dioxide (CO2)

Land Use	Bulk density (kg m^{-3})	Organic Carbon		$C0_2$ kg/ha	pH
		(%)	kg/ha		
Virgin forest	1400	2.48	5208	19113.36	4.4
One year old Cassava farm	1400	2.30	4830	17726.10	4.9
Recent maize farm	1400	1.47	3087	11329.10	5.4
Rubber plantation	1400	1.33	2793	10250.31	4.6
Bush fallow	1400	1.25	2625	9633.75	4.7

TABLE 4

Emissions of CO2 due to agricultural land use using the virgin forest as the standard

Land Use	CO_2 Emission	
	(kg/ha)	%
Virgin forest	-	-
One year old cassava farm	1387.26	7.26
Recent maize farm (slashed and burnt)	7784.07	40.73
Rubber plantation (20 years)	8863.05	46.37
Bush fallow (two years fallow)	9479.61	49.60

In recent years, population growth in the developing countries has been swift due to improved health care delivery (Bonsu, 2007). This implies that the demand for food and other agricultural products will continue to increase. Also, the time allowed for the land to rest for the vegetation to regenerate has decreased. This type of system is non-sustainable and does not permit soil organic carbon to be sequestered enough.

Further, high temperatures in the tropics, for example in Ghana (29.8 – 37.9 °C) promote rapid decomposition of soil organic carbon and the release of carbon dioxide into the atmosphere to compound the problem of global warning. Other limiting factors constraining carbon sequestration include:

- Physical degradation due to erosion
- Chemical degradation due to nutrient mining and acidification and
- Biological degradation due to loss of organic matter through removal of vegetation in the farm of forest clearing and rampant burning of vegetation.

It is important to note that the degradation of soil organic carbon in the tropical ecosystem becomes more serious because of the slow processes of natural fertility restoration. This is due to the fact that most of the soils in the tropics are not resilient, that is, their ability to return to their former condition after being subjected to stresses of land use is very weak (Lal, 1994).

In order to enhance carbon sequestration in the soils of the tropics, the following practices could be adopted (Bonsu, 2007).

- Nutrient requirements of the crops during the production period should be adequately satisfied through use of fertilizers.
- The physical conditions of the soil for crop production should be improved to limit soil degradation due to erosion. For example, adopting leguminous crop rotation and mulching practices
- Reforestation should be carried out using rapidly growing leguminous tree species instead of leaving the land under bush fallow to regenerate naturally.
- Conservation tillage practices should be adopted to boost carbon sequestration in cropped soils.
- Establishment of shelterbelts or windbreaks should be encouraged as a forest regeneration practice.
- Establishment of agroforestry practices involving a mixture of trees, horticultural and arable crops in the same field should be encouraged and finally
- Erodible lands should be retired from cultivation and placed under permanent forests

As a way of tropical land use, when areas covered with natural vegetation are transformed into cultivated fields, the above-ground material that is cut is often burned instead of allowing it to decompose to add to the soil carbon pool. In the process of burning, CO_2 is emitted into the atmosphere. The emitted CO_2 had been sequestered in plant biomass from prior photosynthesis. Estimates indicate that, the soil contains between 1.5 and 3 times as much carbon as living terrestrial vegetation and it is second to the ocean in the amount of carbon it contains (Rosenzweig and Hillel, 1998).

The average carbon loss from conversion of forest to agricultural land use for different eco-system types is shown in Table 5 below (Schlesinger, 1986).

TABLE 1
Carbon released by some countries from industrial sources and land use changes

Ecosystem Type	Mean loss of carbon (%)
Temperate forest	34.0
Temperate grassland	28.6
Tropical forest	21.0
Tropical savannah	46.0

(Schlesinger, 1986)

This study indicates that when tropical forest is converted to agricultural land use, the loss of carbon ranges from 7.3 to 49.6%, depending on the type of agricultural land use. When the vegetation is slashed and burnt and planted to maize, carbon loss can be as high as 40.7% compared to the intact virgin forest. When the land is put under rubber plantation, carbon loss is not retrieved because of low litter fall of the rubber leaves and perhaps due to the poor rate of decomposition of the rubber leaves. When the land is retired as a bush fallow, two years is woefully inadequate for the carbon loss to be restored. Once the forest is cut for agricultural purpose, retiring the land under bush fallow system leads to different types of vegetation in the form of shrub or scrub. Bush fallows take nearly 20 years for the fertility of the soils to be restored, depending on the type of soil, nature of vegetation and climatic condition. In a situation where the soil is acid as in this present study, acid soil infertility becomes a natural constraint for soil organic carbon to accumulate, because under acid conditions, the tendency is for the soil organic carbon to leach (Bonsu, 1991).

CONCLUSIONS

- This study has confirmed that acid soil infertility is a limitation to sequestration of carbon in soil.
- When a tropical forest is slashed and burnt, about 41% of carbon sequestered in the soil may be lost.
- When a tropical forest is converted to rubber plantation, the soils ability to sequester carbon is limited because of poor litter fall in rubber plantation and the difficulty in the decomposition of the leaves or litter.
- Retiring a tropical land under bush fallow system requires many years of fallowing for the rebuild of soil organic carbon.
- There is a decrease in carbon density whenever a tropical forest is cut and fallowed to be regenerated into a secondary forest.

RECOMMENDATIONS

From the current and future trends, it is being recommended that to enhance carbon sequestration in tropical soils;

- ➔ Overgrazing and annual bush burning must be avoided through strict policy enforcement.
- ➔ Farmyard manure must be incorporated into the soil to improve the carbon stock of the tropical soils.
- ➔ No-tillage system must be a recommended soil management practice for the tropical farmer. By incorporating crop residue or stubble mulch into the soil, the soil organic carbon can be enhanced.
- ➔ Improved fallow systems, whereby leguminous crops like Mucuna and Callopogonium are planted as the farmer nests the land to regenerate its fertility after some years of continuous cropping, are recommended.
- ➔ Agroforestry systems comprising leguminous trees such as Senia seamia, planted with food crops in combination that can sequester organic carbon in soil are recommended.

REFERENCES

Bonsu M., 2007. Land Use and Climate Change Proceedings. 4th International Conference of African Soil Science Society (In Press), Accra, Ghana. 9th -13th January, 2007.

Bonsu M. , 1991. Effect of liming on maize production and erosion on an acid soil in South-Western Ghana. Trop. Agric. (Trinidad) 63: 271-273.

Bouyoucos G.J., 1951. A recalibration of hydrometer method for making mechanical analysis of soils. Agron. J. 43:434-438.

FAO, 1994. Cherish the Earth: Soil Management for Sustainable Agriculture and Environmental Protection in the Tropics. Land and Water Development Division.

Lal R., 1994. Sustainable Land Use Systems and Soil Resilience. In: Greenland D.J., Szabolcs I. (Eds.). Soil Resilience and Sustainable Land Use, CAB International, Wallingford, UK. pp 41-67.

Nye P.H., Greenland D.J., 1960. The soil under shifting cultivation. Commonwealth Bureau of Soils. Technical Communication No. 5, Slough, England: CBS.

Parker B.Q., 2009. Contribution of Biomass Burning to Greenhouse Gas Emissions in the Coastal Savanna Ecosystem of Ghana. Unpublished M. Phil Thesis. Department of Soil Science, School of Agriculture, University of Cape Coast, Ghana.

Rosenzweig C., Hillel D., 1998. Climate change and the Global Harvest. Oxford University Press Inc. New York.

Schlesinger W.H., 1986. Changes in soil carbon storage and associated properties with disturbance and discovery. In: Trabalka J.R., Reichie D.E. (Eds.) changing carbon cycle: A Global Analysis. Springer-Verlag, New York. pp. 194-220.

Walkley A., Black I. A., 1934. An examination of the Degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Science 37: 29-38.