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Africa and the Carbon Cycle

Proceedings of the Open Science Conference on "Africa and Carbon Cycle: the CarboAfrica project"

Accra (Ghana) 25-27 November 2008

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by

Bombelli A.

&

Valentini R.

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2011

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Preface

This publication is based mainly on the works presented at the Open Science Conference "Africa and Carbon Cycle", held in Accra, Ghana, from 25 to 27 November 2008. The Conference was organized by the Food and Agriculture Organization of the United Nations (FAO) and the University of Tuscia, the Coordinator of the International project CarboAfrica.

CarboAfrica (www.carboafrica.net) is an international project funded by the European Commission under the 6th Framework Programme. The CarboAfrica partnership includes 15 Institutions from Europe and Africa, and FAO. Directly involved African countries are: Benin, Botswana, Burkina Faso, Ghana, Ivory Coast, Mali, Niger, Congo, South Africa, Sudan and Zambia. Other countries are indirectly affected by project outcomes.

Main project objectives are:

1. to support and expand a network of continued and enhanced observations of carbon stocks, fluxes, atmospheric concentrations and ecological processes in sub-Saharan Africa (SSA);
2. to improve biogeochemical models representing the main African ecosystem types;
3. to better understand the role of fire emissions from SSA in the global carbon cycle;
4. to enhance African capabilities to undertake mitigation and adaptation actions.

The work is organized in a multi-disciplinary integrated research approach through the division of main tasks in seven complementary work-packages.

WP1:	Observation system & data integration & consolidation
WP2:	Ecosystems processes understanding of carbon fluxes
WP3:	Modelling for up-scaling to region and continent
WP4:	Fire-Climate-Carbon cycle interactions
WP5:	Communications and Capacity Development
WP6:	Evaluation of a sustainable carbon sequestration
WP7:	Project Management

Main expected results are:

1. increased network of carbon observations in SSA
2. better quantification of the terrestrial carbon budget of SSA
3. improved understanding of the SSA role in the global carbon cycle
4. estimation of the potential of SSA for emission reduction and carbon sequestration, particularly in soil and forests

Summary

A peer reviewed selection of articles derived from the presentations and posters showed at the Open Science Conference “Africa and Carbon Cycle”, Accra, Ghana (25-27 November 2008) is presented.

The Conference brought together about 100 participants from 28 nations, mainly from Africa and Europe, presenting issues related to the following sessions:

i. Keynote speeches on Africa and Global Carbon Cycle;

ii. Terrestrial Carbon Observations in Africa and Ecosystem fluxes;

iii. Soil and Vegetation: Carbon and GHGs emissions in Africa;

iv. Biogeochemical Modelling;

v. Carbon sequestration and reduced emissions potentialities in Africa;

vi. Demonstration projects and developing capacities in Africa

A poster session was also organized especially to give visibility to African students and young researchers. Contributors belong both to the CarboAfrica consortium and other African or international initiatives.

The conference focused on Africa’s contribution to the global carbon cycle and climate system through an overview of the carbon related studies in sub-Saharan Africa carried out both by the project CarboAfrica and other African and international initiatives.

The Conference showed the high number of initiatives currently ongoing in Africa, related to the study of all the component of the carbon cycle, from science to socio-economic issues, and considering all natural components, from soil to the atmosphere, through terrestrial ecosystems.

In spite of the high number of efforts and of the important results already achieved, it was evident that there is still a strong need for continued and enhanced observations of Africa's carbon stocks and fluxes. The CarboAfrica network has been building a large partnership of relevant African and international institutions especially to meet this need. CarboAfrica will provide a future unique data set to enable a more precise assessment of Africa's carbon balance and its sensitivity to natural and anthropogenic pressures and future climate.

Acknowledgements

The successful organization of the Conference on Africa and Carbon Cycle and the publication of this book were made possible because of the outstanding efforts of many institutions and individuals working in close partnership.

CarboAfrica wishes to express its sincere appreciation to FAO for its contribution to the organization of the conference and the financial support that made possible the participation of many African people. In particular the FAO Regional Office for Africa (RAF) provided valuable logistical support and played a key role in making the conference a success. We are especially grateful to the FAO Deputy Regional Representative for Africa, Ms Maria Helena Semedo, for her participation and precious contribution. Special thanks also to Land and Water Division for the opportunity to publish this book in the FAO World Soil Resources Reports.

The whole CarboAfrica consortium gratefully acknowledges the European Commission, which has been funding the project under the 6th Framework Programme (FP6) and supported the participation of keynote speakers. Special appreciation to Mr Anastasios Kentarchos, Project Officer, Climate Change & Environmental Risks Unit, Directorate Environment, DG-Research of the European Commission, for his participation and stimulating discussion.

The organizers are also grateful to the local hosts, for providing excellent facilities and a warm welcome in Ghana, and to Campbell Scientific Africa, for sponsoring functions in support of the conference.

The CarboAfrica Secretariat wishes also to thank all the participants in the conference, for coming to Accra, the speakers, for their valuable presentations, the authors, who prepared the papers for this publication, and particularly African students and young researchers, who will be the scientific experts and the decision makers of tomorrow: we hope they can make the most of this event.

Thank you very much to Ms. Gerboin Sandrine and Ms. Cárdenas Paola for their support to the preparation of this publication.

Finally thanks to all the CarboAfrica partners and collaborators, and the University of Tuscia in particular, who made this project possible.

List of acronyms and abbreviations

AATSR sensor	Advanced Along-Track Scanning Radiometer
ACT	African Conservation Tillage network
AfDB	African Development Bank
AGB	aboveground biomass
AGRA	Alliance for a Green Revolution in Africa
ANN	artificial neural network
ANOVA	One-Way Analysis of Variance
CARE	CarboAfrica Regional Experiment
CIFOR	Center for International Forestry Research
CSIF	Country Strategic Investment Frameworks
EnKF	Ensemble Kalman Filter
EPA	Environmental Protection Agency
fAPAR	fraction absorbed photosynthetically active radiation
FCPF	Forestry Carbon Partnership Facility
FLEGT	Forest Law Enforcement Governance and Trade
FMC	fuel moisture content
FRLF	Free light fraction
FRP	fire radiative power
FTIR-spectroscopy	Fourier Transform Infra-red (FTIR) Spectroscopy
GCMs	General Circulation Models
GEF	Global Environment Facility
GEMS	General Ensemble biogeochemical Modelling System
GHG	Greenhouse gas
GHGI	greenhouse gas inventories
GPD	Generalised Poisson Distribution
GPG	Good Practices Guidance
GPP	gross primary production
GWP	global warming potential
IALF	Intra-aggregate light fraction
IER	Institut d'Economie Rurale
IGBP	International Geosphere-Biosphere Programme
ILCA	International Livestock Centre for Africa
IPCC	Intergovernmental Panel on Climate Change
ITTO	International Tropical Timber Organization
LandSAF	Land-surface analysis Satellite Applications Facility
LSCE	Laboratoire des Sciences du Climat et l'Environnement

LST	Land-surface temperature
LUCF	land use change and forestry
LULC	land use and land cover
MAE 0.42 gC/m2/day	mass absorption efficiency
MEF	Moist Evergreen Forest
MODIS	Moderate resolution imaging spectroradiometer
NEE	net ecosystem exchange
NEPAD	New Partnership for Africa's Development
NTFPs	non-timber forest products
R_{eco}	ecosystem respiration
REDD	reduced emissions from deforestation and degradation
RLCM	Rapid Land Cover Mapper
SADC	South African Development Community
SCURS	Soil Carbon Uptake for Restoration and Sustainability
SEVIRI	Spinning Enhanced Visible and Infrared Imager
SHARE project	Soil Moisture for Hydrometeorologic Applications in the SADC region
SOC	soil organic carbon
SPITFIRE	fire module
TER	terrestrial ecosystem respiration
TroFCCA	Tropical Forests and Climate Change Adaptation
UNCCD	United Nations Convention to Combat Desertification (citato 1 volta)
UNCED	United Nations Conference on Environment and Development
UNDP	United Nation Development Programme
UNEP	United Nations Environment Programme (citato 1 volta)
UNFCCC	United Nations Framework Convention on Climate Change
UNOPS	United Nations Office for Project Services
UR2PI	Unité de Recherche sur la Productivité des Plantations Industrielles (ex CTFT)

Keynote speeches on Africa and Global Carbon Cycle

1

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

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[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

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[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.

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Terrestrial Carbon Observations in Africa and Ecosystem fluxes

2

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

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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

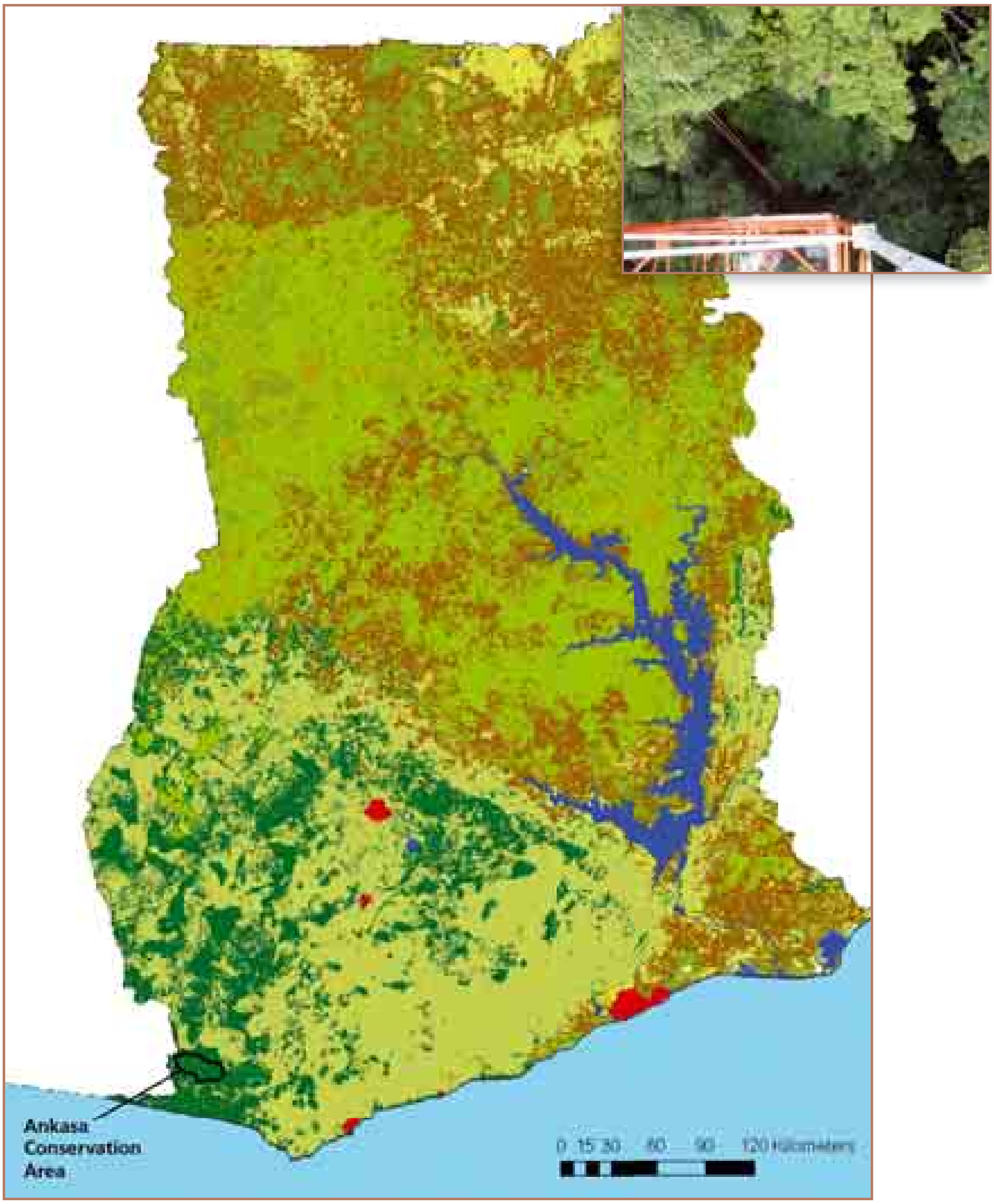
Carbon fluxes

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

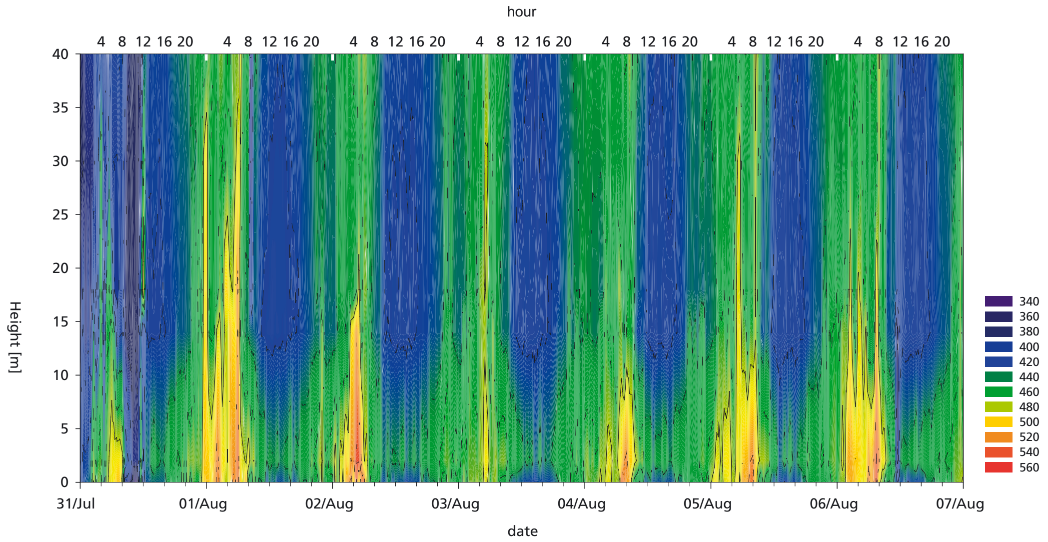
Carbon fluxes

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).

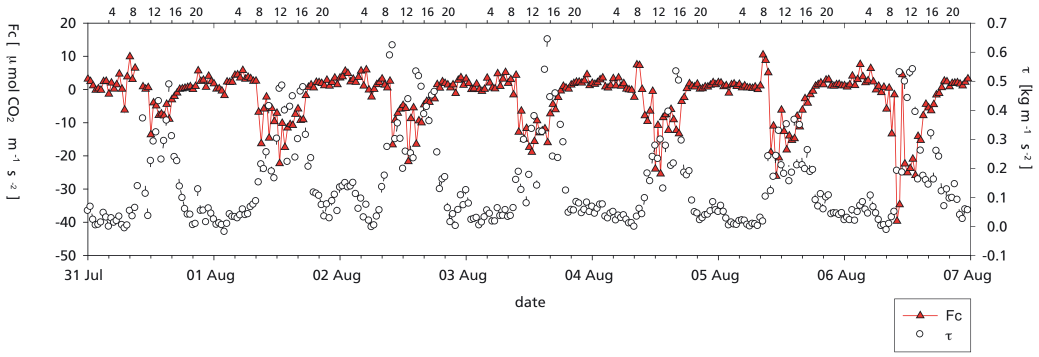
FIGURE 2

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

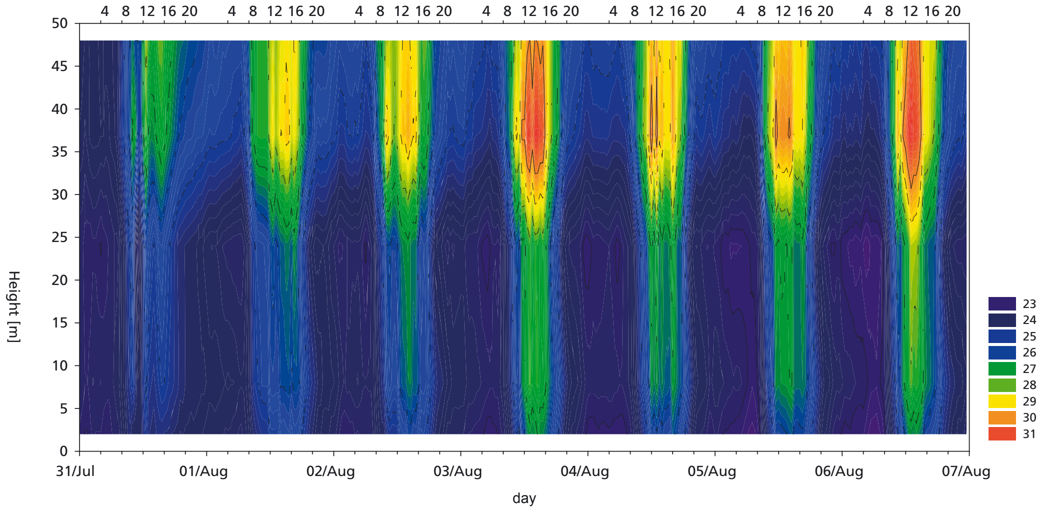
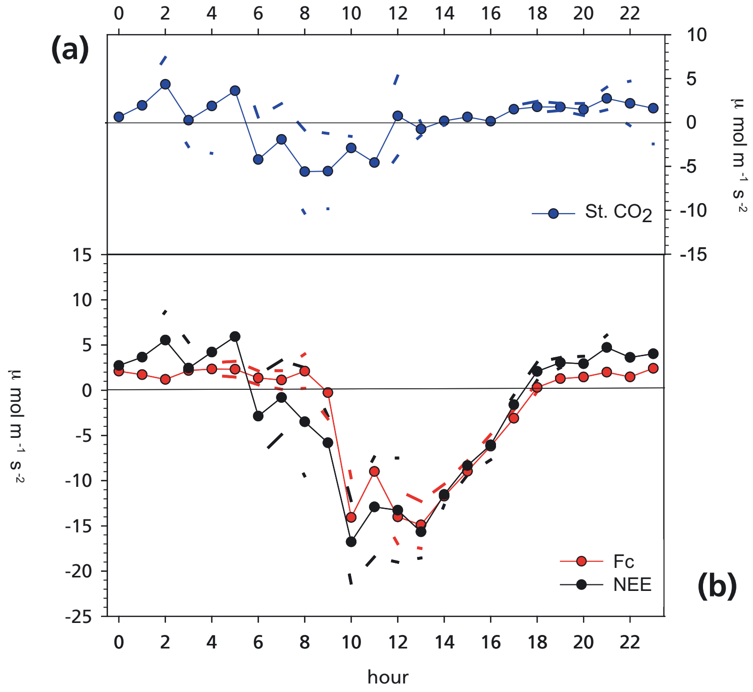


FIGURE 3

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).

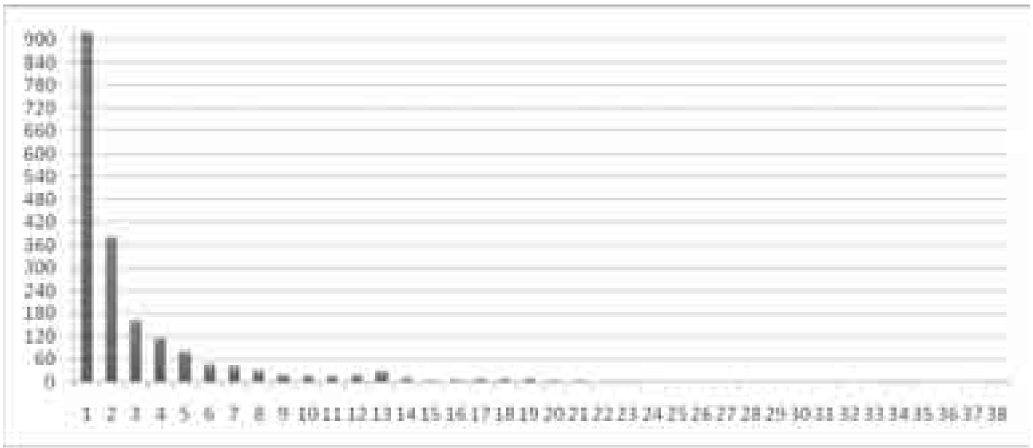
Horizon	C org.	N	C/N	C org.	N
	g kg^{-1}	g kg^{-1}		Mg ha^{-1}	Mg ha^{-1}
Oi-Oe	406.2 (32.1)	15.1 (2.6)	32.1	15.3 (8.6)	0.5 (0.2)
A	60.6 (19.3)	4.4 (1.4)	13.8	30.3 (11.8)	2.2 (0.8)
Bo1	15.8 (3.5)	1.3 (0.3)	12.2	67.6 (15.5)	5.5 (1.6)
Bo2	12.2 (1.2)	0.8 (0.2)	15.3	52.7 (6.3)	3.5 (0.9)
				165.9 (11.2)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

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

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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}.

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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:

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

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}).

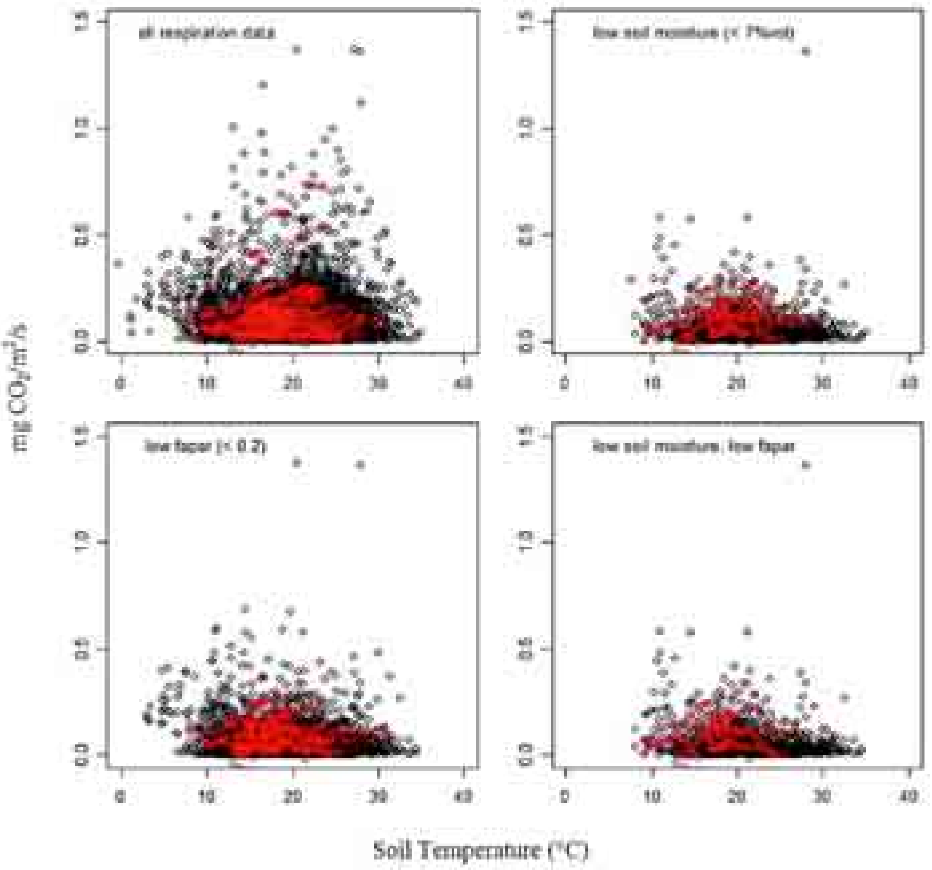
RESULTS & DISCUSSION

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

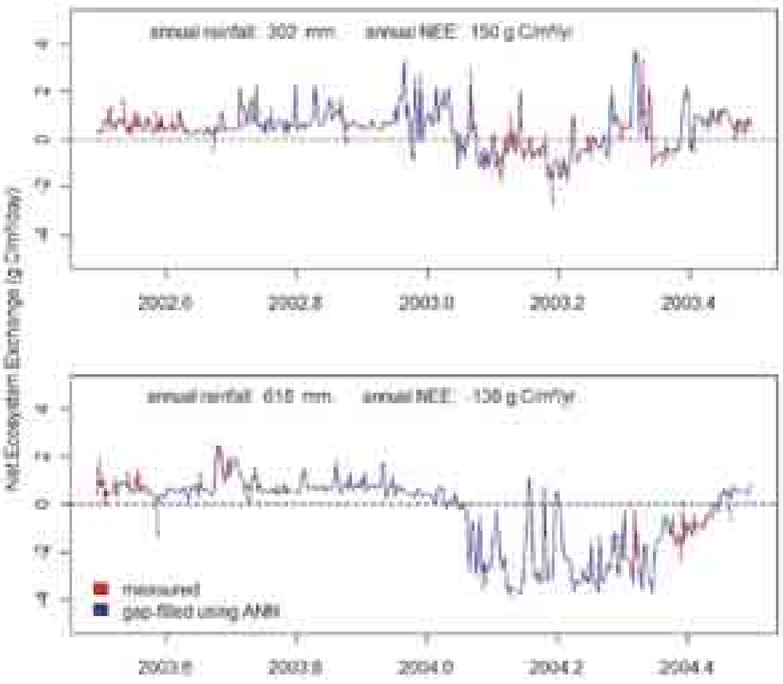
Summary of net ecosystem exchange (NEE) over the 5 year period of flux data

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).

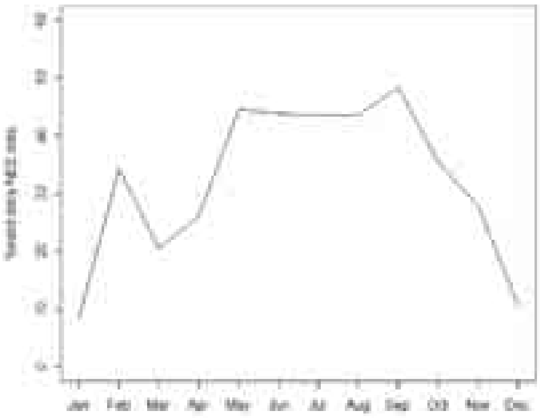
FIGURE 2

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.

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Vegetation dynamics in a littoral savannah in Congo

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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.

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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.

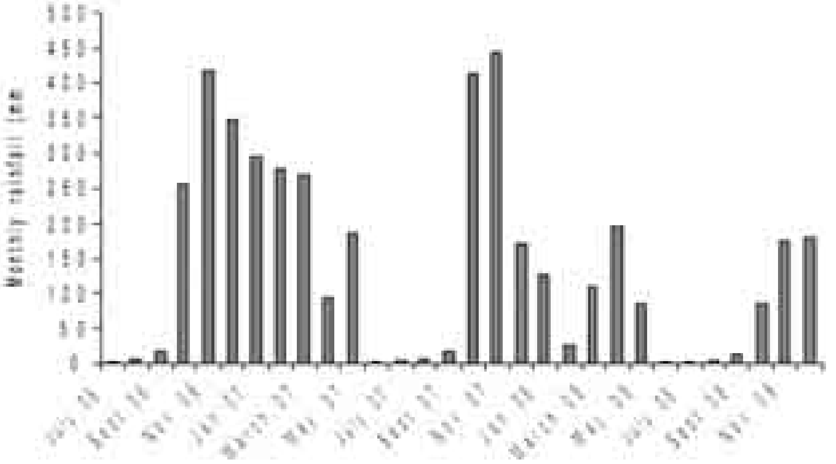
RESULTS AND DISCUSSION

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

Rainfall and soil humidity

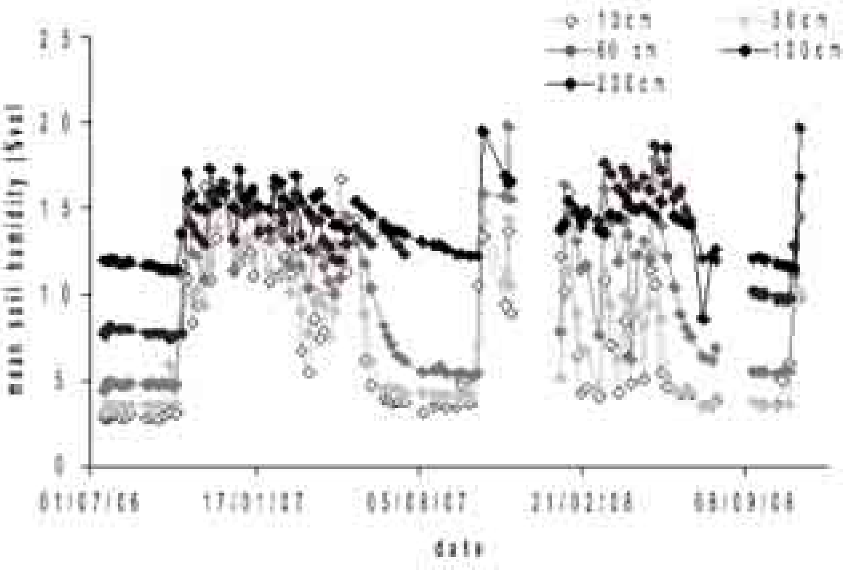
The rainfall presented an interannual variation (fig 1). To study the effect of the rainfall on the vegetation growth, we choose the annual fire as the start point of year of study. During the period July 2006-fire 2007 (June 16, 2007), the rainfall was 2172 mm whereas the rainfall was only 1608 mm between 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

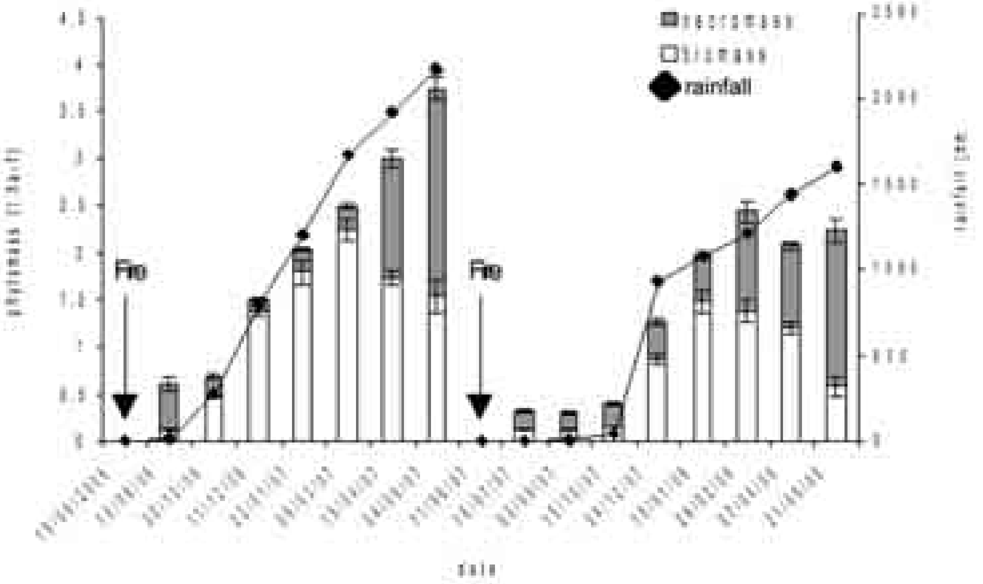
The sandy texture of the soil (more than 90 % of sand, less than 5 % of clay) explains the low values of soil moisture during the dry season and the low water retention capacity of the soil (Laclau *et al* . 2000).

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.

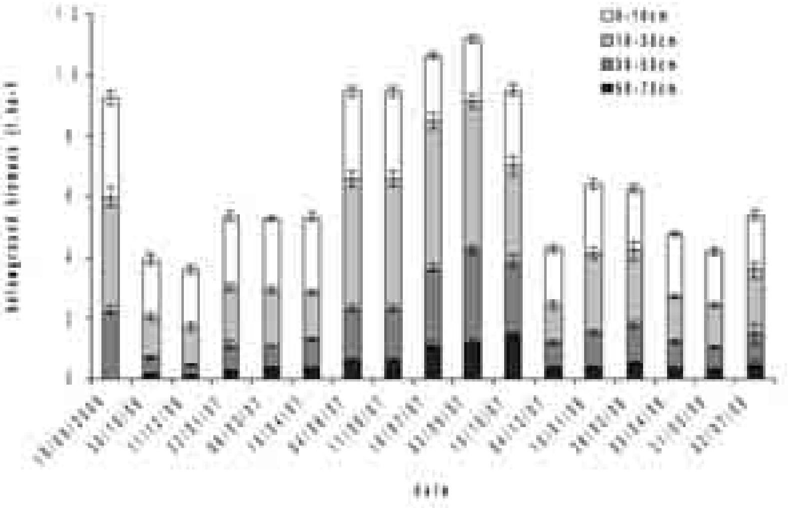
The maximum of the aboveground phytomass (biomass and necromass) was observed in June 2007 with 3.8 t.ha^{-1} (± 0.2 t.ha^{-1}).These results are lower than those of Laclau *et al.* (2002) who obtained a maximum aboveground phytomass (biomass and necromass) of 5.3 t.ha^{-1} (± 0.7 t.ha^{-1}) in June. 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.

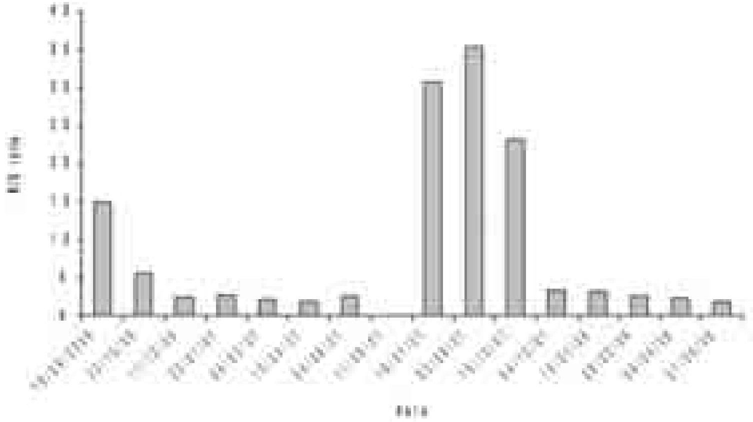
At Kissoko, at 60 km of the site, Nouvellon *et al.* (2008) measured a root phytomass of 6.3 t.ha^{-1} in March.

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.

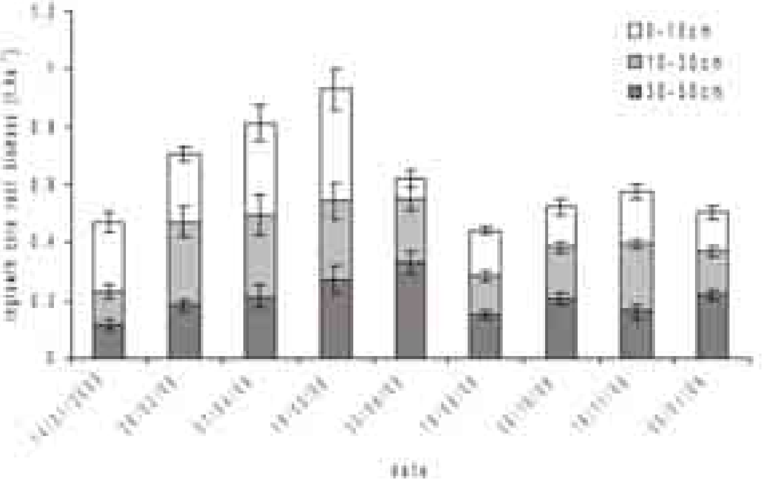
FIGURE 5
Mean Root/Shoot ratio at each biomass harvest calculated from mean aboveground and mean belowground biomass



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.

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

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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

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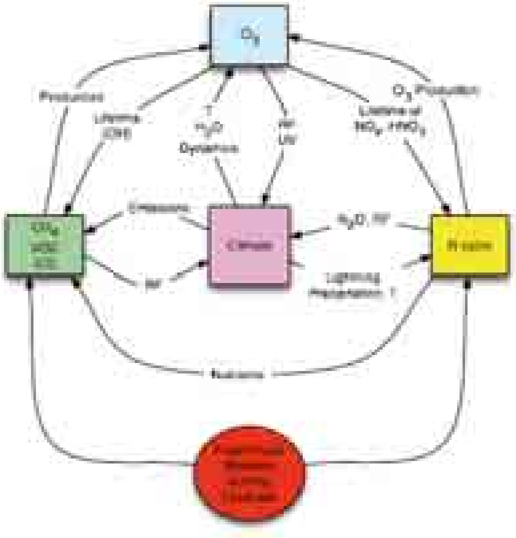
green house gas emission, large scale pollution, amongst others. Followed by the environmental and economic issues arising from these developments,

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.

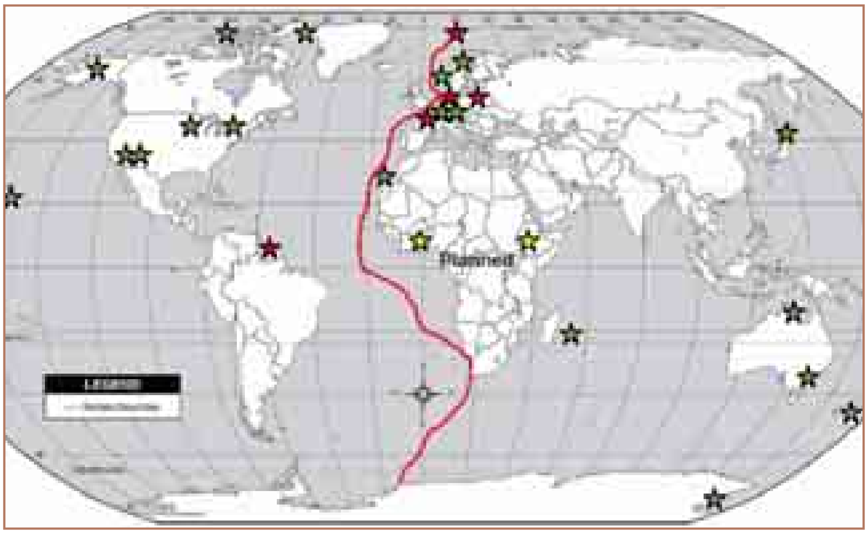
This paper will present results of CO from ship cruise from South Africa through West Africa, as well as results from a ground based observation from Paramaribo in Suriname. In addition, a planned ground based station, which is collaboration between institute of Environment Physics (IUP), University 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

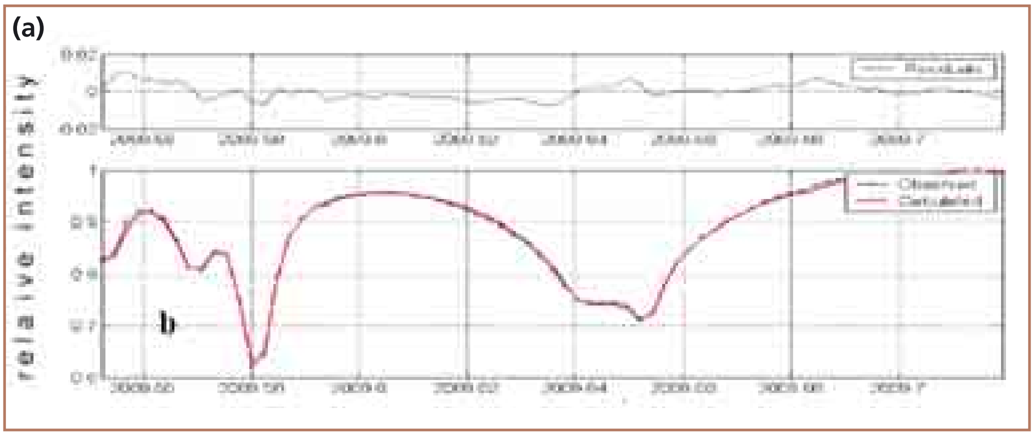
(Velazco 2006)

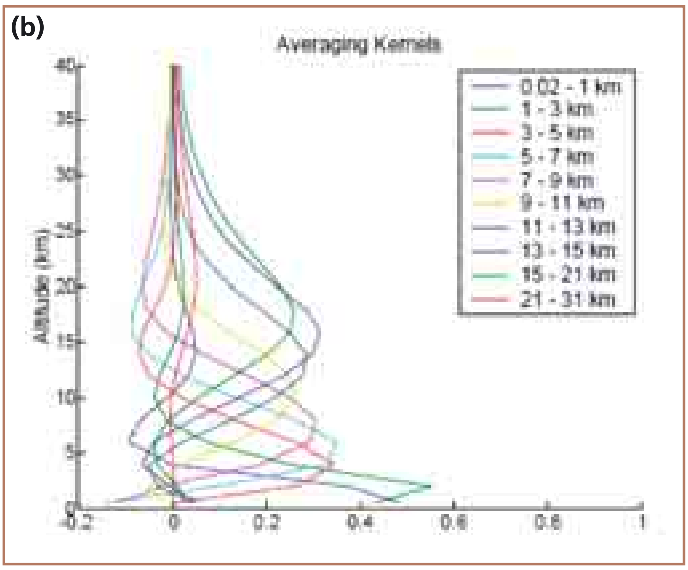
The choice of an appropriate a-priori profile for the retrieval process is very crucial to the optimal estimation retrieval approach employed for retrieving the CO and C_2H_6. For CO retrievals, the a-priori profile used has been adapted from the a-priori profile employed in the MOPITT retrievals (Bremer 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

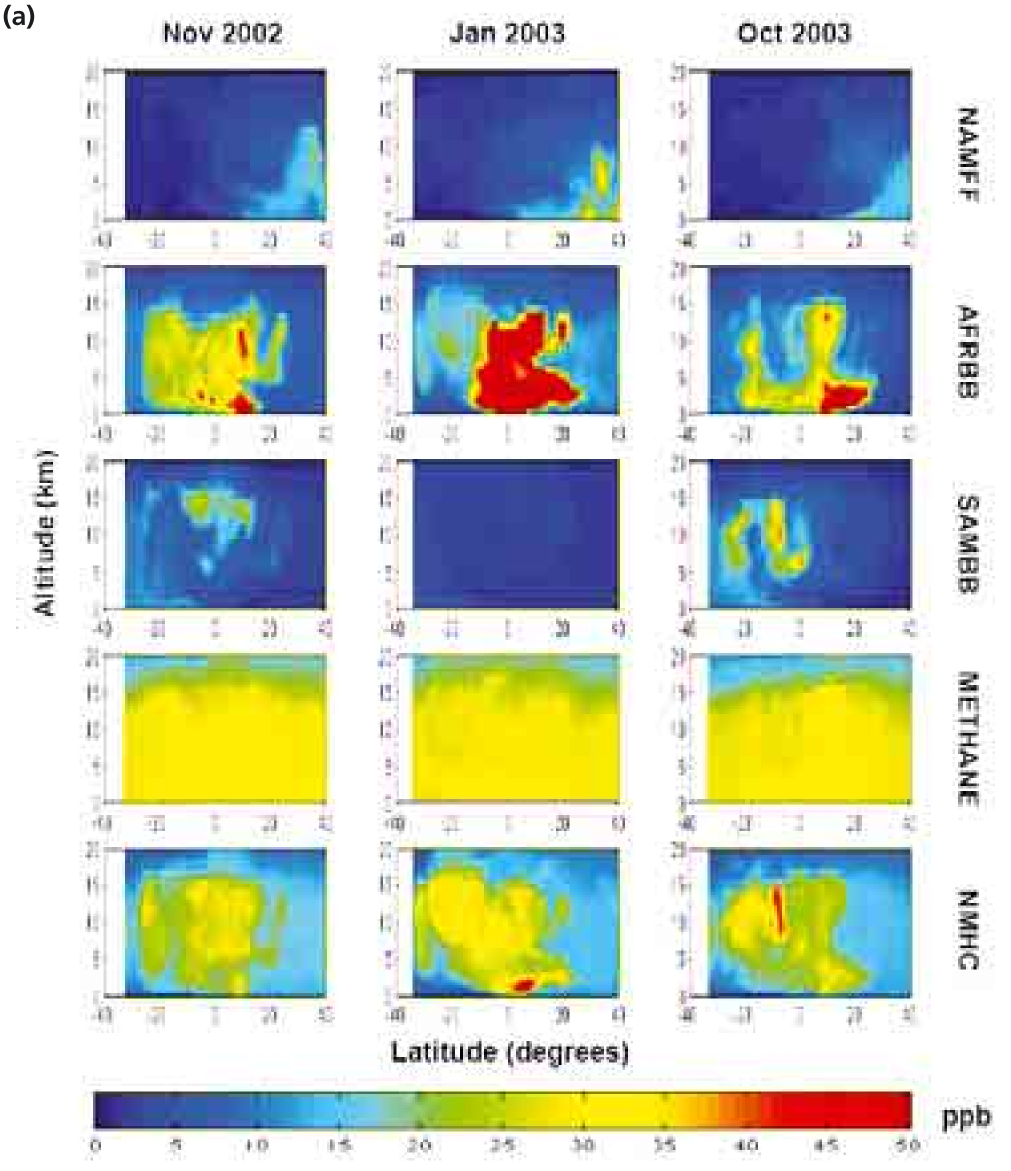
In order to assess the origins of the CO enhancements, the contributions of regional tracer fields from the MATCH-MPIC model were calculated. A selection of the most significant sources for the three cruises and their absolute contributions are shown in Figure 4a. Most of the CO in the equatorial regions 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) $\times 10^{18}$ 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)



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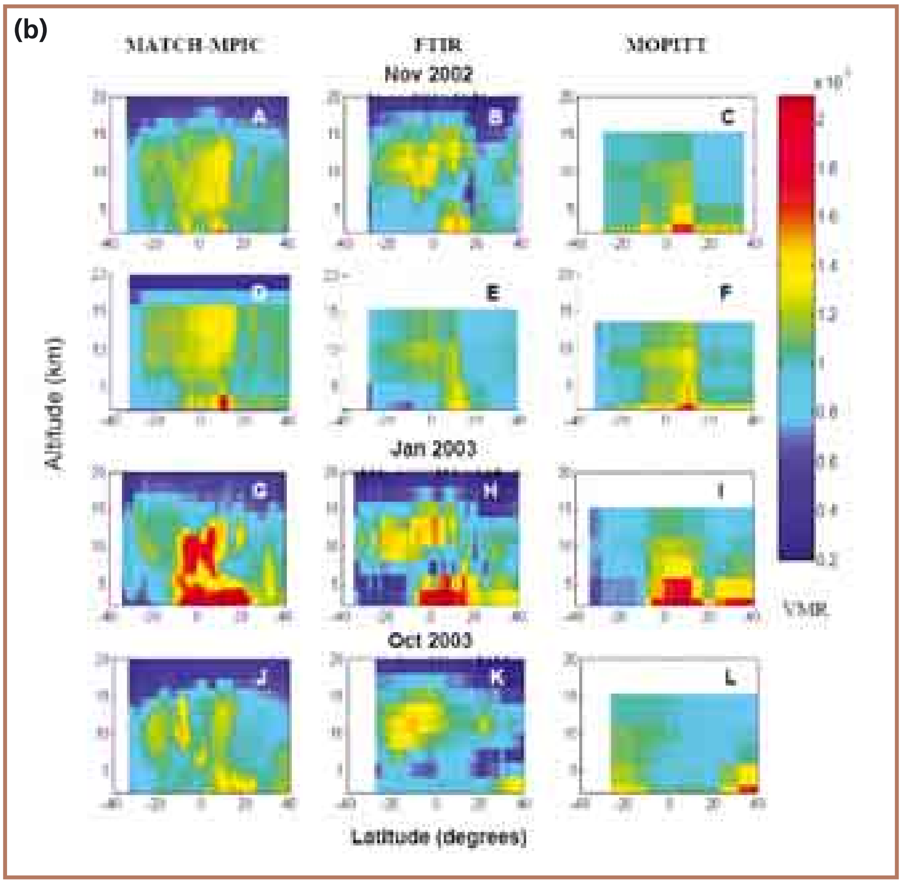
[3] The CO tracer fields are; North American Fossil Fuel (NAMFF), South American Fossil Fuel (SAMFF), African Biomass Burning (AFRBB). There are also tracer fields of CO from methane oxidation (METHANE) and from NMHC oxidation (NMHC).

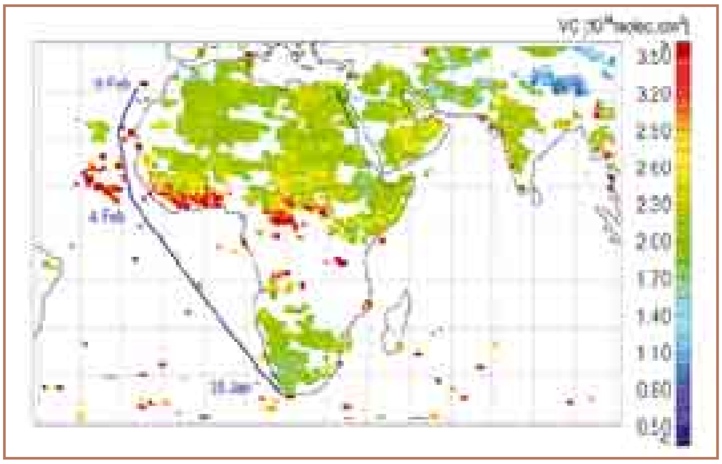


FTIR measurement at Paramaribo

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

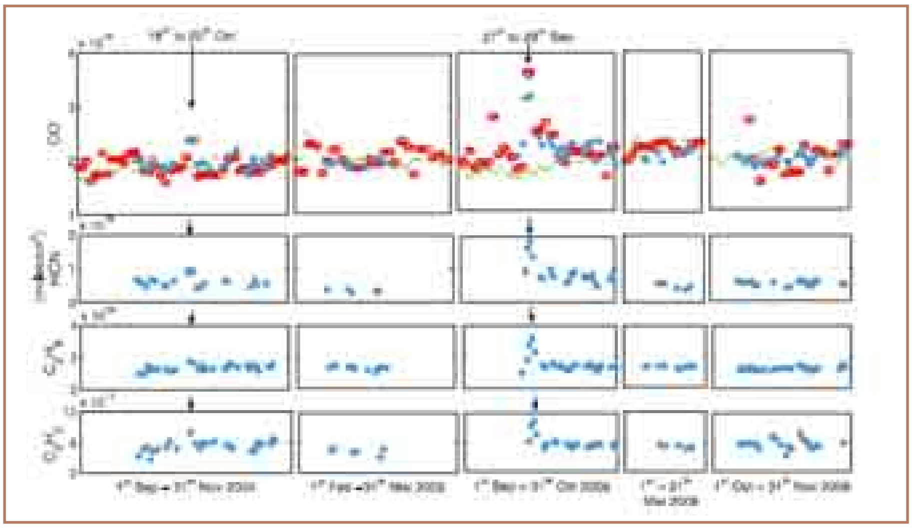
CO vertical columns from SCIAMACHY WFM-DOAS-retrievals (Version 0.4)



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

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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.

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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.

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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)

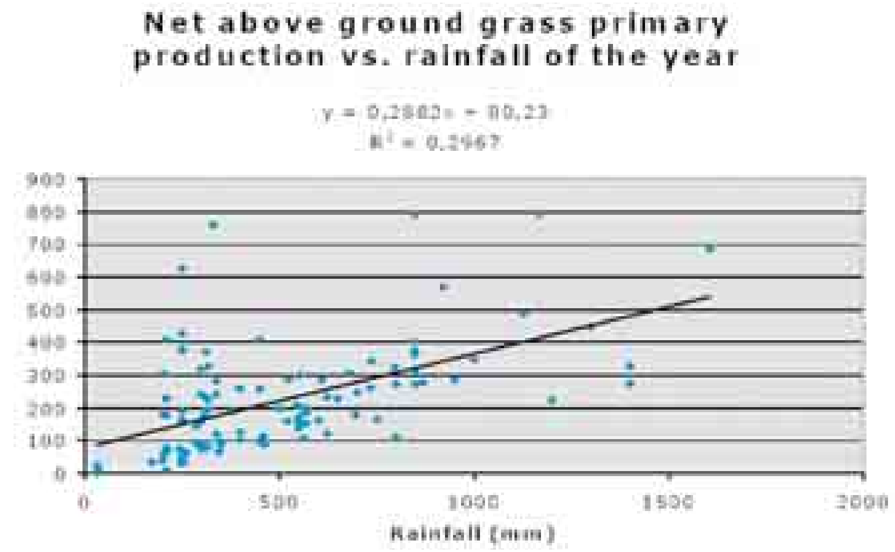


FIGURE 2

Relationship between maximum aboveground grass biomass and soil carbon

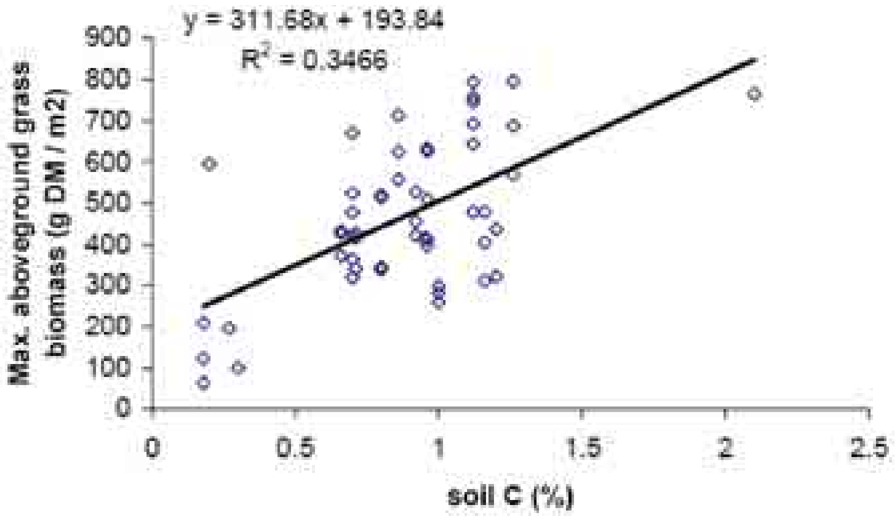
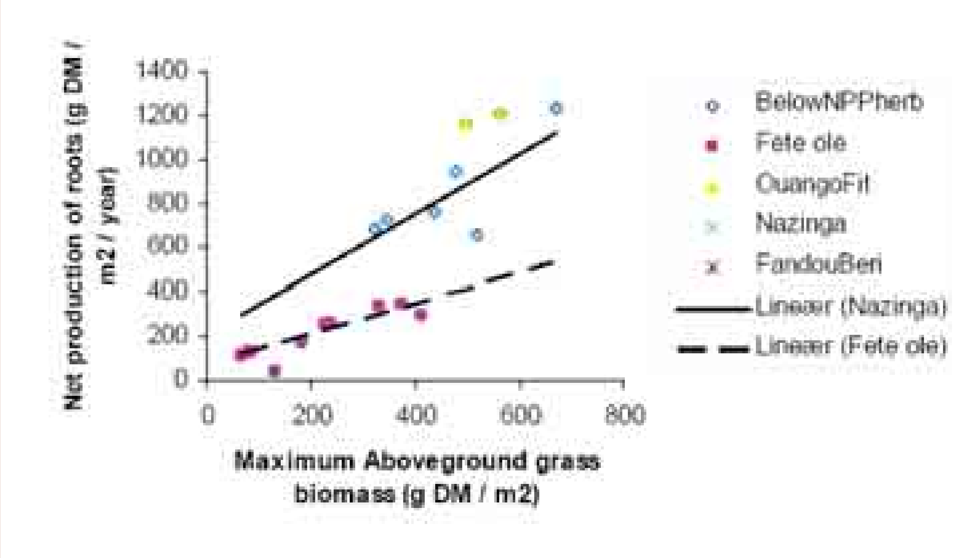


FIGURE 3

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.

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

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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

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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.

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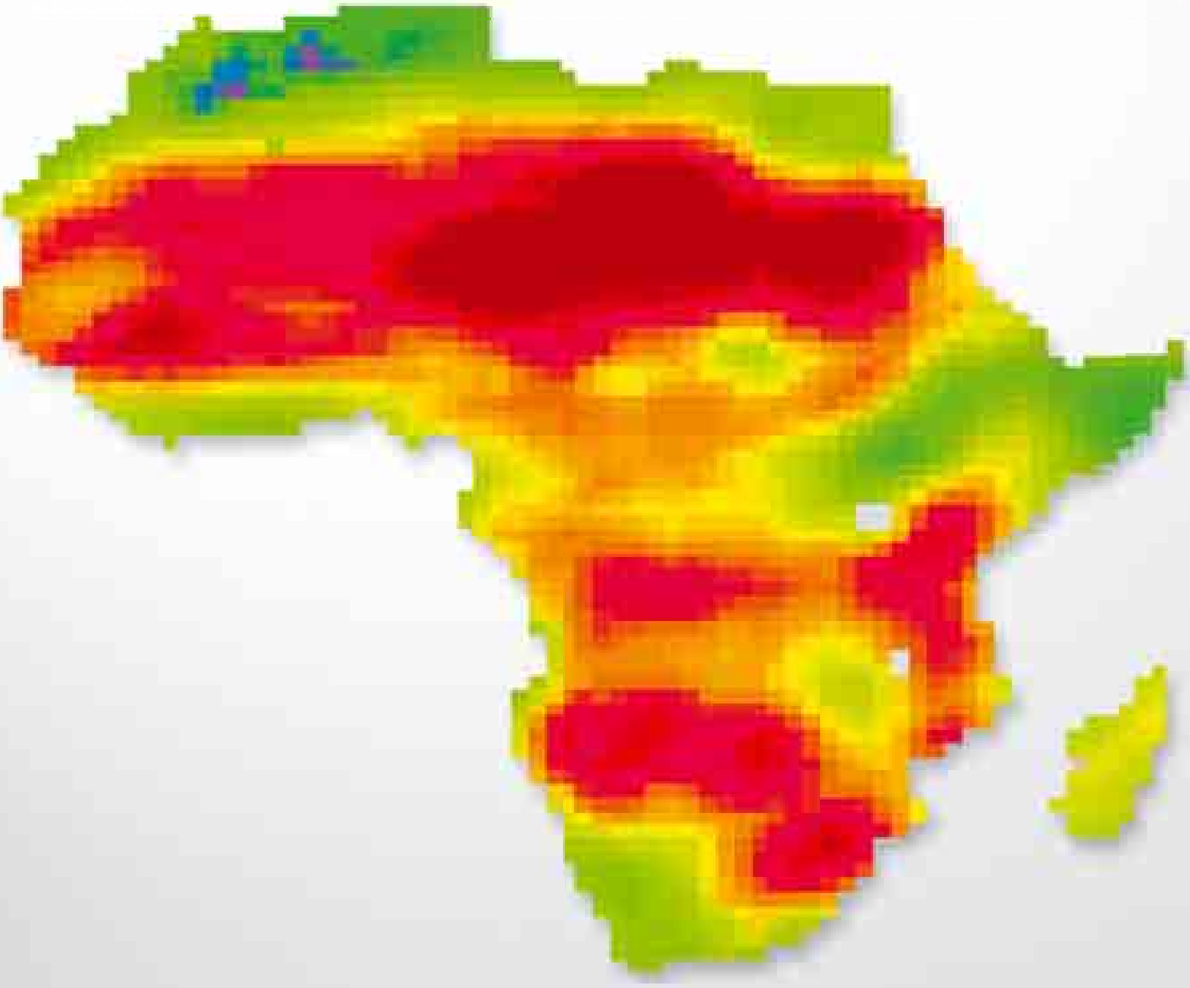

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Biochemical Modelling

Land cover change, biogeochemical modelling of carbon stocks, and climate change in West Africa

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ABSTRACT

The carbon in ecosystems exists in dynamic soil and vegetation pools which vary in amounts and cycle with the global atmosphere at varying rates. These stocks and fluxes play important roles in global carbon regulation and in the maintenance of goods and services. Changes in land cover or ecosystems result in increased or decreased fluxes to the atmosphere and play a major role in climate regulation. Carbon in soil is closely coupled to soil nitrogen and the continued mining of soil for crops or fuel without replenishment of nutrients results in decreased productivity and impacts food security. The assessment of these processes across large areas, although difficult, is aided by the integration of simulation modelling (biogeochemical and ecosystem) and remote sensing.

We acquired satellite imagery for four periods from the 1960s to 2000s, trained environmental scientists from 14 countries on image analysis and interpretation, and now report systematic analyses of land cover changes in select countries of West Africa and quantify potential impacts of climate change and management at specific sites. Statistical changes and maps of land cover are documented for most countries. Senegal, for example, illustrates a 57 percent loss in dense forests between 1975 and 2000 with an even greater loss rate in the preceding 10 years. Bare soil increased 16.6 percent, often related to unproductive "badland" formation. Settlements increased 45.6 percent, and reforestation replaced bare sandy areas for sand dune stabilization. In some countries (Senegal and Ghana), the impact of these conversions and changes in land management and future projections has been incorporated into biogeochemical models to quantify carbon changes and project future carbon and crop scenarios. We present current assessments of carbon fluxes and the availability of data for these West African countries.

Keywords: West Africa, Carbon fluxes, Land cover change, Sequestration, Climate change, Biogeochemical modeling, Agricultural management

INTRODUCTION

Climate change during this century has the potential to modify existing ecosystem (including intensively managed systems, e.g. agricultural and pastoral) functions

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in diverse ways, including both the enhancement and reduction of crop yields and production. These impacts are potentially profound in the areas of the world that are most vulnerable – those that experience the threat of climate change and have limited abilities to adapt. Sub-Saharan Africa contains some of these vulnerable systems (Vagen *et al.* 2005, and Tieszen *et al.* 2004). Recent analyses (Battisti and Naylor 2009) confirm the potentially harmful impact suggested by climate change scenarios, especially those associated with increasing temperature. This was suggested by the simulations conducted in Senegal (Liu *et al.* 2004), which projected crop failure for existing genetic types.

In addition to this vulnerability, the continent plays a major role in the global carbon cycle at scales ranging from seasonal to decadal, even though our understanding of this is severely limited (Williams *et al.* 2007). Africa's major role in the global carbon cycle can be attributed to the substantial releases of carbon associated with land use conversions from forest or woodlands to agriculture (Smith 2008), which accounted for approximately 15 percent of the global net flux of carbon from just land use changes in the 1990s (Houghton and Hackler 2006). Land management following conversion also impacts carbon status, soil fertility, and agricultural sustainability as repeatedly suggested by Lal (2006), Ringius (2002), and others (Graff-Zivin and Lipper 2008; Tieszen *et al.* 2004). Soils often continue to lose carbon following land conversion (Woomer *et al.* 2004; Tschakert *et al.* 2004; Liu *et al.* 2004), resulting in further reductions in crop yields and continued impoverishment; however, these carbon stocks can be replenished with combinations of residue retention, manuring, N fertilization, agroforestry, and conservation practices (Lal 2006). This understanding has led to continuing suggestions of the importance of soil carbon sequestration and the Clean Development Mechanism (CDM) of the Kyoto Protocol.

This publication describes the results of two development projects undertaken in West Africa. The West Africa Land Cover/Land Use project built capacity with teams in each country to use remote sensing and ground validation to document current land cover and recent changes. The Environmental Management and Information Systems project quantified carbon changes with Spatially Explicit Modelling of Soil Organic Carbon (SEMSOC). We summarize our quantification of changes in land cover types in West Africa, evaluate associated changes in ecosystem and soil carbon stocks in selected study areas of Ghana and Senegal, and simulate changes in carbon status under selected management and projected changing climate during the twenty-first century.

MATERIALS AND METHODS

Since 1972, earth resource observation satellites from the Landsat series have furnished numerous time-series images of Africa. These images made it feasible to map and quantify land use and land cover (LULC) changes over time. These historical and recent satellite images allowed us to spatially document changes in the natural resources, many of which are driven by human activity. We mapped and assessed trends in LULC across 12 West African countries based on two time periods of imagery: Landsat multispectral scanner (MSS) images with a nominal date of 1975 (using images from 1972 to 1978) and Landsat enhanced thematic mapper (ETM+) images with a nominal date of 2000 (using images from 1999 to 2001). We defined 18 general LULC classes that could be readily identified on Landsat imagery. LULC trends statistics for Mali and Chad are not yet available.

A manual photo-interpretation approach was used to identify and map the LULC classes because it accommodates images from different satellite systems and formats, it allows expert interpreters to integrate local knowledge with the many dimensions of information contained in images, and it resolves some problems of seasonality, differences in illumination, and atmospheric effects. Furthermore, the human interpreter can effectively distinguish real LULC changes from many of the ephemeral factors such as annual grass fires. The interpretation was verified where possible with field visits, high resolution commercial satellite imagery, and by reviewing thousands of aerial photographs. This led to very high interpretation accuracy and consistency.

We developed a new approach to map LULC efficiently over 12 participating countries and several periods in time. This tool, the Rapid Land Cover Mapper (RLCM), is a vector–raster hybrid approach that lends itself to time-series LULC mapping. The tool overlays a dot grid on an image within ESRI's ArcMap GIS software, and the analyst identifies the discrete LULC class for each dot. The RLCM tool facilitates both the selection and attribution of dots within a common LULC class. It also facilitates the management of multiple time period classifications for the study area. Once the dot grid matrix is completely classified for a given time period, a raster LULC map can be generated. The same process can be applied to different time periods, and the resulting maps can be compared to assess change over time. We produced 2 km resolution raster LULC maps for the nominal time periods of 1975 and 2000 (Figure 1) and derived both trends and change maps.

We used the General Ensemble biogeochemical Modelling System (GEMS, refer to Liu *et al.* 2004; Tan *et al.* 2009b for details) to simulate historical changes in ecosystem and soil carbon stocks in the twentieth century and predicted their dynamic trends under projected climate change scenarios in the twenty-first century for three ecoregions of Ghana (Figure 2). The input geospatial data consisted of mean monthly precipitation, mean monthly minimum and maximum temperatures from 1971 to 2000, three interpreted images from 1972, 1986, and 2000, and the FAO soil database. Management practices (crop composition, crop rotation, fallow, tillage, harvesting options, frequency of fuelwood production, etc.) were synthesized from field observations across all studied areas and literature. GEMS automates the processes of downscaling those data for carbon budget simulations. The field data of ecosystem and soil carbon stocks collected by Ghana EPA in 2006 from three districts of Bawku, Ejura, and Assin of Ghana) and the grain yields of major crops were used as references to verify modelling outputs. The details in GEMS architecture and ensemble simulations and the scenarios of climate change and nitrogen fertilization rates for model simulations are published (Liu *et al.* 2004; Tan *et al.* 2009a, 2009b).

RESULTS AND DISCUSSION

Research teams were trained in image interpretation, including the use of the RLCM (http://edcintl.cr.usgs.gov/ip_dev/new/rlcm/index.php), and were provided imagery for 1975, ca. 1985, and ca. 2000. Initial land cover analyses with Landsat imagery was aided with high resolution imagery and ground validated at some specific sites. These national maps and change products are now available(http://edcintl.cr.usgs.gov/ip_dev/new/africalulc/index.php) and will only be summarized here.

Figure 1 represents the land cover for the area of West Africa completed with year 2000 imagery. Details of each country are available including assessments of major drivers of land cover change. Table 1 summarizes the results for six countries in West Africa revealing similar patterns in land cover change during the period 1975–2000. All countries lost forest cover ranging from around 8 percent loss in Senegal to slightly over 30 percent in Niger. Similar losses characterized the savannah classes in all countries. These changes were accompanied by substantial increases in the agricultural classes approaching 90 percent increases in Ghana and Togo. Although Senegal revealed a very small increase in agriculture land cover, closer inspection reveals the necessity for close and detailed inspections of these country level statistics.

In Senegal, although there was only a small increase in agricultural land, there was a substantial loss of this class in the "old peanut basin" as these lands were abandoned but a substantial conversion to agriculture in other ecoregions. Thus the summarized statistics mask a change in land cover that has potentially large impacts on carbon budgets for the country.

FIGURE 1

TABLE 1

Summary of the percent changes in major land use/land cover classes for eight West African countries during the period 1975 to 2000

	Ghana	Senegal	Guinea	Niger	Benin	Togo	Burkina	Mauritania	Total Area in 2000 (km²)	Change (%) for entire area
Forest	-18	-60.6	-29.9		27.1	-34	0	-54.5	19280	-22.4
Gallery Forest	-10.9	-1.6	-10.2	-30.9	-8.8	-5.1	-24.1	0	21000	-12.6
Total Forest	-16.4	-7.9	-19.5	-30.9	-12	-20.8	-23.6	-54.5	40280	-17.5
Steppe	0	4.9	0	-3.4	0	0	1	3.6	401020	-2.8
Savannahs	-15.7	-1.1	-2.5	-16.2	-13	-12.8	-13.6	-30.7	841744	-10.9
Wetland - Floodplain	4.1	10.3	7.2	-13.7	6.3	7.9	24.9	15.4	31512	6.0
Water Bodies	-8.9	8	39.5	9.1	5.7	17.6	52.4	17.6	19264	6.3
Plantation	41.7	10.3	0	0	125	650	0	0	764	91.0
Mangrove	0	-4	-0.2	0	0	0	0	0	4028	-1.6
Agriculture	96	0.4	29.4	42.7	77.7	80.1	50.7	37	316496	48.0
Irrigated Agriculture	325	102.4	0	27.3	9.1	233.3	13.5	353	3584	50.1
Total Agriculture	96.2	1.4	29.3	42.5	77.1	80.9	22.8	76.1	320080	48.0
Sandy surfaces	0	-70.9	0	71.5	-100	0	0	37.8	66884	38.1
Bare Soil	104.8	0	80	54.9	53.3	333.3	36	24.4	20576	34.8
Settlements	48.9	44.1	34.3	26.9	45.2	70	56.5	300	6024	45.3

The table also presents percent change per class for the entire eight-country area. Note the major declines in forest and savannah classes, and the significant increase in agriculture.

Earlier research (Woomer *et al.* 2004) summarized countrywide estimates of carbon status in Senegal and estimated the changes in carbon stocks between 1965 and 2000. These estimates showed that seven of the eight zones (aggregated ecoregions) lost substantial carbon and that the terrestrial losses for the country were 293 Mt during this period, an average of 418 kg C $ha^{-1}year^{-1}$. Only one area, "Northern Coast," showed increasing carbon stocks, an increase accounted for by afforestation associated with long-term projects to introduce forest species for dune stabilization. Furthermore, this study showed that 95 percent of the carbon loss resulted from land cover conversion or decreases in woody cover (thinning, for example). Extensive simulation modelling over two areas in Senegal revealed continuing soil carbon losses from agriculture, mostly caused by residue removal and lack of nitrogen inputs (Tschakert *et al.* 2004; Liu *et al.* 2004). Opportunities for soil carbon restoration were defined; however, most of them were not economically viable under existing conditions without increased commodity prices, credit for fertilizer, or the sale of carbon credits. Simulations also suggested continued soil carbon deterioration under climate change scenarios and even crop failures resulting from higher temperatures and greater evapotranspiration. Interestingly, this response to increasing temperature was highlighted recently by Battisti and Naylor (2009).

In addition to the summary land cover data for Ghana presented above, the details of land cover change and carbon cycling have been studied in three ecoregions (Fig. 2) encompassing the terrestrial range across Ghana (Tan *et al.* 2009a, 2009b, 2009c). Bawku, in the semi-arid region, lost woody savannah and gallery forest mainly to agricultural use (Tab. 2). Similar conversions of forest to agriculture occurred in Ejura and Assin. Table 3 summarizes the changes in ecosystem and soil carbon stocks from 1900 to 2000 in each intensively studied area. The combination of land cover change and management resulted in losses of ecosystem carbon approaching 50 percent in each area. This amounted to an average loss of 153 Mg ha^{-1} (294, 168, and 76 Mg ha^{-1} from closed forest, degradaed forest and cropland, respectively) in the humid forest area of Assin. Simulations of three climate change scenarios show losses of both ecosystem carbon and soil carbon by 2100. Interestingly, soil carbon was not depleted in the semi-arid Bawku region but declined sharply in humid Assin, probably a legacy of the larger carbon stores from forest-derived soils. Because nutrient replacement is essential to maintain soil carbon, we simulated the responses to climate change under three levels of nitrogen fertilization. The addition of nitrogen fertilizer at rates of 30 and 60 kg N ha^{-1}yr^{-1} actually stimulated carbon sequestration in soils at all sites. Even this stimulation, however, was overridden by both low and high climate change scenarios around 2050. Crop yields declined slightly with climate change but were stimulated under all climate change scenarios with nitrogen fertilization.

FIGURE 2

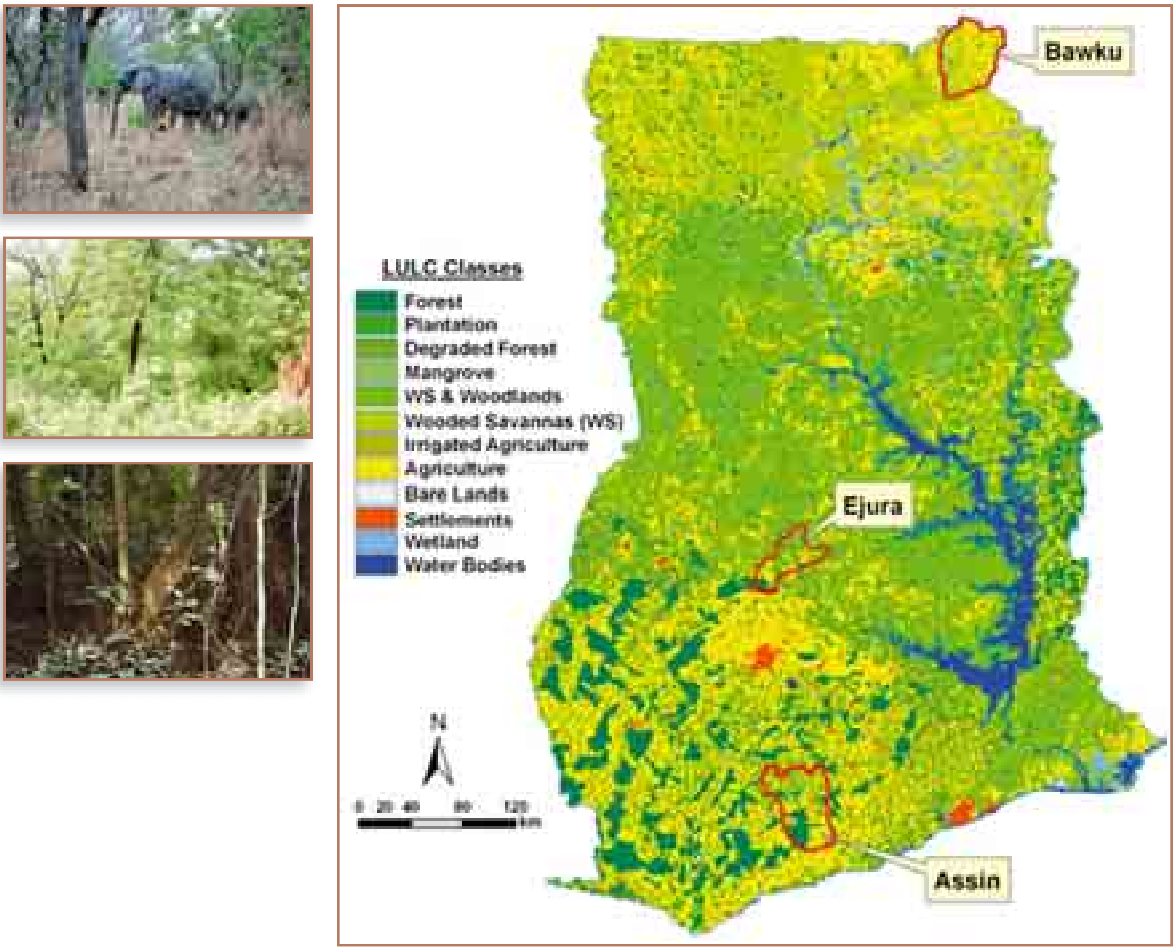

TABLE 2
Areal change (%) of major land use and land cover classes by 2000 from 1975 detected within three ecoregions in Ghana

District	Forest	Gallery Forest	Agriculture	Wooded Savannahs and woodlands	Wooded Savannahs	Degraded Forest	Wetlands	Settlements
Bawku		-56	41		-27		27	
Ejura	-8		159	-23		-62		
Assin	-22		53			-23		40

TABLE 3
Ecosystem and soil carbon changes associated with projected climate scenarios for three ecoregions in Ghana

District	Carbon stock	1900	2000	Change*	NCC		LCC		HCC	
					2100	Change**	2100	Change**	2100	Change**
		Mgha^{-1}		%	Mgha^{-1}	%	Mgha^{-1}	%	Mgha^{-1}	%
Bawku	Ecosystem	131	36	-73	31	-12	30	-17	29	-19
	Soil	32	20	-38	20	1	19	-5	18	-7
Ejura	Ecosystem	135	77	-43	74	-4	73	-5	71	-8
	Soil	27	21	-20	20	-6	18	-16	17	-20
Assin	Ecosystem	306	153	-50	146	-5	145	-5	143	-6

*) Percentage change in carbon stock by 2000 from 1900.
**) Percentage change in carbon stock by 2100 from 2000.
NCC, LCC and HCC represent no, low and high climate change scenarios, respectively.
This Table was synthesized from Tan *et al.*, 2009a, 2009b and 2009c.

CONCLUSIONS

Remote sensing has allowed the documentation of land cover changes across West Africa and offers the opportunity for continued assessments with the availability (http://landsat.usgs.gov/science_GLS2005.php)of Global Land Survey 2005 data at no cost. These analyses have shown substantial conversions of land cover from forests (deforestation) and woodlands to agricultural uses in all countries. These changes have resulted in substantial releases of carbon from these systems to the atmosphere, and land uses for agriculture in the absence of fertilizer inputs and residue retention have continued to degrade soils as both carbon and nitrogen have been mined. Simulations of the biogeochemical conversions and fluxes under various management and climate scenarios show dramatically that the “business as usual” land use and management scenarios will result in continued carbon losses and reduced crop sustainability, thereby threatening food security. Furthermore, the simulations of suggested climate change scenarios suggest that the increased temperatures will threaten traditional crop species and reduce yields in the hotter parts of West Africa.

Opportunities for adaptation, and even mitigation, do exist and can be implemented. Soil carbon can be restored with improved conservation practices, appropriate residue management and increased nitrogen input, either from inorganic sources or biological fixation, even as temperatures in West Africa increase with climate change. This restoration has the potential to improve food security, restore depleted soil carbon, reduce expanded deforestation, and improve the livelihoods of subsistence farmers. These benefits can be secured with greater attention to the importance of soil carbon for both mitigation and adaptation for climate change. Therefore, these results proclaim the importance of carbon crediting for ***Soil Carbon Uptake for Restoration and Sustainability (SCURS)***, our proposed analogue to Reduced Emissions from Deforestation and Degradation (REDD).

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Assimilation of land-surface temperature in the land-surface model JULES over Africa

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ABSTRACT

Land-surface models calculate the surface to atmosphere fluxes of heat, water and carbon; and are crucial elements of General Circulation Models (GCMs). Much variation however, exists in their parameterization and representation of physical processes, leading to uncertainty in how climate change influences the land surface. There is therefore a requirement to improve the algorithms for predicting key variables.

Land-surface temperature (LST) is one such variable, being important on a regional and global scale for the calculation of the surface energy budget. Furthermore, it can be applied to the estimation of live fuel moisture content (FMC); a critical variable determining fire ignition and propagation. For the continent of Africa this is pertinent, since there is much uncertainty in the carbon budget of the fire dominated savannahs.

This study assesses the feasibility of LST data assimilation into the land-surface model JULES, for optimizing the prediction of a crucial fuel variable. Findings indicate an improvement in the estimated LST when remotely sensed thermal observations are assimilated into the model.

Keywords: Land-surface temperature, Africa, Data assimilation, JULES

INTRODUCTION

Despite the importance of Africa in the global carbon cycle, climate scenarios for the continent are highly uncertain; and it is even unknown whether Africa is a net source or sink of CO_2 (Williams *et al.*, 2007). These uncertainties can only be reduced by the incorporation of representations of the most relevant processes into models, and constraining the model uncertainty with observations. The simulation of realistic fire disturbance regimes with biophysical and biogeochemical models is a prerequisite for reducing the uncertainty of the African carbon cycle.

LST, which is the radiative skin temperature of the land, is a critical variable for vegetation fires. It is derived from solar radiation and influences the partitioning

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of energy into sensible and latent heat fluxes. LST is useful in applications such as vegetation water stress monitoring, and surface energy balance assessment (Pinheiro *et al.*, 2006). Additionally, LST has an important relationship to the fire regime. It has been argued in previous studies (Sandholt *et al.*, 2002; Snyder *et al.*, 2006) that the ratio between the Normalized Difference Vegetation Index (NDVI) and LST can be expressed as a surface dryness index representing live FMC, which is a critical variable in the prediction of fire occurrence and propagation.

However, despite the importance to fire modelling and the fact that LST is more closely related to the physiological activities of leaves than air temperature (Sims *et al.*, 2008), it is air temperature that is more commonly employed in land-surface models. The aim of this study is to investigate the possibility of constraining the simulation of surface energy fluxes, and furthermore the prediction of FMC, through the assimilation of remotely sensed LST into the land-surface model JULES (Joint UK Land Environment Simulator), which is the community version of MOSES (Met Office Surface Exchange System).

JULES was developed to calculate the surface-to-atmosphere fluxes of heat and water when coupled to a GCM, as described by Cox *et al.* (1999). JULES updates variables which affect these fluxes, with each gridbox represented as a mixture of nine surface “tiles”. These consist of five plant functional types: broadleaf trees, needleleaf trees, C_3 grasses, C_4 grasses, and shrubs; and four non-vegetation types: urban, inland water, bare soil and ice. LST in JULES is a diagnostic variable derived at each timestep from the surface energy balance equation, given in Cox *et al.* (1999):

$$1) \qquad SW_N + LW\downarrow - \sigma T_s^4 = H + LE + G_0$$

where T_s is the surface temperature, σ is the Stefan–Boltzmann constant, SWN is the net downward short-wave radiation, $LW_\downarrow$ is the downward long-wave radiation, H is the sensible heat flux, LE is the latent heat flux, and G_0 is the heat flux into the ground.

Like all land-surface models, JULES has uncertainties due to its approximation of physical processes, and the heterogeneity of the land surface. Data assimilation is a method of minimizing these deficiencies, by adjusting the model state at observation times with measurements of a predictable uncertainty. Here the feasibility of assimilating LST into one the leading land-surface models is investigated. Potential deficiencies in the existing state variable estimation are discussed and improvements through assimilation are presented.

MATERIALS AND METHODS

For this study, JULES was run at an hourly timestep for the year 2006, at 1° x 1° spatial resolution. Initial conditions were set from the final state of the spin-up cycle. The duration of the spin-up was over 200 years, until soil temperature and moisture content reached an equilibrium state. Meteorological input data were taken from 6-hourly NCEP reanalysis datasets (Kalnay *et al.*, 1996); with precipitation data calibrated from monthly TRMM precipitation data (Kummerow *et al.*, 1998). Vegetation distribution was derived from the IGBP land-cover classes, and mapped onto the nine JULES surface tiles. Soil parameters are derived from the global vegetation and soils data set of Wilson and Henderson-Sellers (1985). The simulations were compared with three thermal satellite products, for the months of March, June, September and December.

Spinning Enhanced Visible and Infrared Imager (SEVIRI) is the main payload on board the geostationary satellite MSG1. It is centered over the equator, and acquires an image every 15 minutes at a spatial resolution of between 3 km and 5 km for the African continent. LST is processed using a split-window algorithm for channels IR10.8 and IR12.0, with an accuracy for most simulations between nadir and 50° viewing zenith angle of 1.5 K (Sobrino and Romaguera, 2004).

Moderate resolution imaging spectroradiometer (MODIS) LST is acquired from thermal IR sensors on board the sun-synchronous, near-polar orbiting satellite Terra, with a swath width of 2330km. LST is acquired twice daily at a spatial resolution of 1 km using a generalized split-window algorithm for bands 31 and 32 at an accuracy better than 1 K (Pinheiro *et al.*, 2006). Version 4 of the global LST product MOD11A1 was used here.

The AATSR sensor on board the sun-synchronous, polar orbiting satellite Envisat, has a swath width of 512 km; and is able to provide measurements at two viewing angles, forward and nadir. Only measurements from the nadir view, with a spatial resolution of 1 km, were employed in this study. The uncertainty in these observations is reported by Coll *et al.* (2005) as less than 0.9 K.

In order to compare model simulations, satellite data was re-projected onto a 1° x 1° grid covering the African continent. This was achieved by averaging all geo-referenced, cloud free ("good" quality) pixels within each gridbox. To account for the temporal variability in the different sources, intercomparison was performed at each JULES timestep only when this corresponded with SEVIRI observations, and matched the MODIS overpass times within a ±10 minute tolerance. Comparison was made with AATSR observations when these fell within the time windows. Observations over Africa were grouped as "Day" (approximately 07:00 - 12:00 UTC); and "Night" (approximately 19:00 - 24:00 UTC).

The assimilation experiment was performed with the Ensemble Kalman Filter (EnKF), first proposed by (Evensen, 1994), and which is a variant of the widely used Kalman Filter sequential assimilation method. The model estimates ψ^a are nudged towards the observations based on the respective state and observation error covariance matrices at each timestep according to the update equation, given by (Evensen, 2003):

$$\psi^a = \psi^f + K (d - H\psi^f) \tag{2}$$

where H is the observation operator (in this experiment a unit operator could be applied); and d are the observations. The Kalman gain K determines the correction to the forecast state vector ψ^f, with the optimum estimate of the model state taken as the mean of the ensemble members. K≡0 when no observations are available for a timestep, with K specified as:

$$K = P^f H^T [H P^f H^T + R]^{-1} \quad (3)$$

where R is the observation error covariance matrix, representing the ensemble of SEVIRI observations with randomly generated perturbations. R is constructed using the observation uncertainty of 1.5K (Sobrino and Romaguera, 2004); P is the model error covariance matrix determined from the ensemble spread. Assimilation was performed with an ensemble size of 100; with perturbations to the meteorological forcing data generated as normally distributed random numbers with zero mean and unit variance. In this experiment, only uncertainty in the forcing data was considered; model parameters and initial conditions were not perturbed.

RESULTS AND DISCUSSION

Our results (Tab. 1) indicate AATSR to be the warmest, with positive mean biases for day and (night) of 0.976K (0.85K) and 3.475K (3.725K) against SEVIRI, and MODIS respectively, and the largest standard deviation. MODIS was the coldest satellite product, with the largest daytime discrepancies corresponding with larger MODIS viewing angles; a result due to differential heating rates between sunlit and shadow scenes.

TABLE 1

Mean monthly day and night LST composites (K) [standard deviation] for March, June, September and December 2006

Time	LST Source	March	June	September	December
Day	AATSR	306.7 [8.5]	307.9 [9.8]	310.3 [9.5]	303.3 [9.2]
	MODIS	303.6 [6.6]	304.2 [8.7]	305.9 [7.4]	300.6 [7.0]
	SEVIRI	303.6 [5.6]	308.1 [8.9]	308.6 [6.8]	304.0 [7.0]
	JULES	300.3 [6.5]	300.9 [6.3]	299.4 [3.4]	297.1 [6.1]
Night	AATSR	292.2 [7.3]	298.4 [3.6]	298.2 [4.0]	289.5 [7.4]
	MODIS	288.9 [4.7]	294.0 [3.0]	293.9 [3.3]	286.6 [5.3]
	SEVIRI	293.7 [5.2]	296.1 [3.0]	296.9 [3.3]	288.2 [5.3]
	JULES	287.6 [7.3]	291.3 [4.7]	289.9 [4.9]	287.8 [6.4]

These results are in general agreement with the findings of previous intercomparison studies: SEVIRI was found to be warmer than the corresponding MODIS product over Central Africa and the Iberian peninsula, with strong dependency on the MODIS viewing angle (Trigo *et al.*, 2008a); and generally across ten sites in Europe and North Africa (Noyes *et al.*, 2006). Furthermore, this latter study reported AATSR to be warmer still for these sites.

When we compared the simulated LST from JULES with the remote sensing products (Fig. 1; Tab. 2), the larger biases between JULES and the mean remote sensing LST were found for less vegetated surface types, especially during daytime. There are several possible reasons for this. The first is overestimation of LST, as found in the study by Trigo *et al.*, (2008a), whereby daytime SEVIRI LST was found to be systematically warmer than *in-situ* measurements. The accuracy of this sensor was reported (Trigo *et al.*, 2008b) as failing to meet the LandSAF (Land-surface analysis Satellite Applications Facility) 2.0 K target over desert and semi-arid regions. Other possibilities include poor parameterization of soil thermal and hydrologic properties, and inadequate representation of soil albedo.

FIGURE 1
Mean daytime LST (K) during March 2006 for AATSR (top left); MODIS (top right); SEVIRI (bottom left); and JULES (bottom right)

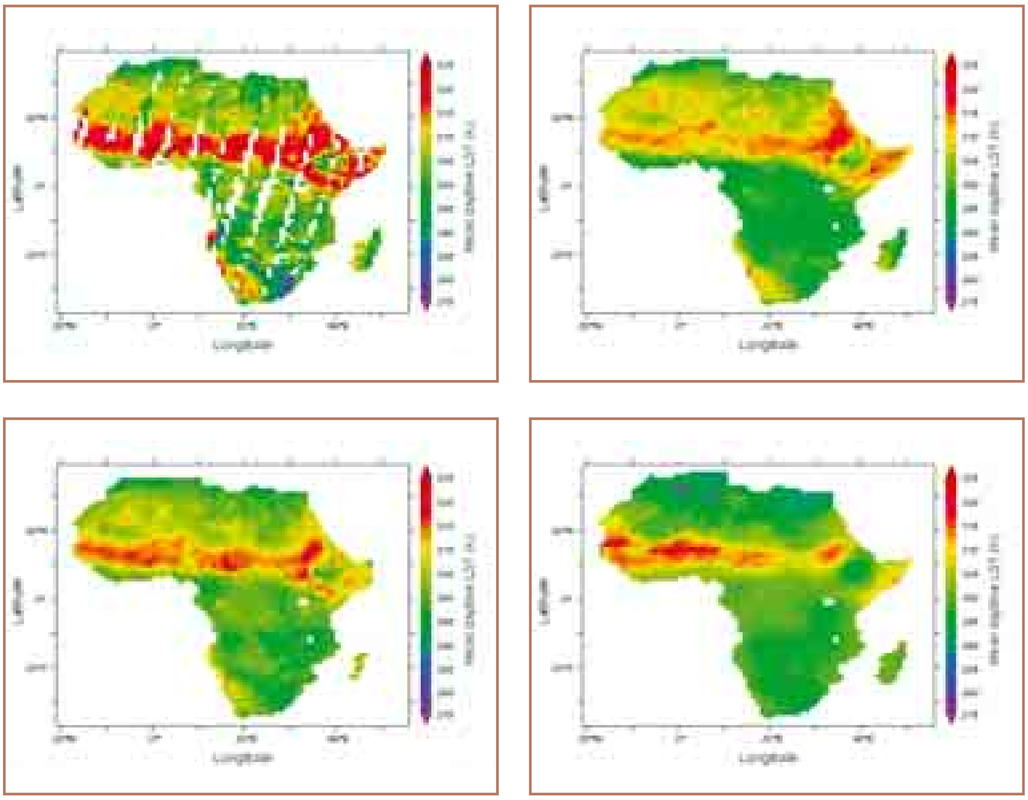


TABLE 2

Mean monthly day and night LST composites (K) [standard deviation] for March, June, September and December 2006.

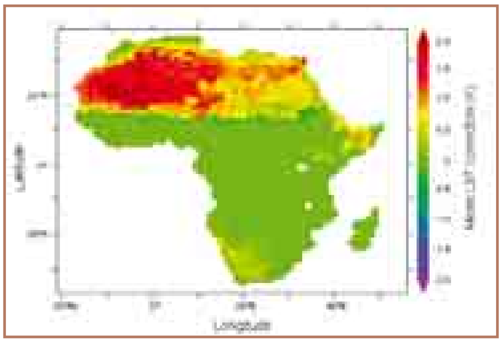
Time	Month	Evergreen Broadleaf Forest	Closed Shrublands	Open Shrublands	Woody savannahs	Savannahs	Grasslands	Barren / sparsely vegetated
Day	March	0.6	-3.6	-7.2	-0.7	-4.3	-0.3	-6.7
	June	-0.9	-4.5	-5.8	-2.5	-3.9	-1.1	-10.3
	September	-0.4	-6.8	-9.1	-5.7	-4.5	-2.5	-15.3
	December	0.7	-9.7	-9.5	-2.2	-7.1	-1.7	-7.5
Night	March	0.9	-2.3	-3.1	-0.5	-2.0	1.0	-5.8
	June	0.7	-1.4	-3.2	1.4	0.5	2.4	-8.5
	September	1.8	-2.8	-4.0	1.7	-0.1	2.2	-10.4
	December	0.8	-0.8	-0.6	1.9	0.3	1.6	-1.9

In JULES, the soil parameters currently derived for the model do not adequately represent the spatial variation in soil albedo or soil moisture content, particularly over desert regions (Houldcroft *et al.*, 2008). Indeed, two of the most determinant factors in surface temperature change reported by (Goward *et al.*, 2002) are soil moisture; with higher LSTs a feature of dry, bare soils; and downward radiation, with surface albedo determining the fraction of energy available for partitioning between surface exchange heat fluxes.

For the assimilation experiment, SEVIRI LST was assimilated into JULES for March 2006. An improvement to the simulated LST resulted, with the mean negative bias between JULES and SEVIRI being reduced by 0.45 K. The largest corrections, as much as +2K, were experienced in the arid regions of the continent; corresponding to the barren / sparsely vegetated IGBP land-cover class (Fig. 2). This result indicates a considerable benefit in updating the modeled state with remotely sensed observations.

FIGURE 2

Mean LST correction (K) for JULES during March 2006 following assimilation of SEVIRI observations.



CONCLUSIONS

LST is related to soil water content, and is important in the calculation of surface to atmosphere heat fluxes. The accurate modelling of this variable is crucial in constraining land-surface models. A complete verification with *in-situ* measurements is a difficult task, due to sparse availability of measurements and the heterogeneity of the land surface. A realistic alternative is therefore an intercomparison with remotely sensed observations, which although subject to uncertainties have themselves undergone validation studies. The results presented here indicate, though differences exist for sparsely vegetated regions, that LST simulated by JULES is comparable with remotely sensed products.

The bias between model and satellite can be reduced through data assimilation; in this investigation the mean negative bias was reduced by almost half a degree, with the largest corrections being applied in the arid regions of Africa. Assimilation of remote sensing products into land-surface models, as suggested here from applying the EnKF to the JULES model, can prove to be a significant method of improving land-process simulations. The EnKF is a flexible and practical data assimilation method; being simple to implement, with an affordable computational burden.

Further investigation is desirable. Specifically, experimentation with perturbed initial conditions and model parameters; optimization of the selection of ensemble size; improvement in the parameterization of soil thermal and hydrological properties; and quantification of the impact upon the partitioning of downward radiant energy into ground, sensible and latent heat fluxes through the full integration of the scheme into the model. It is anticipated that the improvement of land-surface modelling through assimilation of LST will lead to the optimization of a surface dryness index to estimate live fuel moisture content; an important variable in modelling fire occurrence and propagation, which are critical properties for understanding the carbon budget of fire dominated ecosystems, such as the African savannahs.

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Evaluation and improvement of the representation of Sahelian savannah in the vegetation model ORCHIDEE

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ABSTRACT

It is necessary to better understand and quantify surface processes that affect fluxes of carbon, sensible and latent heat over Sahelian savannah and steppe landscapes. We present an approach using the process-based vegetation model ORCHIDEE, with site level measurements, to build up a preliminary for a spatial analysis of CO_2, H_2O and energy fluxes at different scales. A calibration and preliminary validation of phenology, and other key physiological parameters have been conducted at Agoufou, Mali, a site established in the framework of the AMMA project. At this site, measurements of leaf area index, biomass, energy fluxes, soil water and temperature profiles were available. This enables us to identify some of the deficiencies of the modeling approach employed.

Keywords: Sahel, Surface hydrology, Vegetation model

INTRODUCTION

This study fits within a more general research effort which aims at improving our appraisal of the geographical distribution of carbon, water and energy fluxes over African savannahs and grasslands at large scale, in order to proceed to long term studies and scenarios.

To our knowledge, two main ways have been envisioned to tackle these kinds of questions. On the one hand, various authors have conducted data-mining analyses, trying to find transfer functions between what may be observed directly and the variables of interest (simple regressions, Neural Networks, decisions trees, or even inversion may be considered as such). In a simplistic way, all these classes of methods may be described broadly as optimising the fraction of explained variance with a constrained number of degrees of freedom. If theoretical arguments back our confidence in the capacity of interpolation of most of these techniques, the

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situation is completely different if one considers their capacity of extrapolation. Indeed, there are very few reasons for which they may remain accurate outside of the domain of observed data for which they have been trained.

On the other hand, we may try to incorporate all the processes that are likely to have significant impact on the relation. It is the kind of approach that we have employed here, integrating some part of the knowledge acquired through site studies in the Malian Gourma into a global vegetation model, ORCHIDEE, developed mainly at the Institut Pierre Simon Laplace, in Paris (Krinner *et al.*, 2005). On a practical point of view, the following characteristics allow us to do so: it is process-based and modular in form, which allows the introduction of new features. Besides, its scale-independent formulation let us consider it matches within the footprint of a flux-tower whereas it is initially conceived for estimates at much larger scales. Admittedly, the first inherent source of difficulty with this kind of method is that we have really little possibilities to control in an objective manner the delimitation of the set of processes that are bound to be sufficient (all the more so since there are usually developed in order to answer numerous and rather evasive goals), leading *de facto* to the inclusion of a very large set of loosely constrained degrees of freedom. That having been said, one may still develop various complements to the architecture of a model and then proceed to assimilation/optimisation schemes with a set of fixed-architecture models. Once an objective is given, it is possible to identify which one performs best in this regard. By doing so, we are just getting closer to the kind of data-mining activities describe above, but with a model which is more likely to exhibit a meaningful behaviour when proceeding to extrapolation exercises.

MATERIALS AND METHODS

Description of the site of study and of the site-level information that we could use

Situated in the Gourma region of Mali which stretches from the loop of the Niger River southward down to the border with Burkina Faso, Agoufou (15.3°N, 1.5°W) is steered by a semi-arid tropical climate. The rainy season, controlled by the Guinean Monsoon, starts usually at the end of June and finishes in September. On that site, which covers fixed dunes, the vegetation is mainly composed of annual grasses and shrubs. The grasses strata is dominated by Cenchrus biflorus, Aristida mutabilis and Zornia glochidiata; their development starts after the first rain (not prior to June) and unless the annual plants wilt before maturity due to lack of rain, the senescence follows the fructification which is usually loosely concomitant with the end of the rainy season.

The Agoufou site has been instrumented with an eddy-flux tower and various ancillary data are frequently monitored (Mougin *et al.*, 2009 submitted). For this presentation, we employed the local micro-meteorological measurements made on the Eddy-flux tower in 2005-2006 (courtesy E. Mougin). We could also consider sensible heat fluxes (courtesy Kergoat, L.) soil humidity profiles (De Rosnay *et al.*, 2008) and biomass and Leaf Area Index measurements (courtesy Hiernaux, P., 1992, 2008).

The Gourma has been extensively studied since the early 1980 decade throughout various projects, among which the ones conducted by ILCA (International

Livestock Centre for Africa) and IER (Institut d'Economie Rurale) between 1983-1994 and the AMMA project since 1998.

Description of the general characteristics of the model

ORCHIDEE is a (dynamic) global vegetation model designed as an extension of an existing surface-vegetation-atmosphere transfer scheme. The model simulates the principal processes of the continental biosphere influencing the global carbon cycle (photosynthesis, autotrophic and heterotrophic respiration, etc.) as well as latent, sensible, and kinetic energy exchanges. By default, the whole seasonal phenological cycle is prognostically calculated without any prescribed dates or use of satellite data.

In the case of a semi-arid environment like the one we are considering here, it is the hydrological balance that strongly controls the different aspects of the evolution of the outputs of the model throughout the year.

Model optimisation and “improved” process formulations

In this study, the representation of the dynamic of the vegetation on inter-annual scale has not been activated (the maximum share of surface cover of each vegetation type has been prescribed). Considering that the share of shrubs is close to 5%, we have pushed our attention on the representation of the herbaceous layer.

Hence, we have conducted (manually) tests of sensitivity on the parameters that describe the impact of hydric stresses on the phenology of the herbaceous layer (start of the growing season, turnover rate,...). Besides, we have proceeded to the implementation of photoperiodism that was not integrated in the model before.

This is the basis of a comparison between the standard model implementation and a set of “optimised” version that we present briefly here:

v1: carbohydrate translocation and hydraulic stress at the beginning of the growing season

We have increased the threshold of humidity above which the growing season may start. The values themselves can hardly be discussed as the hydrological scheme is conceptual and thus no direct comparison with measurement is possible. We have also drastically reduced the modelled translocation of carbohydrates as it is not relevant for a strata mainly composed of annuals (Tracol 2005, Hiernaux 2008), keeping a non null value for initialisation reasons.

v2: v1 + modification of the impact of abiotic factors on the senescence rate.

We have increased both the values of the threshold of humidity leading to the start of senescence and the turnover rate (20 days for the later, which is among the quickest value registered in the literature).

v3: v2 + integration of the photoperiodism (Breman) and adjustment of LAImax

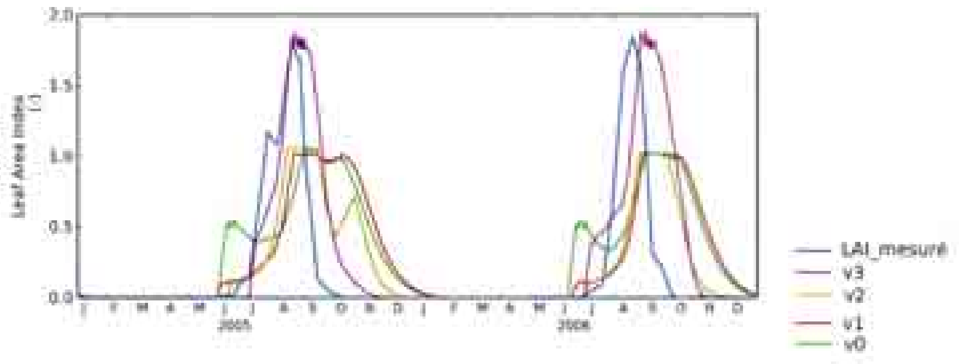
Following Breman *et al.* (in Vries de, P. 1991), we have represented the impact of photoperiodism on the length of the anthese (part of season of growth before flowering). A critical daylength was assumed beyond which development rates increase lineary when photoperiod shortens. This assumption is based on the flowering behaviour of several short day crops in tropical and sub-tropical areas (Hadley *et al.*, 1983). As the length of the last phases of growth tend to be constant when the hydric stress doesn't happen to be limiting earlier on, this concept may be used to add a complementary constraint on the maximal length of the growing season in the model.

RESULTS AND ELEMENTS OF DISCUSSION

As a result of the sensitivity test that we have conducted (focusing on Leaf Area Index), we present the result of various steps in the modification of the model toward a more realistic representation of the herbaceous strata (*cf.* Fig. 1 for main characteristics of the version considered). With regards to the modelled translocation of carbohydrate, we may say that the "non autotrophic growth that it supported was not only not appropriate mechanistically but also led to a very strong overestimation of possible increase of the Leaf Area Index of the herbaceous strata at the beginning of the season (Fig. 1). In practice, with a time-serie which let us consider only two repetitions, the representation of photoperiodism that we integrated is nearly equivalent to the introduction of a cut-off at the end of the growing season before that the hydric stress starts to be significant. Even as such, it is necessary to help us represent a well established fact: that the poaceae don't fully use the soil water reserve, there are provided with at the end of the raining season. An educated guess that we may push to explain this fact is that the cohort of annuals only contains significant amount of colonies that have been in position to aliment the soil seed banks even during the less favourable years. The remaining discrepancy at the end of the growing season is likely due to a difference of nature between the green LAI measured in the field and the LAI of the model which also integrates wilting plants, just considering that old cohorts maximum rate of carboxylation is strongly reduced (*cf.* Krinner 2005).

FIGURE 1

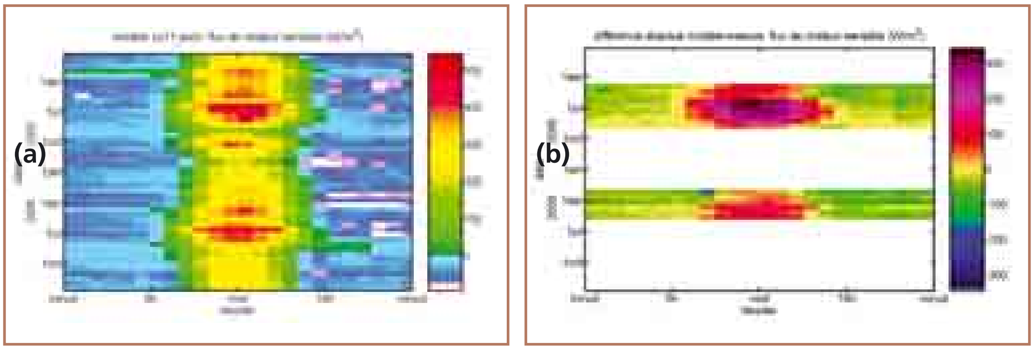
Leaf Area Index of the grasses strata. Results of different versions of the model against field measurements



Results of different versions of the model against field measurements.

Although the LAI and the biomass are fitted to a correct range, many sides outputs of the model continue to be out of the observed range (example of the diurnal cycle of sensible heat flux on Fig. 2).

FIGURE 2
Sensible heat fluxes (W/m²)



Each point representing the 15 days average of the observed value during one hour of the day. a) Model output. b) Difference between modelled (v3) and measured sensible heat fluxes (W/m^2). Each point representing the 15 days average of the observed value during one hour of the day.

CONCLUSIONS

Aiming at a more satisfactory representation of the Sahelian-savannah ecosystems at large scale, the results presented here on the local scale must indeed be considered as work in progress. Above the remaining discrepancies that still exist between our model and the measurements, one of the important complement that we have to tackle is the accurate translation at aggregated scale of the kind of information we have acquired at the local level. The different satellite products are obviously our main crutches to do so and this will be handled in conjunction with the effort that has been undertaken in the frame of the CAMELIA project (Peylin *et al.*). By a study at the scale of 50 km x 50 km, we will also be in position to assess the impact of the negligence of the spatial redistribution of water, which is crucial in the functioning of these ecosystems and is not taken into account for endoreic systems in ORCHIDEE.

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Carbon Sequestration and reduced emissions potentialities in Africa

5

Carbon stock under four land use systems in three varied ecological zones in Ghana

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ABSTRACT

The terrestrial ecosystem, in which carbon (C) is retained in the live biomass, decomposing organic matter and soil, serves as reservoir of C and hence plays an important role in the global C cycle. Rates of land-use change and changes in C stock following degradation and deforestation are the major factors determining the emissions of C from the tropical forest. The study was undertaken to assess the impact of four different land-use systems namely natural forest, teak (*Tectona grandis*) plantation, fallow land and cultivated land, on system C stock, and as well determine C stock trends at various ecological zones. This was carried out in three varied ecological zones namely Moist Evergreen Forest (**MEF**), Dry Semi-Deciduous Forest (**DSDF**) and Savannah (**SAV**) zones. Carbon accumulation in trees, herbaceous plants, litter and soil (up to 40 cm depth) was assessed. The C stock in the various land-use systems in the MEF and DSDF was in the increasing order, cultivated land, fallow land, teak plantation and the natural forest. However for the savannah zone, the teak plantation accumulated more biomass C than the natural forest. Under each of the four land-use systems, the highest biomass C accumulation was exhibited by the MEF, followed in a decreasing order by the DSDF and the SAV ecological zones.

The trend in the soil C stock under the various land-use systems within each of the ecological zones was different among all the ecological zones. The least soil C stocks in the MEF and the DSDF zones was in the cultivated land, whereas in the savannah zone it was in the teak plantation. The highest soil C stock was in the fallow land in both the DSDF and savannah zones, whereas the highest was in the natural forest land in the MEF. Vertical distribution of soil organic C was affected by climate, represented by the ecological zones, but the influence was minimal with the land-use system. For the 0-20cm soil depth proportion of the soil C, with respect to the total (0 – 40 cm depth) was 67.10 % ± 0.018 (SD), 60.52 % ± 0.074 and 55.56 % ± 0.008, for SAV, DSDF and MEF sites, respectively.

Using the Natural forest as the benchmark, impact of C loss on the conversion of the natural forest to the other land-use systems was found to be more pronounced in the DSDF and MEF zones than in the SAV zone. Within the land-use systems, the C loss was in the increasing order Teak, Fallow and Cultivated lands. The study

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should be extended to cover more sites in all the ecological zones of the country and as well expand the land-use systems. This will allow the results to be related to environmental variables to enable predictions to be made.

Keywords: Cultivated land, ecological zones, fallow land, natural forest, system carbon stock, Teak plantation

INTRODUCTION

The terrestrial ecosystems, in which carbon (C) is retained in the live biomass, decomposing organic matter, and soil, serves as reservoir of carbon and thus plays an important role in the global carbon cycle. A consequence of deforestation and degradation is the release of the carbon originally held in the forest to the atmosphere, either immediately through the burning of the vegetation or more slowly as unburned organic matter decays. Cultivation further oxidizes 25-30% of the organic matter in the upper part of the soil and these are released into the atmosphere (Houghton, 2005). Deforestation and forest degradation are said to contribute to between 20 and 25% of the global greenhouse gas emissions. However, these C losses can be reversed through reforestation and afforestation. Rates of land-use change and changes in C stock following degradation and deforestation are the determined factors of the emissions of carbon from the tropical forest. Ecosystem and land-use systems have major influence on changes in C stock. The net flux of C between the terrestrial biosphere and atmosphere is determined by the changes in the various reservoirs namely, living vegetation, soils, woody debris and wood products. It is therefore necessary to examine how C flows between different reservoirs and how C stocks change in response to various land-use activities (IPCC, 2000). The main causes of the land use change in West Africa are shifting cultivation, timber extraction and conflicts.

Plant production and decomposition determine C inputs into the soil profile. The type of vegetation cover may influence the abundance of organic C in the soil, which in turn affects plant production (Jobbagy and Jackson, 2000). The conversion of the natural forest to other land uses may affect both biomass C and soil C stocks. The IPCC (2000) report specifies that for full C accounting system, changes in C stock across all C pools should be completely accounted for. It is therefore imperative that C stock data under various land-use systems are collected and related to environmental variables. This will enable rate of change of C stock with respect to land-use system as well as environmental variables to be predicted and also to help in understanding the influence of the terrestrial ecosystems on the climate. Data on soil and vegetation C stock that could aid in elucidating the impact of land-use change under various climatic conditions are scarce in Ghana. However, a fairly representative soil organic C stock value, up to the depth of 20 cm, was reported for forest, forest-savannah transition zone and savannah soils by Acquaye and Oteng (1972), but vegetation C was not included. The aims of the study are to assess the impact of four different land-use systems on the C stock and to determine the carbon stock trends at various ecological zones.

MATERIALS AND METHODS

Sites from three ecological zones in the country namely Kakum in the Moist Evergreen Forest (MEF) (5° 21’ N, 1° 23’ W), Ejura in the Dry Semi-Deciduous Forest (DSDF (7° 19’ N, 1° 22’ W) and Bawku in the Savannah (SAV) (11° 00’ N, 0° 15’ E) zones, were selected for the study. Mean annual rainfall for the MEF, DSDF and SAV sites is about 2000 mm, 1260 mm and 1000 mm, respectively. The MEF and DSDF sites experience bimodal rainfall with major and minor peaks mostly in June and in October, respectively, whereas the SAV site experiences unimodal with the peak in July, August or September. Mean maximum temperature is 32.14 ^{O}C, 33.04 ^{O}C and 33.91^{O}C, whilst mean minimum temperature is 22.30 ^{O}C, 18.21 ^{O}C and 22.88 ^{O}C, for the MEF, DSDF and SAV sites, respectively.

Four land-use systems were identified in each of the three sites. These are the natural forest, teak (*Tectona grandis*) plantation, fallow land and cultivated land (farms). Temporary sampling plots (**TSPs**) of size 25 by 25 m, giving rise to an area of 0.0625 ha, were established in the various land-use systems in the selected sites in the three ecological zones. The TSPs were established, to capture variability of the particular stand characteristics. All trees in the various land-use systems that were above two meters in height were inventoried and stem diameter at breast height of 1.3m was measured.

In addition, four sub-plots (quadrates) of size 1.0 m by 1.0 m were established in all the TSPs. All herbaceous and woody plants on the sub-plots were destructively sampled and the litter collected. Fresh weights were immediately determined, and samples of the plants and litter were collected for dry weight determination, by oven-drying to constant weight. Sub-samples were also reserved for carbon content analysis.

In the sub-humid regions C accumulates to greater depth in the soil profile, however in the semiarid regions C is mostly contained in a relatively shallow depth of 15 to 25 cm (Tiessen *et al*., 1998). Soil samples were consequently collected from the soil depth of 0 to 20 cm and 20 to 40 cm within the quadrates, air dried and sieved through 2.0 mm mesh, and then texture and organic C content determined. Accompanying bulk density samples were collected from the same soil depths, allowing carbon contents to be expressed on an area basis and as well to assess the vertical distribution of soil C stock. The undisturbed soil samples were used for the bulk density determination. Soil organic C was obtained in the laboratory by Walkley and Black (1934) method and particle size distribution was measured using Bouyoucos Hydrometer. The bulk density was determined from oven-dried core samples at 105°C for 24 h. Soil C per hectare was calculated from the organic C content and the bulk density. The diameter at breast height measurements were used to estimate aboveground phytomass of individual trees in the stand. Aboveground phytomass, *W*, of the individual trees was estimated from stem diameter at breast height, *d*, of 1.3 m by employing various equations. The equation used for the teak (Asomaning 2006) was;

$$W = 0.066\, d^{2.565},\ R^2 = 0.965 \tag{1}$$

For the natural forest in the MEF and DSDF, the revised equation of Brown *et al.* (1989) for moist forest (*cf.* Brown 1997) was used;

$$W = \mathrm{Exp}\,(2.134 + 2.530 \times \mathrm{Ln}(d)),\ R^2 = 0.97 \tag{2}$$

For the natural forest in the savannah, the revised equation of Brown *et al.* (1989) for dry zones of rainfall greater than 900 mm per annum (*cf.* Brown 1997) was utilized;

$$W = \mathrm{Exp}\,(-1.996 + 2.32 \times \mathrm{Ln}(d)),\ R^2 = 0.89 \tag{3}$$

Below-ground biomass, W_b, was estimated from the knowledge of the aboveground biomass based on the revised equation of Cairns *et al.* (1997) for tropical forest (*cf.* Pearson *et al.* 2005) as;

$$W_b = \mathrm{Exp}\,(-1.0587 + 0.8836 \times \mathrm{Ln}(W)),\ R^2 = 0.83 \tag{4}$$

Stand tree biomass was calculated from the summation of individual tree phytomass per plot, whereas the herbaceous and litter biomass was calculated from the data obtained from the quadrates. Carbon content was analysed for 38 wood samples, 25 herbaceous samples and 30 litter samples, drawn from all the ecological zones. The C content values were used to convert the biomass of the various plant functional types to C equivalent. The C content of the wood was used for the trees.

RESULTS AND DISCUSSION

Carbon content

Carbon content of the litter, herbs and wood was in the increasing order 29.98% ± 6.06 (SD), 37.46% ± 6.33 and 47.48% ± 2.33, respectively. There was significant difference in the C content among the various plant functional types ($P < 0.05$). However for a particular plant functional type, there was no significant difference in the C content among the ecological zones ($P < 0.05$). For *Chamaecyparis obtusa* (Hinoki cypress) trees, Adu-Bredu *et al.* (1996) found the C content to be between 45.9 and 54.7%, with the average value being 50.0%. It is a common practice to regard C content as 50% of biomass, but Pearson *et al.* (2005) pointed out that local data should be preferred if available and that the Clean Development Mechanism (CDM) Executive Board may require local measurement of C content in the future. The results of this study indicate that C content of various plant functional types may be different and that the 50% C content should be used with caution.

Soil Carbon

For the savannah, the soil C stock in the fallow land-use system was slightly higher than that of the cultivated and natural forest, which was similar, while the teak stand had the lowest. The total soil C stock (0 – 40 cm soil depth) in the SAV was 34.05, 32.02, 32.14 and 23.64 Mg C ha^{-1} for the fallow, cultivated, natural forest and teak stand, respectively. The very low value for the teak can be attributed to the fact that teak leaves decompose slowly and the intensity of the annual bush fires that sweep through the teak stands burn all the litter on the forest floor. Bruijnzeel (1998) pointed out that loss of soil C is affected by fire intensity and ambient weather conditions, as this prevents the incorporation of the litter into the soil through decomposition. The range of 15.33 to 22.89 Mg C ha^{-1} for the top 20 cm soil depth given in this study for the various land-use systems in the SAV (Tab. 1) is comparable to average value of 25 Mg C ha^{-1} given by Tiessen *et al.* (1998) for the semi-arid regions, as well as the value of between 11.7 and 41.3 Mg C ha^{-1} reported by Manley *et al.* (2004*a*,*b*) for various land-use systems with varying crop intensities for the top 20 cm depth for the savannah of west Africa.

The soil C stock was lowest in the cultivated land-use type in both the DSDF and MEF zones, but the highest was in the natural forest for the MEF and in the fallow for the DSDF. The high soil C in the MEF can be attributed to the high rainfall and high relative humidity as well as the high turn-over of leaf litter fall, resulting in high decomposition rate. The total soil C was 56.72, 28.37, 30.88 and 47.57 Mg C ha^{-1} for the DSDF while for the MEF, it was 86.95, 72.30, 93.47 and 87.21 Mg C ha^{-1} for the fallow, cultivated, natural forest and teak stand, respectively. The soil C of the top 20 cm soil depth given in this study (Tab. 1) for the natural forest in the MEF is comparable to the range of 58.3 to 63.9 Mg C ha^{-1} given by Solomon *et al.* (2002) for the tropical humid forest of south-eastern Ethiopia. The soil C stock value of 40.82 Mg C ha^{-1} given for the top 20 cm depth of the cultivated land-use system in this study for the MEF (Tab. 1) is comparable to range of 33.9 to 39.7 Mg C ha^{-1} given by Solomon *et al.* (2002) for similar land-use system for south-eastern Ethiopia.

For each of the land-use systems, there was the tendency for the soil C stock to increase along a climatic gradient from savannah, DSDF to MEF. However for the cultivated and the teak land-use systems, the soil C stocks tended to be slightly higher with the SAV than at the DSDF zone. The low soil carbon stock exhibited in the SAV and the DSDF compared to the MEF can be attributed to the frequent occurrence of bush fires in the two former ecosystems, as fire intensity affects soil C stock (Bruijnzeel 1998).

The land-use system did not significantly affect the vertically distribution of soil C stock but the climate, represented by the ecological zones, influenced the distribution. However, Jobbagy and Jackson (2000) found out that plant functional type significantly affected the vertical distribution of soil C. Allocation of C to the 0-20 cm soil depth, with respect to the total (0 – 40 cm depth) was 67.10 % ± 0.018 (SD), 60.52 % ± 0.074 and 55.56 % ± 0.008 for the SAV, DSDF and MEF sites, respectively. The results of this study conforms to the assertion by Vagen *et al.* (2005) that the highest soil C stock is concentrated in the top 20 cm soil depth. The allocation of soil C to the top 20 cm soil depth decreased with increasing rainfall and increasing ambient temperature, as represented by the ecological zones.

TABLE 1

Components of carbon stock (Mg C ha^{-1})

Land-Use	Ecological Zone	Trees	Herbs	Litter	Soil Carbon	
					0-20 cm	20-40 cm
Fallow	Savannah	0.95	4.28	0.08	22.89	11.16
	DSDF	1.68	3.28	2.40	31.09	25.69
	MEF	2.57	2.51	3.44	47.29	39.66
Cultivated	Savannah		1.09	0.08	21.45	10.57
	DSDF	0.82	0.67	1.34	16.12	12.15
	MEF	2.23	1.34	0.42	40.82	31.88
Teak stand	Savannah	26.09	0.77	0.50	15.33	8.31
	DSDF	25.61	1.49	2.11	33.93	13.64
	MEF	97.69	1.68	3.08	48.87	38.34
Natural Forest	Savannah	15.92	2.68	0.26	22.28	9.86
	DSDF	178.30	1.57	1.70	18.21	12.67
	MEF	229.40	0.61	3.27	52.02	41.45

DSDF, Dry Semi-Deciduous Forest; MEF, Moist Evergreen Forest; SAV, Savannah

Biomass Carbon

Tree C stock under the various land-use systems among the ecological zones was in the increasing order SAV, DSDF and MEF (Tab. 1), reflecting the climatic gradient. In the MEF and DSDF the highest tree C stock was from the natural forest followed by the teak plantation, while the least was from the cultivated land-use system in all the ecological zones. However, in the SAV the highest tree C stock was from the teak while the cultivated land-use system had no tree C stock. This can be attributed to the harvesting of the trees as fuel wood in the cultivated land-use system. The aboveground tree C stock of the natural forest was 13.60, 156.60 and 202.07 Mg C ha^{-1} for the SAV, DSDF and MEF, respectively. The value for the SAV given in this study is comparable to the average value of 10.0 Mg C ha^{-1} given by Brown (1997) for the savannah. The reported value for the MEF in this study is similar to average value of 204.0 Mg C ha^{-1} given by Koto-Same *et al.* (1997) for six different sites in the humid forest zone of Cameroun. The value for the DSDF is also within the range of 60.0 to 200.0 Mg C ha^{-1} given for the tropical humid forests by Brown (1997).

The herbaceous C stock increased from MEF, DSDF to savannah for fallow and the natural forest but the reverse holds for the teak stand, whereas for the cultivated land-use system the highest was in the MEF and the smallest in the DSDF. This trend can be attributed to the fact that the canopy in the natural forest and the fallow land is more opened in the SAV followed by the DSDF and then MEF. Light can therefore easily penetrate to the forest floor in the SAV and DSDF than the MEF resulting in the presence of more abundant herbs in the former two than in the latter. With regard to the teak stand, fire annually runs through the stand in the SAV, while in the MEF fire hardly runs through the stand. The high rainfall in the MEF provided the environment conducive for more abundant herbs to grow in the cultivated land than in the SAV and DSDF zones, since there is no problem of tree canopy closure in the cultivated land.

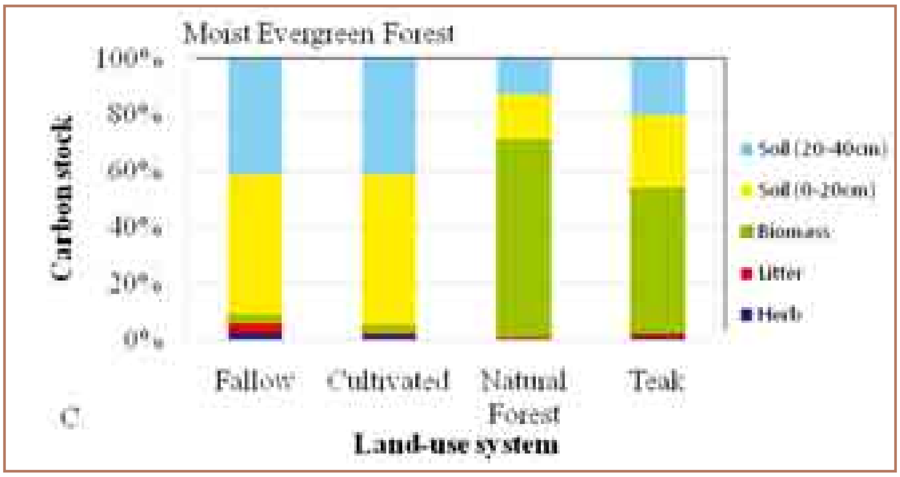
When considering the litter component, the highest C stock was found in the MEF followed by DSDF and savannah for the fallow, natural forest and the teak stand. The cultivated land exhibited different trend. The prevalent annual fire in the savannah results in the burning of the litter. The fire also encourages the growth of herbs and retards the growth of the woody plants. This is also aggravated by the low amount of rainfall and the severity of the dry season. The high litter C exhibited in the MEF can be the result of high leaf turnover due to the favourable environmental conditions.

Total System Carbon Stock

On the average, contribution of Soil C stock to the total system C stock decreased in the order cultivated, fallow, teak and natural forest land-use types (Fig. 1). However, for the SAV the contribution from the natural forest was greater than that of the teak land-use. Soil C stock is therefore very critical in cultivated land-use system; hence agronomic practices that enhance soil C stock should be pursued. Carbon stored in soil organic matter is important in improving soil properties such as nutrient supply, moisture retention and as a consequence, increase land productivity and crop yields (Lal *et al.* 1999; FAO, 2001). Even though the natural forest land-use system exhibited a very high soil C stock compared to the other land-use systems, the biomass C stock was far greater. The contribution of soil C stock to the total system C stock for the cultivated land-use was 96.47, 90.89 and 94.80%, for the fallow land-use it was 86.51, 88.52 and 91.08%, for the teak land-use it was 46.35, 61.96 and 45.98%, whereas for the natural forest land-use it was 63.02, 14.53 and 28.61% for the SAV, DSDF and MEF, respectively.

FIGURE 1

Contribution of the various ecosystems components to the total carbon stock in the Savannah (A), Dry Semi-deciduous Forest (B) and Moist Evergreen Forest (C).



In all the land-use systems, the largest total system C stock was exhibited in the MEF followed in a decreasing order by DSDF and SAV zones (Tab. 2), except for the cultivated land-use where the smallest carbon stock was in the DSDF. Considering the land-use systems, the largest C stock was in the Natural forest followed in a decreasing order by Teak stand, Fallow and cultivated land-use systems. Analysis of variance indicated high significant differences ($P < 0.05$) among the land-use systems in each of the sites. But for the SAV, the Natural forest and the Teak stand had similar total system C stocks.

Using the Natural forest as the bench-mark the C loss from converting the Natural forest to other the other land-use systems was found to be more pronounced in the MEF and DSDF than in the SAV. Within the land-use systems, the loss of C stock was in the increasing order Teak, Fallow and Cultivated land-use systems. For the SAV, the C stock loss was 0.00, 22.82 and 34.92 %, for the DSDF it was 63.86, 69.84 and 85.47%, while for the MEF it was 57.66, 70.78 and 77.01% for the Teak, Fallow and Cultivated land-use systems, respectively.

TABLE 2

Total carbon stock (Mg C ha^{-1}) under the various land-use systems in the three ecological zones

		Land-use systems			
Ecosystems		Fallow	Cultivated	Natural Forest	Teak stand
Savannah	**Mean**	**39.36**	**33.19**	**51.00**	**51.00**
	Minimum	36.63	33.17	47.18	43.57
	Maximum	42.09	33.21	54.17	58.43
	SD	3.86	0.02	3.28	10.50
DSDF	**Mean**	**64.08**	**30.87**	**212.46**	**76.78**
	Minimum	63.83	30.76	135.61	72.32
	Maximum	64.33	30.98	285.34	81.24
	SD	0.35	0.16	61.68	6.31
MEF	**Mean**	**95.46**	**75.12**	**326.75**	**138.33**
	Minimum	92.83	75.09	283.30	133.14
	Maximum	98.09	75.15	368.33	143.53
	SD	3.72	0.04	43.89	7.35

DSDF, Dry Semi-Deciduous Forest; MEF, Moist Evergreen Forest

CONCLUSIONS

It has been shown from the results of this study that high proportion of the soil C is allocated to the top 20 cm soil depth and that climate has high influence on the vertical distribution of soil C. Land-use systems have high influence on the contribution of soil C stock to the total system C stocks and is very critical in cultivated land-use system. Consequently agronomic practices that can enhance soil C stock should be pursued since C stored in soil organic matter is important in improving soil properties such as nutrient supply, moisture retention and thus increase land productivity and crop yields. If fire, which is a major force that affects soil C stock retention in the savannah, is controlled soil C stock can be improved.

The conversion of the natural forest to cultivated land-use system led to the reduction in biomass C and subsequently gradual depletion of soil organic carbon in all the ecological zones. However, the impact of total system C loss was found to be more pronounced in the DSDF and MEF zones than in the SAV zone. The conversion of cultivated land to fallow land-use or tree plantation can reverse this trend. The scope of the study needs be expanded to cover more sites and land-use systems in most of the ecological zones in the country. This will allow the results to be related to environmental variables to enable predictive models of land-use change and its consequences to be carried out.

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Potential for country-level aboveground carbon sequestration and emission reductions through forestry activities in Sub-Saharan Africa – evidence from Ghana

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ABSTRACT

In the context of climate change and researches on C cycle in sub-Saharan Africa, the estimation of the potential for carbon (C) sequestration en emission reductions using forestry is poorly known. Using the example of Ghana, this study aims to assess the C stocks in the various land cover types and ecoregions of the country and to estimate the potential C sequestration and emission reduction through afforestation and reforestation, forest restoration and conservation. Aboveground C stock in Ghana was found 1,158 Tg and most of it was in broadleaf forests (62%) and in the Eastern Guinean forest zone (81.56%). Soil C stock (SOC) was found to represent 40% of the total C stock when considering the 0-30cm soil layer. Most of the SOC was found in the Eastern Guinean forest zone (39%) and in Luvisols (44%). Forest restoration was found to have the highest C sequestration potential (6.7 Tg C yr^{-1}) than the other forestry activities. However, the estimation of C stocks and sequestration potential is mainly limited by the availability of data, the resolution and the calibration of the land cover products with a hypothetic area for degraded forests between 2,938 and 45, 334 km^2. When considering the potential implementation of C forestry activities in sub-Saharan Africa, the main constraints resides in the lack of data to estimate C stocks and calibrate the remote sensing products, lack of capacity building to build national inventories, the complexity when developing projects which are adapted to the land tenure and management systems and the lack of funds

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to develop projects. While sub-Saharan Africa represents a significant potential to mitigate climate change, development of capacities to support and implement forestry projects is necessary.

Keywords: deforestation, forest degradation, restoration, MODIS, carbon cycle

1. INTRODUCTION

Climate change is now considered as the main environmental crisis and even the best case scenario is going to have major impacts on global weather patterns. Forests are a vital part of any global effort to address climate change. Forestry activities are seen as a potential alternative either to mitigate climate change because of its potential effects on emission reduction and carbon (C) sequestration or to play a role in adaptation scenarios (Guariguata *et al.* 2008). In the attempt to develop C sequestration forestry projects in developing countries, the Clean Development Mechanism for Afforestation and Reforestation (CDM A/R) activities was developed under the Kyoto protocol. While only one CDM A/R is currently operational at global scale, Reducing Emissions from Deforestation and forest Degradation (REDD) is now becoming one of the main alternative to mitigate climate change - as deforestation is estimated to contribute for 17% of global greenhouse gas emissions (IPCC, 2007).

However, whereas forestry projects are seen as an important option to mitigate climate change, no CDM A/R project was developed on the African continent. There is great need to analyse the potentialities to develop forestry projects on the African continent. Population density especially in sub-Saharan Africa is increasing and ecosystem degradation has never been so important (UNEP, 2006).

Ghana is particularly interesting when analysing the potential for C forestry projects for various reasons. Ghana is representative of the different ecological zones found in West Africa (from dry savannah to wet evergreen forests). The population is highly dependent on forestry products which represent an important part of the economy (Falconer, 1994). Several ethnical groups compose the population of the country and they have different land tenure systems, natural resource management, practices etc. Several attempts tended to improve the governance of the country. Ghana is a pilot country for the Forest Law Enforcement Governance and Trade (FLEGT), the Forestry Carbon Partnership Facility (FCPF), and Ghana received a Millennium Challenge Corporation (MCC) grant in 2006.

The objectives of this study are to estimate the potential emission reduction and C sequestration through REDD and CDM implementation and identify the main constraints for project development. Analysing the REDD and CDM A/R potentials in Ghana helps understanding the potential of C forestry projects in Africa.

2. CALCULATION OF C STOCKS AND C SEQUESTRATION

2.1 Study area

Ghana is almost centrally placed among the West African countries that lie along the shores of the Gulf of Guinea. It lies between latitudes 5° N and 11° N and between longitudes 1° E and 3° N. Ghana covers an area of about 23 million ha. About 80% of the forest cover disappeared in the last century at a deforestation rate of 65,000 hectares per annum (Opoku *et al.*, 2005). The net loss in cubic meter was ranged between -8,372 and -14,578 per year between 1970 and 1987 (Baytas *et al.*, 1993). The annual rate of deforestation was said to have slowed in the 1980s to about 22,000 ha (FAO, 1988, and IUCN, 1992) but the proportion of illegal logging is poorly known and the deforestation rate is supposed to be higher (Sarfo-Mensah, 2005). In 1992, it was estimated that only about 1.5 million ha of "intact closed forest" were remaining in Ghana. The country was a total net CO_2e remover over the inventory period of 1990-1996 even as its sinks rapidly decreased in size (EPA, 2000). This rapid decline in sinks has been attributed to deforestation, specifically a sharp increase in fuelwood consumption, timber harvesting, agricultural and settlement expansion, mining and low rates of reforestation (Osafo, 2005).

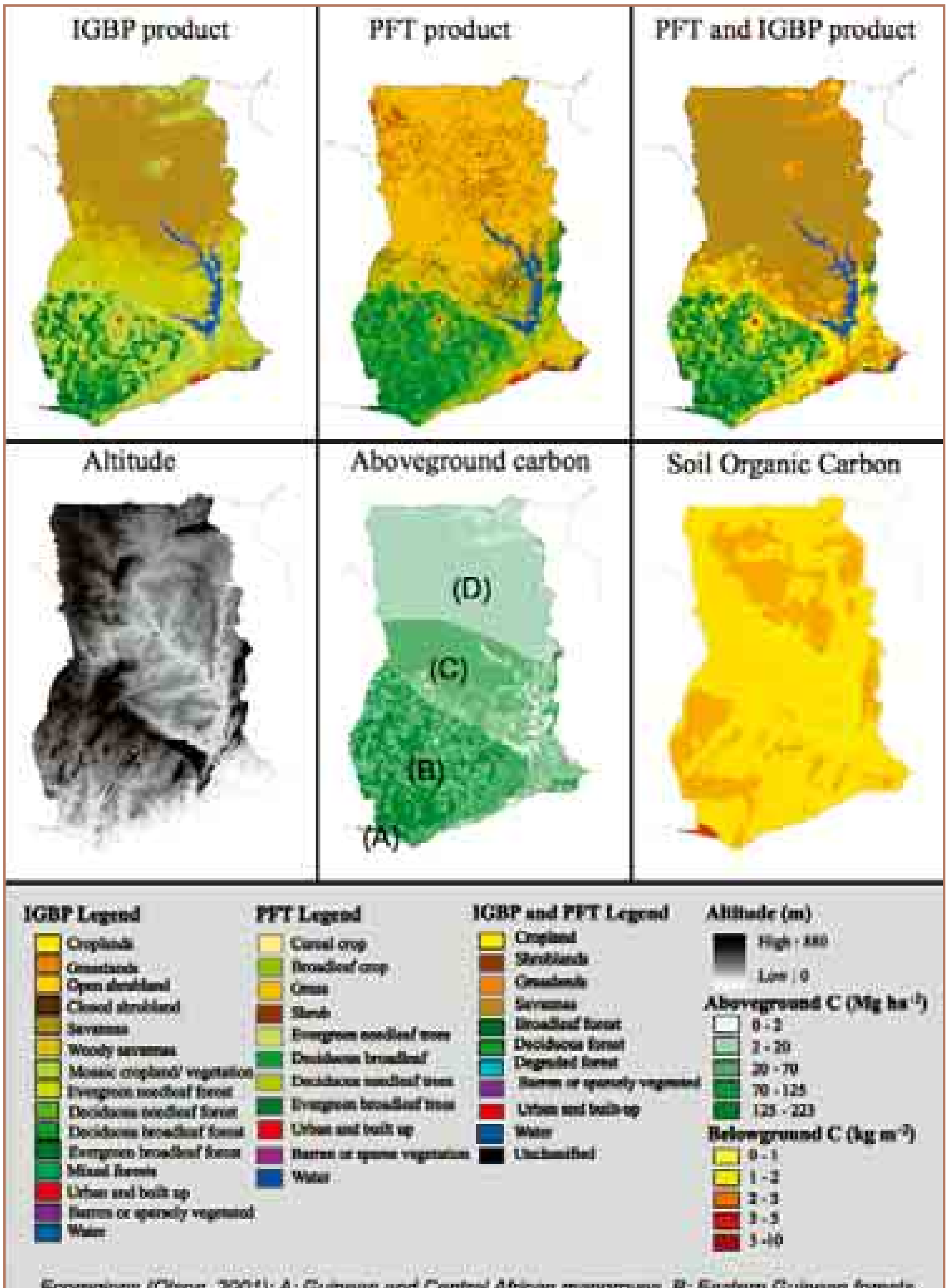
2.2 Map of carbon stocks

The map of carbon stocks was developed for the aboveground compartment by combining ecological zones and land cover classifications and ground field measurements found in the literature (Fig. 1). Several ecological classifications were developed based on structural, floristic, functional characteristics (Hall *et al.*, 1981). However, most of them focused on forests and not all the ecosystems were represented, or considered an important variety of ecosystems types.

In order to estimate the changes of C in the various ecosystem types Ghana was divided into five well-defined zones according to the WWF's Global 2000 terrestrial ecoregions from Olson *et al.* (2001): (1) Central African mangroves, (2) Eastern Guinean forests, (3) Guinean forest-savannah mosaic, (4) Guinean mangroves and (5) West Sudanian savannah. Within each region, 10 land cover types were considered. The land cover classification was obtained using the Moderate Resolution Imaging Spectroradiometer (MODIS) land cover (IGBP) and the MODIS plant functional type (PFT) classification categories (Friedl *et al.*, 2002). Despite the technical refinement to improve the accuracy of vegetation representation, there is still some misclassification. The vegetation class *cropland/natural vegetation mosaic* of the IGBP product was considered not to be enough reliable to estimate C stocks. In this study, the pixels that fell within this class were reclassified using the PFT product. A new land cover classification was obtained mixing the IGBP and the PFT products and averaging the images for the year 2002, 2003 and 2004.

Two methods were used to estimate the land area under degraded forest (A_{deg}). The A_{deg} was estimated using two methods. The first method considered that the mosaic of vegetation/cropland corresponded to degraded forest. It is mentioned as RES1. The second method considered that degraded forest corresponded to the pixels that moved from natural vegetation to cropland. It is mentioned as RES2. Data on C density (Mg C ha^{-1}) were obtained from a metadatabase of C densities for sub-Saharan Africa (n=62). All the data were georeferenced and classified per land cover types. C density data were averaged for each land cover and ecological zones found in Ghana. The soil organic carbon (SOC) densities were obtained from Henry *et al.* (2009).

FIGURE 1
The different steps used to map above and belowground carbon stocks



Ecoregions (Olson, 2001): A: Guinean and Central African mangroves, B: Eastern Guinean forests, C: Guinean forest-savanna mosaic, D: West Sudanian savanna

The MODIS products *Land Cover* (IGBP) and *Plant Functional Type* (PFT) were provided by the geographic department of Boston University. The two products were integrated to make a more convenient and robust land cover map for estimating aboveground carbon stocks. The estimation of belowground carbon stocks was achieved using the digital soil map of the world (Henry *et al.* 2009). Above and belowground carbon stock estimations considered the altitude (Shuttle Radar Topography Mission version 4).

2.3 Land cover of Ghana

Most of Ghana corresponded to West Sudanian savannah (38%) while 33, 28 and 1% of land cover corresponds to Eastern Guinean forest, Guinean forest-savannah mosaic, and Central African and Guinean mangrove. Most of total land cover corresponded to savannahs (51%) while 15, 13, 12 and 9 % corresponded to broadleaf forest, cropland, grassland and others land cover respectively. Savannah represented most of the vegetation into the West Sudanian savannah (88%), while broadleaf forest and cropland represented 43 and 28% of Eastern Guinean forest zone and grassland represented 34% of Central African mangrove zone. The total forest area of Ghana (degraded forest not included) was estimated 42,557 km^2 and represented 18% of the total country area. The potential area suitable for afforestation/reforestation activities represented 6,387 km^2 and 2.67% of the country area, and 4.4% of the grassland and savannah together. The forests under production were 7624 km^2 and represented 3% of the country area and 18% of the total forest area. When considering the estimation of degraded forest (RES1), degraded forest represented 45,334 km^2. When considering the estimation of degraded forest (RES2), degraded forest represented 2938 km^2. Furthermore, estimates of degraded forest area ranged 3.71-57.27% of the Eastern Guinean forests zone area.

2.4 Carbon stocks of Ghana

In total, 1 158 Tg was stored into the aboveground C stocks of Ghana. Most of aboveground C stock was located into the Eastern Guinean forests (945 Tg) while 147, 63 and 3 Tg C were stored into the Guinean forest-savannah mosaic, West Sudanian savannah, and the Central African and Guinean mangroves. Most of aboveground C stock was located into the broadleaf forest vegetation type (714 Tg), while 117, 37, 9, 14, 183, 75, and 10 Tg C were stored into the deciduous forest, degraded land, shrubland, grassland, savannahs, cropland and wetland.

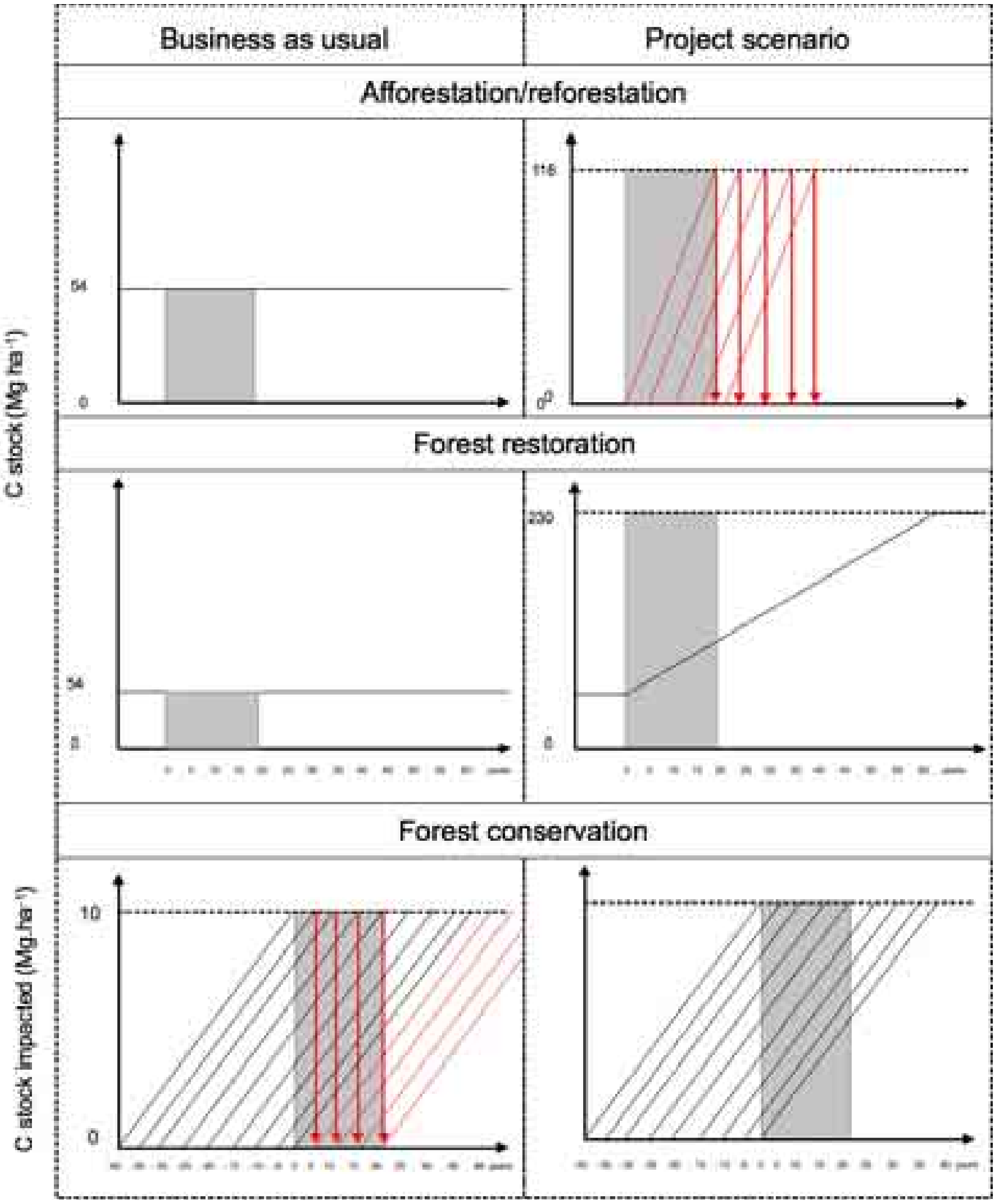
Semi-deciduous forests in Eastern Guinean forest zone represented the highest C density with 223 Mg ha^{-1}, while urban, water and barren or sparsely vegetated land had no C. C density varied between ecoregions and vegetation forms i.e. broadleaf forest had 223 Mg C ha-1 in the Eastern Guinean Forests zone and 105 Mg C ha^{-1} in Guinean forest savannah, degraded broadleaf forest had 125 Mg C ha^{-1} in the Eastern Guinean Forest zone. Soil organic carbon (SOC) represented 759 Tg into the 0-30cm soil layer and 1,384 Tg into the 0-100cm). SOC differed between soil types. i.e. SOC ranged 1.8-8.1 kg m^{-2} in Ferric Luvisols and in Arenosols respectively.

3. BASELINE C STOCKS AND POTENTIAL FOR C SEQUESTRATION COUNTRY WIDE

The aboveground C sequestration and emission reduction potentials were estimated by assessing the difference of C stock between a reference level (assumed to be the current situations) and project scenarios. It was not possible to analyse the belowground C sequestration potential because it was not possible to find in the literature soil organic carbon changes in the various land cover change and soil types found in Ghana. Here, we analysed three potential scenarios for the first 20 years project period of project implementation (Fig. 2). The total amount of C sequestrated was assumed to be the sum of the annual C sequestration.

FIGURE 2

C sequestration and emission reduction project scenarios



The grey rectangles represent the project time period. The dark black lines represent the amount of C under buisness as usual (on the left) and the red lines represent the amount of C under project scenario (on the right). The red arrows represent the logging activities. While the total C stock is represented for afforestation and reforestation, and forest restoration scenario (up to 116 and 223 Mg ha^{-1}), the impacted amount of C by logging is represented under the forest conservation scenario. While the forest restoration is supposed to start into the whole country at the same time (only one line is represented), planting activities and logging activities are distributed egally during the project period (represented every 5 years in the diagram).

3.1 Assessing carbon sequestration and emission reduction potentials

Aboveground C sequestration through afforestation and reforestation

The aboveground C sequestration potential through CDM A/R projects was estimated assuming that the suitable land for plantation identified by Zomer et al. (2008) was converted by teak plantation because they represent 80% of the plantation area of Ghana (Adu-Bredu, personal communication). C density of Teak plantation was assumed to be 116 Mg ha^{-1} (Boateng, 2005) at the end of a 20 years rotation while the initial land use was assumed to be a short fallow with C density of 54.25 Mg ha^{-1} (Kanmegne, 2004). The area converted to forest plantation was equally distributed over the 20 years project period (Tpp).

1) $$C_{seq} = \sum_{i=0}^{20} \left(\frac{A_{A/R_i} \times (C_{A/R} - C_B)}{T_{pp}} \right)$$

Where C seq is the potential C sequestrated (Mg ha^{-1}yr^{-1}), A/R_i is the area converted to forest plantation every year I (ha), $C_{A/R}$ is the C density at the end of the rotation (Mg ha^{-1}), C_B is the initial C density (Mg ha^{-1}) and Tpp is the year period to reach $C_{A/R}$.

C sequestration through forest restoration

The C sequestration through forest restoration was obtained assuming that all degraded forest is recovered after a 60 years period (Tr). Assessment was performed only for the Guinean forest zone because it was considered that identification of degraded forest was reliable only for this zone.

2) $$C_{res} = \frac{A_{Deg} \times (C_{NF} - C_{Deg})}{Tr}$$

Where C_{res} is the amount of C sequestrated through forest restoration (Mg ha^{-1}yr^{-1}), A_{deg} is the total area of degraded forest, C_{NF} is the C density in natural forest, C_{deg} is the C density in degraded forest and Tr is the years period after which the amount of C is recovered (60 years). It is assumed that a 60 year period for forest recovery is conservative as according to Kotto-Same, et al. (1997), the same amount of natural forest C density would be reached after a 28 years period. C_{NF} and C_{Deg} were assumed to be 223 Mg ha^{-1} and 125 Mg ha^{-1} respectively (data obtained from the metadatabase).

C sequestration through forest conservation

The C emission reduction from forest conservation is estimated assuming that all the forests under production would become protected. This means that there would be no more logging activities and that previous logged forest will continue to regenerate.

3) $$A_{pi} = \frac{A_p}{Tc}$$

Where A_{pi} *is the forest area under production activities during the year i (ha* yr^{-1}*),* A_p *is the total area under forest production in Ghana (ha) and Tc is the production cycle period (40 years).*

4) $$C_R = \frac{C_E}{40}$$

Where C_{Ri} *is the annual regeneration of C (Mg* ha^{-1} yr^{-1}*),* C_E *is the impacted amount of C by logging (10.2 Mg* ha^{-1}*) and Tc is the production cycle period (Gineste, et al., 2008).*

The amount of C impacted by logging activities corresponds to the quantity of C which is damaged by the logging operations. From this amount, a part is extracted (logs) and a part is left into the forest and is then decomposed.

5) $$C_{ER} = \sum_{i=0}^{20} A_{Pi} \times (C_E - C_R)$$

Where CER is the C emission reduction during the project period (Mg), Api is the annual area of forest under production (ha yr^{-1}*) and* C_E *is the C emission factor under selective logging (10.01 Mg* ha^{-1}*) (Gineste, et al., 2008).*

3.2. C sequestration and C emission reduction potentials

Implementation of CDM A/R project on all the suitable lands identified by Zomer *et al.*(2008) (total available area=6 387 km² or 2.67% of the country area) would potentially sequester 61.75 Mg C ha^{-1} and 3.1 Mg C ha^{-1} yr^{-1} in the aboveground compartment (when considering that this amount could be reached after a 20 years period). When considering an equally distribution of plantation during the 20 years project, it resulted that, in total, 20.7 Tg C would be stored through CDM A/R project at national scale.

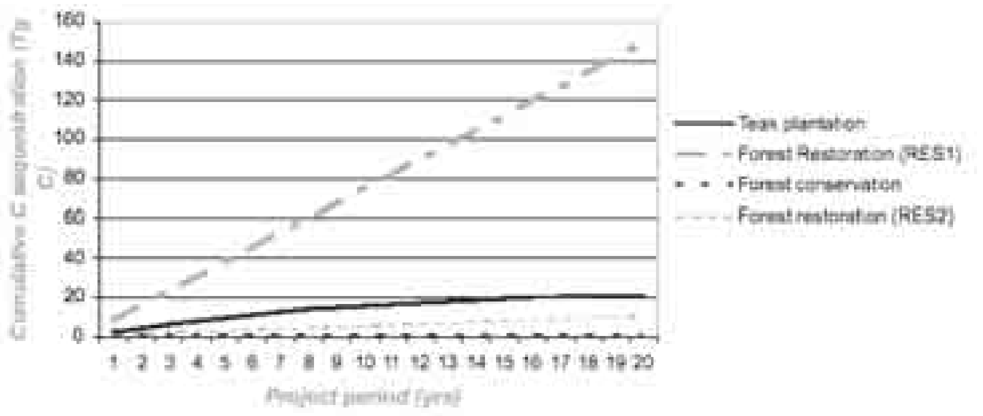
Under scenario RES1, leaving degraded forests to restore during a 20 years period would represent a potential C sequestration of 148 Tg C with an annual C uptake of 6.7 Tg C yr^{-1}. Under scenario RES2, forest restoration sequestrated 9.60 Tg of C after 20 years with an annual C uptake of 0.48 Tg C yr^{-1}.

Selective logging decreased forest C density of 10.01 Mg C ha^{-1}. After logging, regeneration of C density was estimated to be 0.25 Mg ha^{-1} yr^{-1}. As forest is regenerating on the whole production forest area while exploitation is achieved on only 50% of the forest area during a 20 years project, forest exploitation would emit a total of 0 Mg C ha^{-1} yr^{-1}. Under forest protection, 2.81 Tg C would be additionally sequestrated during a 20 years period forest protection scenario.

The different options revealed different aboveground C sequestration potentials (Fig. 3). While forest restoration (RES1) presented the highest C sequestration potential (148 Tg) it also presented the highest C uptake per ha (98 Mg C ha^{-1}) and the highest potential suitable land area (19% of the country area). On the other hand, forest conservation presented the lowest C sequestration potential (2.81 Tg) and presented the lowest average C sequestration potential (7 Mg C ha^{-1}) but also the lowest suitable land area (3% of the country). Afforestation/reforestation scenario presented the second C sequestration potential (21 Tg), and it presented the second C uptake (62 Mg ha^{-1}). When considering the scenario RES2, forest restoration had the second C sequestration potential (9.6 Tg), while the C uptake was the same than for RES1 but the suitable land area was much lower (1.23% of the country).

FIGURE 3

C sequestration and emission reduction potentials under three project scenarios



4. CONSTRAINTS TO THE IMPLEMENTATION OF C FORESTRY PROJECTS

4.1. Identification of land cover

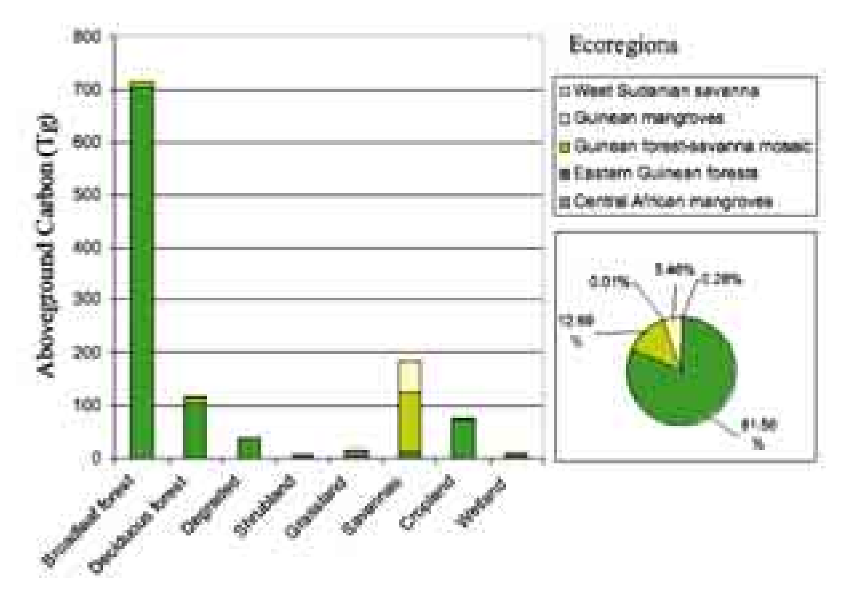
Using MODIS images is useful for a national land cover accounting when most of land cover analysis in Ghana focused only at regional and local scale i.e. (Braimoh, 2006, Tan *et al.*, 2008, Tutu, 2008). However, the land cover estimates obtained in this study differ from other national forest inventories. The FAO (2005) and Agyarko (2001) reported that in 2000 and 2005 the forest area was about 5.5 and 9.2 million ha while 4.3 million ha was estimated in this study. Estimation of forest area differs between different authors because of use of different forest definitions and technical means to evaluate the forest area. There is great need to develop national land cover accounting system that uses the definition of forest communicated by the DNA to the UNFCCC in the attempt to evaluate the national C stocks and land use change. However, while a definition of forest exists, forest degradation does not have definition under UNFCCC. Furthermore, there is no standardized method to identify and assess forest degradation. It results that the estimation of forest degradation differs between authors. Using two different methods of identification of degraded forest gives area ranging 4-57% of the Eastern Guinean Forest zone.

4.2. Estimation of C stocks

C stock estimates are of main importance when analysing the potential for terrestrial ecosystems to uptake CO_2. The data provided by this study are the first C estimate at national scale that considers various land cover types and ecological zones in an African country. Previous estimates considered only the forest ecosystems. Aboveground C stocks of forest ecosystems of Ghana were estimated 363 Tg and 831 Tg of C according to the FAO (2005) and this study respectively. The difference is mainly explained by differences in C estimates and the methods of identification of land cover types. While C stock estimates of this study are based on averaging C stocks reported by the literature, the C stock estimates from FAO are obtained from the average stem volume, average wood density of Africa, general biomass expansion factor specific for timber production, permanent protection and open forest area and a general C conversion factor. C stock estimates of forest based on FAO data were 108, 100 and 49 Mg C ha^{-1} for timber production, permanent protection and open forest while 210, 105, 46 and 47 Mg C ha^{-1} were contained in Eastern Guinean forest, Guinean forest savannah, west Sudanian savannah and mangrove, respectively. FAO C estimate for broadleaf forest in the Eastern Guinean forest zone is about two times lower than the C stocks obtained in this study. This study overestimates the C stocks compared to the FAO reports. On the other hand, forests areas in the FAO document were reported by the Ghanaian Forest Commission and were respectively 12,552, 3,525 and 39,092 km^2 for timber production, permanent protection and open forests, respectively (Fig. 4). In this study, those three different forest types were not considered, but ecological zones were taken into account. There is great need to improve C stock estimates that are specific for the ecological zones, the vegetation types and the management types.

FIGURE 4

Distribution of aboveground carbon in the ecoregions of Ghana



4.3. C sequestration

This study is a first try to estimate the national potential C sequestration and emission reduction for an African country. While the countries are currently negotiating the modalities for the implementation of REDD, there is a great need to provide scientific data that would help them to negotiate and better consider the potential of their ecosystem to mitigate climate change. However, different ways to estimate C stocks and potential C sequestration area could result in different estimates of C sequestration.

In this study, the C potential estimates are rough and needs to be improved. The estimates focus only on the aboveground C while 54% of the total C stock is contained into the soil compartment and no data were available for litter, dead wood and the roots. On the other hand, this study considers only teak plantation while other plantation and agroforestry systems are developed in Ghana and would sequester different amounts of C: for example, rubber plantation would sequester 80 Mg C ha^{-1} (Wauters *et al.*, 2008) instead of 116 Mg/ha for teak at the end of the rotation.

The potential area suitable for afforestation and reforestation activities was based on the study of Zomer (2008) and corresponded only to 4.3% of the total area of grassland and savannah together. The potential area calculated by Zomer was estimated using socio-ecological characteristics including current land use, population levels and ecosystem characteristics. We suppose that the aridity criteria have decreased the potential area for afforestation as plantations were considered only on optimal bioclimatic conditions defined as having a minimum threshold as aridity index > 0.65. However, the biophysical potential for afforestation/reforestation in Ghana might be higher than the one estimated in this study.

When estimating the potential area for restoration activities it ranged 3.7-57.1% of the Eastern Guinean forest area and the C sequestration potential ranged 9.6-148.1 Tg C for a 20 years project period. The amount of C sequestration through forest restoration is particularly difficult to estimate as the forms of degradation differ according to the geographical location and the anthropic activities. In addition it is difficult to differentiate the various forms of degradation using remote sensing (Lambin, 1999). The use of satellite imageries is limited by the presence of clouds, the spatial, temporal and spectral resolutions, particularly when considering national scale.

The potential area suitable for conservation activities concerned only the forests under production. However, this does not include the forests outside the productive area which are illegally logged. Current estimates indicate that illegal chainsaw activities alone account for about 1.7 million cubic meters of timber harvested in the country while legal activities harvest 1.1 million cubic meters (Birikorang *et al.*, 2001). It means that the potential emission reduction by stopping illegal logging would be of about 4.34 Tg C for a 20 years period. However, illegal logging have less impact on the C stocks as in many case illegal logging is referred to chainsaw operations without building road or skid trail. At current status, no study exists on the impact of illegal logging on C stocks.

The estimates of impact of selective logging given in this study consider only the ground impact and do not consider the fuel consumption of the logging operator and the permanence of C into the extracted roundwood. While a part of the roundwood is used to produce firewood or electricity, an other part is used to build houses or furnitures. Improving the estimates would consist in estimating the part of the C in the wood which is released to the atmosphere directly and the part which is stored for a mid or a long term period.

5. LIMITATIONS OF THE ACCOUNTING METHODS

The biophysical potential for C sequestration in Ghana is important. In addition, the economy of Ghana is stable in comparison with other African countries. However, implementation of C forestry activities faces several constraints.

Development of forestry activities in Ghana is limited by problems of: (1) land tenure, (2) financial capacity, (3) climate and plant disease, (4) social management, and (5) capacity building. Those constraints limit the adaptation, the adoption and the feasibility of the projects.

Land tenure could be considered as one main constraint as most of the land in Ghana belongs to the stools and is leased to the farmers or private enterprise by the government. When considering the process of decision making of foresters, farmers and private enterprise would invest into agroforestry or forest plantation systems only when they will secure the land property. Food security is an important problem in Ghana and it would be difficult to develop forestry activities on the land used for food production purpose. Planting forest has financial and labor costs and the capital availability is limited. Moreover, the investor (farmer or private enterprise) would have to recover the money invested. In addition, forestry activities are limited by plant disease i.e. increasing the tree cover into cocoa farms may increase the humidity and the spread of pod rot disease (*Phytophthora megakarya*). In this case the only alternative for the farmer is to increase the use of fungicide and the financial investment into chemical products. Since the diversion of forestry law application in the 60s, farmers fear logging operators. During the 60-70s, forestry operators destroyed a large part of forest outside the reserve while the farmers used to keep trees within their farm as an agroforestry system. When most of the forests outside reserves were exploited, many logging operators decided to exploit the trees within the farms and in most of the case never compensated the farmers for the damaged occurred in their farms. The damages were particularly important, particularly in cocoa farms (Tropenbos International, 2004). The farmers have to be convinced by the positive externalities of planting trees so they will maintain the trees within their farms.

The constraints faced by developers of forest activities in Ghana are in most of the case present in the countries of sub-Saharan Africa. However, in most of the countries the problem of access to the funds, food security, and land tenure conflicts, are even more important. Developing C forestry activities faces the general constraints of forestry project development and the specific constraints for CDM and REDD projects.

6. CONCLUSION

The study shows that most of the aboveground C sequestration potential of Ghana would be through restoration of degraded forest outside the national forest reserves. CDM A/R would represent half of this potential while the potential for forest conservation would be smaller. However, the estimation of forest area is uncertain and varies according to the methods and definitions. The definition of forest degradation will determine the potential for C sequestration through forest restoration in Ghana. When developing the modalities for international mechanism such as the REDD, there is a great need to analyse it feasibility and to make it enough flexible to adapt to the regional, national and local constraints.

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Carbon storage and the health of cocoa agroforestry ecosystems in south-eastern Ghana

Asase A. [1], Wade S. A. [2], Ofori-Frimpong K. [3], Hadley P. [4], Norris K. [2]

ABSTRACT

Tropical forests hold large stores of carbon and play a major role in global carbon cycle. But conversion of tropical forests to agricultural land has been a major cause of global carbon emissions and biodiversity loss. Agroforestry ecosystems store significant amounts of carbon. However, there is little economic incentive for smallholder farmers to protect agroforestry ecosystems and their associated services, resulting in the intensification of production methods for commodity crops such as cocoa. Diversifying rural livelihoods through carbon trading might change the economic incentive to cocoa farm intensively, thereby protecting ecosystem health and improving agricultural sustainability. In this study, C stocks in three land-use systems namely, remnant forest, traditional shaded cocoa farm with indigenous trees and un-shaded intensive cocoa farms were estimated, and related to cocoa productivity and measures of ecosystem health. The standing cocoa crop, above and below ground C stocks, soil nutrients and nutrient cycling and forest biodiversity were assessed, over a three year period from 2005 to 2007. Forests stored the greatest amount of C with a mean of 224.1Mg C ha^{-1} (95% confidence limits, 185-272), followed by traditional cocoa agroforest with a mean of 155.1 Mg C ha^{-1} (95% confidence limits, 113-207) and more intensive cocoa with a mean 71.9 Mg C ha^{-1} (95% confidence limits, 53-94) of carbon. Productivity of the cocoa crop was significantly greater in the un-shaded farms (73% higher than shaded cocoa farms), so there is a trade-off between cocoa productivity and C stocks. Soil fertility, litter fall and decomposition declined from remnant forest, shaded cocoa farm to un-shaded intensive cocoa farms, making intensive farming less sustainable. Species richness of mammals, birds, butterflies and plants showed a similar pattern to carbon stores. By considering C stocks and cocoa productivity in tandem, land management strategies can be adopted to maximise benefits from both the former and the latter. Ecosystem health and biodiversity value are related to carbon storage thus providing a potential economic mechanism for wider ecosystem protection if carbon stored could be traded. Comparable integrated studies within Ghana and across the entire West African region are needed to provide baseline data.

Keywords: Cocoa agroforest, Carbon storage, Biodiversity, Nutrient cycling, Ghana

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INTRODUCTION

Tropical forests hold large stocks of carbon and play a major role in global carbon cycle (Dixon *et al.*, 1994; Phillips *et al.*, 1998). However, conversion of tropical forests to agricultural lands has been a major cause of global carbon emissions (Paustian *et al.*, 2000) and biodiversity loss (Primack and Corlett, 2005). The concentration of CO_2 in the atmosphere has considerably increased, the rate being 3.5 Pg *per annum* (Paustian *et al.*, 2000; Albrecht and Kandji, 2003). Scientific evidence suggests that increased atmospheric CO_2 could have negative effects such as rising temperature, higher frequency of droughts and floods on the global climate. The effects of these changes on ecosystem functioning and human well-being have resulted in the development of mitigation initiatives (UNFCCC, 1992; MEA, 2005).

Cocoa production has played an important role in the transformation of lowland tropical forest landscapes in Latin America, Africa and Asia over the past centuries and continues to do so today (Schroth and Harvey, 2007). Cocoa is now grown in 50 tropical countries with smallholder farmers growing most of the world's 3 million tons of annual cocoa production (Lass, 2004). Despite being a plant of Amazonian origin, cocoa has become the major agriculture commodity crop in lowland forests in West Africa (Rice and Greenberg, 2000). The cocoa industry is a critically important component of the agricultural sector in Ghana. It occupies a key position in terms of foreign exchange revenues and domestic incomes (Asante, 2005). It is estimated that currently there are about 2,988,395 acres of land cultivated with cocoa in Ghana, with about 445,145 farmers in rural communities dependent on cocoa farming for their livelihoods (Asante, 2005).

However, there is little economic incentive for small-holder farmers to protect cocoa agroforestry ecosystems and their associated services, resulting in the intensification of production methods for cocoa in Ghana. Diversifying rural livelihoods through carbon trading might change the economic incentive to cocoa farm intensively, thereby protecting ecosystem health and improving agricultural sustainability as agroforestry ecosystems store significant amount of carbon (Albrecht and Kandji 2003; Montagnini and Nair 2004).

The aim of this study was to estimate the magnitude of carbon stored in different cocoa agroforestry ecosystems and relate these to cocoa productivity and measures of ecosystem health. Different land-use systems for cocoa production were studied and the cocoa crop, above and below ground carbon stocks, nutrient cycling, soil fertility and forest biodiversity assessed.

MATERIALS AND METHODS

Study area

The study was conducted in the Eastern Region of Ghana, where cocoa is the most economically important cash crop, from March 2005 to October 2007. Three broad land-use types, namely, remnant forest, traditional shaded cocoa farms with indigenous trees species and intensive un-shaded cocoa farms almost devoid of trees were selected for the study. The remnant forest was located at the Atewa Range Forest Reserve (6°14`N, 0°32`W). The shaded cocoa farmlands were located around Adjeikrom in the Fanteakwa District (6°18`N, 0°24`W), while the unshaded cocoa farmlands were located near Kwabeng in the Atewa District (6°20`N, 0°35`W).

Data collection was done along a series of permanent transects in the different land-use types. Transects spanned many farms in each cocoa land-use type, each farm being only a few hectares in size. Twelve transects distributed across the three land-use types were randomly located. The length of transects varied between 450 and 1000 m and were placed at least 200 m parallel to each other in each land-use type.

Estimation of carbon stocks

The total amount of carbon stored in each land-use types was estimated by sampling tree biomass and Soil Organic Carbon (SOC). At every 50 m on transects there was a 10 m x 10 m permanent plots within which the diameter at breast height (DBH) of every cocoa tree with a DBH $\geq$ 5 cm (1.3 m aboveground level) was recorded. There were 56 10 m x 10 m plots in the shaded cocoa and 23 plots in unshaded cocoa farms. Trees (including palms) were surveyed in 25 m x 25 m plots because forest trees function at a larger scale than smaller cocoa trees. The DBH of all non-cocoa trees $\geq$ 5cm at 1.3 m aboveground level were individually identified and DBH measured. Sixteen 25 m x 25 m plots were studied in the remanat forest, 22 in shaded cocoa and 6 in unshaded cocoa farms.

Diameter measures of trees were individually converted to measures of aboveground biomass (AGB), and then summed by plot. We estimated the AGB of trees $\geq$ 5 cm DBH using the allometric model of Chave *et al.* (2005). The Chave *et al.* (2005) model was calculated using the formula $\rho i^{-\ \exp}(-1.499 + 2.148 \ln(DBH) + 0.207(\ln(DBH))^2 - 0.0281(\ln(DBH))^3)$, where ρi = species specific wood density value (g cm^{-3}) of tree i, and DBH = diameter at breast height (cm). The model is based on trees harvested from moist tropical forest sites around the world and requires data on DBH and wood density for each tree. A literature search was conducted to ascertain species-specific wood densities primarily from the World Agroforestry Wood density database (www.worldagroforestry.org / Sea / Products / AFDbases / wd /) . For those species that were not found (69%) the mean wood density of all species of the same genus found in the literature search was used, as genus is a good predictor of species wood density (Chave *et al.*, 2006). This accounted for a further 38% of species. For those species where no species of the same genus was found the mean wood density of all species sampled during this study and subsequently found in the literature search was used (0.53g cm^{-3}). A value of 0.42 g cm^{-3} for cocoa wood density was used (Chave *et al.*, 2006). Root biomass was estimated indirectly from aboveground biomass following the method of Cairns *et al.* (1997). This method estimates root biomass to be in the region of a quarter of aboveground biomass. As convention, carbon stocks were calculated by multiplying total biomass, including both above and below ground, by 0.5 (Albrecht and Kandji 2003; Glenday, 2006).

The percentage of soil carbon content was determined using the wet combustion method of Walkley and Black (1934). Ten ml of 1N potassium dichromate ($K_2CR_2O_7$) solution and 20 ml concentrated sulphuric acid (H_2SO_4) were added to 0.5 g soil which had been passed through 0.5 mm sieve. The flask was swirled to ensure full contact of the soil with the solution after which it was allowed to stand for 30 minutes. The unreduced $K_2CR_2O_7$ remaining in solution after the oxidation of the oxidizable organic material in the soil sample was titrated with 0.2 N ammonium ferrous sulphate solution after adding 10 ml of orthophosphoric acid and barium diphenylamine sulphate indicator. The percent organic carbon was calculated as % C = [10.0 - (XN)* 0.3] / W., where X = ml of ferrous ammonium sulphate solution required for the titration, N = normality of ferrous ammonium sulphate solution and W = weight of soil sample. Bulk density was also determined for every soil collected. Finally, SOC per hectare was determined according to the following formula: [%C] x [bulk density] x [soil depth], with bulk density measured in gcm^{-3} and soil depth in cm.

Cocoa productivity, nutrient cycling and soil fertility

Using the same plots as for the biomass estimates all healthy cocoa pods over 10 cm in length were counted. Smaller pods were excluded from the count because fruit abortion is common in cocoa during early development (Bos *et al.*, 2007) and to avoid counting the same pods twice as far as possible. The number of cocoa pods greater than 10 cm in length was counted at random periods for the various plots between one and twelve times due to logistics constraints.

The efficiency of nutrient cycling was studied by measuring the quantity of litter produced and the rate of litter decomposition in the cocoa farms. Three litter traps of size 1.0 m^2 were set up, by raising the traps to 50 cm aboveground, along each transect. The traps were emptied of intercepted litter at 2-week intervals over a period of one year. Litter decomposition was monitored to determine the rate of transfer of nutrients from the litter to the soil. This was done by loosely packing an equivalent of 20 g oven dry weight of leaf litter into a 20 cm^2, with 5.0 mm mesh, litter bags. Samples were collected at 2-month intervals over a period of one year for the chemical analyses of N, P and K using standard laboratory methods (Bremner, 1965; Bray and Kurtz, 1945; Ofori-Frimpong, 2007).

Cocoa is a surface feeder whose active roots do not penetrate beyond the 30 cm depth in the soil. Soil samples were therefore collected up to the depth of 30 cm at three spots along each transect in each of the three land-use types. The soil samples were air dried, sieved and analysed for pH, % carbon, N, P and K using the same methods as above.

Biodiversity surveys

Plants were surveyed using the same 25 m x 25 m plots used for the biomass estimates. Within each plot, all non-cocoa trees with DBH ≥ 5cm at 1.3 m aboveground level were individually identified and their DBH measured, and recorded in standard field data sheets. Only individuals of plants rooted within the quadrats were considered. Plant species identification was done using relevant literature (Hawthorne, 1990). Plants were surveyed only once throughout the entire period of study.

The point count methodology (Sutherland, 1996; Sutherland *et al.*, 2004) was used to survey birds at regular intervals of 200 m along each transect. To coincide with maximum activity of forest birds, all counts were undertaken between 5:30 and 09:00 GMT. Upon reaching a point, the observers waited quietly for at least one minute to allow any birds disturbed by their arrival to resume their normal activity. A count was then undertaken for 10 minutes, and then moved over to another spot to repeat the process. Each individual bird either seen or heard was identified and the distance from the point where the bird was first seen or heard recorded. Efforts to avoid 'double counting' individuals or groups already recorded were made wherever possible. Bird species were identified with the aid of field identification guide (Borrow and Demey, 2004).

Under storey fruit-feeding butterflies were sampled using rotten banana baited aerial traps (Daily and Ehrlich 1995). Traps were set at 100m intervals along each transect. Captured butterflies in the traps were removed after 24 hours and placed into labelled glassine envelopes. The traps were re-baited for 24 hours and captured butterflies removed after which the traps were collapsed. Butterflies captured were kept in a deep freezer till they were later identified mostly using the Butterflies of West Africa (Larsen 2005), an identification guide.

Forest mammals were sampled using line transects (Buckland *et al.*, 2001). For each individual mammal seen or heard the perpendicular distance to transect, the distance on the point where the mammal was detected and the species of mammal were recorded. The identification of species of mammals was confirmed using the Kingdon Field Guide to African Mammals (Kingdon, 2001).

Data analyses

To compare the differences in carbon storage between the land-use types a series of pair-wise comparisons using permutation testing were made. Carbon storage values for each carbon pool (i.e. forest trees, cocoa, other crop trees and soil) were randomly re-sampled without replacement 10,000 times and a mean was taken for each land-use type for each carbon pool. The means for each carbon pool were summed to provide 10,000 re-sampled total carbon storage values for each land-use type. In each pair-wise comparison the number of re-sampled means that were less than the observed, field sampled difference in carbon storage between land uses was calculated and divided by 10,000 to give a P-value.

The difference in standing trees and pods between shaded and unshaded cocoa was compared using a generalised linear mixed model. The number of pods and month were fixed factors, plot identification was a random factor and a quasipoisson distribution was applied. The fitted values from the model were extracted and back transformed to produce model-fitted values of standing crop for each plot. Using the model-fitted values, a proportional difference in yield of cocoa pods between the land-use types was estimated. The differences in amount of litter produced and soil chemical properties among the three different land-use types were analysed using One-Way Analysis of Variance (ANOVA) after testing for normality. The statistical software R version 2.6.0 (Crawley, 2007) was used for the analysis.

The rarefaction method (Gotelli and Colwell, 2001) was used to estimate the expected number of species for the construction of species accumulation curves with 95% confidence intervals. We used the statistical software EstimatesS version 8.0 (Colwell, 2006) for the species accumulation curves.

RESULTS AND DISCUSSION

Carbon stocks

The mean total C stock in the various land-use types decreased from 224.1, 155.1 to 71.9 Mg C ha^{-1} for remnant forest, shaded cocoa stand and intensive un-shaded cocoa stands, respectively (Tab. 1). Pair wise comparisons between the three land use types revealed significant differences in mean carbon storage for all comparisons (permutation tests, forest and shaded cocoa: $p < 0.01$, forest and unshaded cocoa: $p < 0.0001$, shaded cocoa and unshaded cocoa: $p < 0.01$).

TABLE 2

Summary by land use type of the carbon stored in each carbon pool sampled and the total carbon storage for each land use

	Carbon Mg ha $^{-1}$ Bootstrapped 95% confidence limits are shown in square brackets.		
	Forest	**Shaded Cocoa**	**Unshaded Cocoa**
Forest trees[a]	155.5 [116.7, 202.2]	87.1 [46.4, 137.8]	14.8 [0, 32.7]
Soil[b]	68.6 [62.7, 76.1]	51.4 [44.4, 58.1]	33.3 [31.2, 35.3]
Cocoa trees	0	12.1 [9.5, 16.1]	17.4 [11.1, 25.5]
Other tree crops[c]	0	4.5 [0.3, 11.3]	6.5 [0.8, 16.2]
Total	224.1 [184.7, 271.8]	155.1 [113.23, 206.6]	71.9 [53.1, 94]

a Trees species that have a diameter at breast height (DBH) >5cm and have not been planted or retained specifically to provide food.

b Soil organic carbon to a depth of 30cm.

c Tree species besides cocoa with a DBH >5cm which have been planted or retained specifically to provide food.

Forest trees made up the largest proportion of stored carbon in both the remnant forest and shaded cocoa farms. Forest trees made up 69.4% of the carbon stored in the forest. There were very few forest trees in unshaded cocoa, only four trees were observed in seven plots (9.1 trees ha^{-1}) compared to 56 trees in 11 shaded cocoa plots (81.5 trees ha^{-1}) and 1009 trees in 16 forest plots (1009 trees ha^{-1}). Second to forest trees in remnant forest and shaded cocoa was soil. Forest soil contained a mean of 68.6 Mg ha^{-1}, just under a third of the total carbon stored in forest. Soil in shaded cocoa farms contained 75% of that stored in forest soils with a mean of 51.4 Mg ha^{-1}. Unshaded cocoa farm soils contained less carbon under half of that found in forest soils with a mean of 33.3 Mg ha^{-1}. This, however, was nearly half of the total carbon stored in the unshaded cocoa farms.

Although cocoa is a tree crop and is thus associated with relatively high carbon value compared to annual crops, cocoa's contribution to net carbon storage in shaded cocoa farms was minimal, with a mean of just 12.1 Mg ha^{-1}. When other crop species are included, this increases to 16.6 Mg ha^{-1} or 10% of the total carbon stored in shaded cocoa. Unshaded cocoa had a higher biomass of crop trees as would be expected of more intensive systems with the associated higher density of crops. Cocoa and other tree crops combined stored a mean of 23.9 Mg ha^{-1} of carbon in unshaded cocoa farms, around a third of the total carbon stored in this land use type.

The magnitude of C released due to the establishment of the farms depends on the method of tree removal and fate of any wood products (Kotto-Same *et al.*, 1997). Forests have variable but consistently high values. For example, Amazonian forest has been found to store 372 Mg ha^{-1} of carbon (Hughes *et al.*, 2002) and Kenyan forest to store 330 Mg ha^{-1} of carbon (Glenday, 2006). Lower forest carbon storage in this study may be caused by degradation through logging which is widespread in Ghana's forests including protected reserves (Adam et *al.*, 2006).

Under the current discussions for the replacement of the Kyoto Protocol in the next commitment period of the UNFCCC, it is likely that selling carbon stored in trees will be possible, mainly in the context of forests (Hall, 2008). The present study show that cocoa agroforests can have high carbon storage value and, in conjunction with degraded forest, should be included in the discussion. Selling carbon stored in trees on farms would be an effective way of conserving traditional practices that benefit not only carbon storage, but other ecosystem services such as higher biodiversity (Harvey and Villalobos, 2007), better quality soil (Neupane and Thapa, 2001) and greater sustainability (Beer *et al.*, 1990).

Cocoa productivity, nutrient cycling and soil fertility

Unshaded cocoa had a higher density of cocoa trees than shaded cocoa with 10.2 ± 1.02 (±S.E) and 7.6 ± 0.7 (±S.E) cocoa trees per plot. Productivity was 73% higher in the unshaded cocoa farms. The mean standing crop in shaded cocoa was 27.4 ± 3.1(±S.E) pods per plot and in the unshaded cocoa 47.3 ± 5.3 (±S.E). The higher cocoa yields in the unshaded cocoa could be explained by higher density of cocoa trees and reduction in the density of canopy trees (Cunningham and Arnold, 1962). Reduction of shade in cocoa farms is also known to be associated with significant ecological stress on cocoa trees (Entwistle and Yeodeowei, 1964). There is however, a disadvantage of heavy shading in cocoa agroforest which is low yields that might also increase pod rot by *Phytothora megakarya*, the most serious cocoa disease in West Africa (Bos *et al.*, 2007). It is also important to note that higher productivity could be attributed to higher management intensity indicating that management methods could influence yields (Bisseleua *et al.*, 2008).

The quantity of cocoa leaf litter produced was significantly higher ($p < 0.05$) in unshaded cocoa farms with a mean of 600 kg ha-1 than that of shaded cocoa farms with a mean of 400 kg ha^{-1}. The amount of shade tree litter produced was however significantly higher ($p < 0.05$) for the shaded cocoa farm with a mean of 200 kg ha^{-1}. Unshaded cocoa farms recorded a mean of 50 kg ha^{-1} shade tree litter. After 12 months of litter decomposition experiment, the amount of nutrients released from the litter were 75% and 90% for Nitrogen, 66% and 90%, for Phosphorous and 88% and 93% for Potassium for the unshaded and shaded cocoa farms, respectively. Differences in microclimate as a result of higher density of canopy trees and the probably higher population of decomposer organisms in the shaded farms could be responsible for the differences in the amount of litter produced and the faster decomposition rates observed (Ofori-Frimpong *et al.*, 2007).

The soils in the cocoa farms were more acidic than that in the remnant forest. Mean pH recorded was 5.1, 6.4 and 6.3 for remnant forest, shaded cocoa and unshaded cocoa farms, respectively. This could be due to the protection of the soil in the cocoa farms from erosion by the layer of partly decomposed cocoa leaves on the soil surface. The results of the chemical analysis of soils are presented in Table 2. The percentage carbon content in the remnant forest was significantly ($p < 0.05$) higher than in the cocoa farmlands. Total nitrogen and available Phosphorous contents of soils significantly ($p < 0.05$) reduced in the unshaded cocoa when compared with the remnant forest. These trends may be due to the greatest diversity of plant species that produce more litter as well as the faster decomposition rates observed in the remnant forest. The exchangeable K contents of soils were lower under the cocoa systems than in the remnant native forest although the differences were not significant because of the ability of the soil to replenish the lost potassium through cropping (Ahenkorah *et al.*, 1974).

TABLE 2

Summary by land use type of the soil physical and chemical properties

Soil property	Remnant forest	Shaded cocoa	Unshaded cocoa
pH (1:2.5,H_2O)	5.1 ± 0.31	6.3± 0.10	6.3 ± 0.12
% Carbon	4.0 ± 0.23	2.4 ± 0.18	1.7 ± 0.21
% Nitrogen	0.46 ± 0.012	0.24 ± 0.023	0.19 ± 0.033
Available P (ug/g)	24.1 ± 1.26	15.5 ± 1.88	9.9 ± 1.92
Exchangeable K (cmol/($^+$))	0.20 ± 0.023	0.10 ± 0.014	0.10 ± 0.012

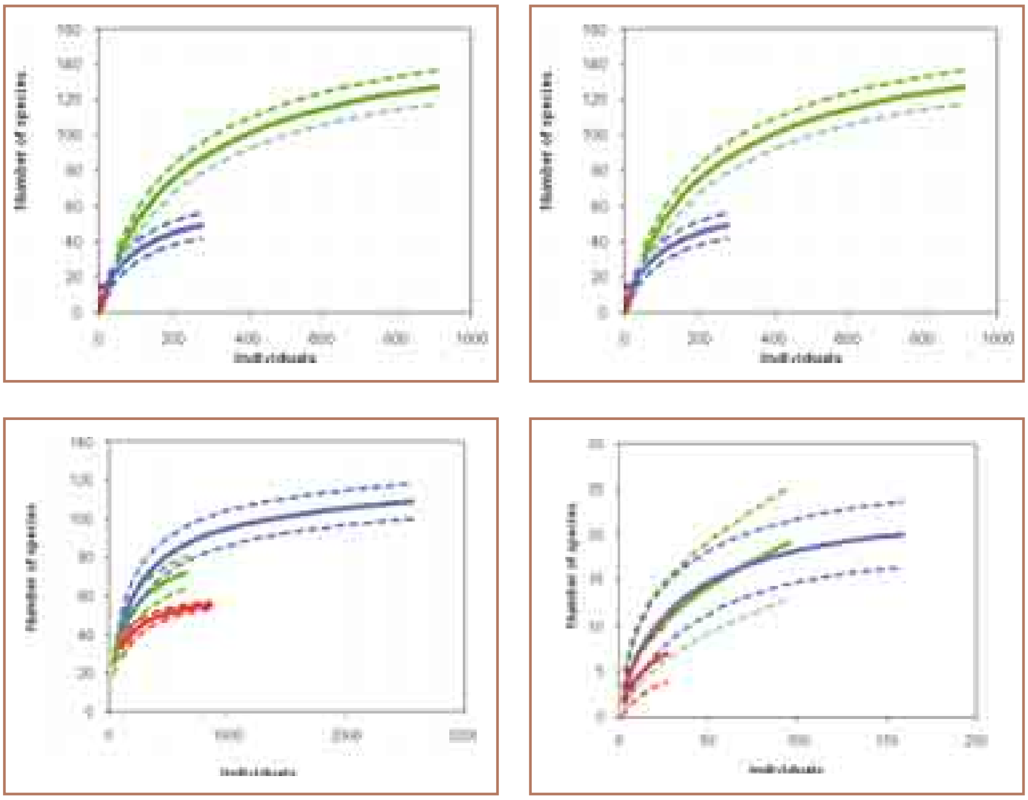
Values are presented as ± Standard Error.

Biodiversity

Plants and fruit-feeding butterfly species richness were significantly (95% Confidence Interval) higher in the remnant forest followed by shaded cocoa farms and least in the unshaded cocoa farms (Fig. 1A and 1B). In contrast, bird species richness was significantly (95% Confidence Interval) higher in the shaded cocoa farms compared to that in the remnant native forest (Fig. 1C). The data for mammals was few but species richness was comparable between remnant forests and shaded cocoa farms (Fig. 1D).

FIGURE 1

Individuals-based species rarefaction curves for (A) plants, (B) fruit-feeding butterflies, (C) birds and (D) mammals with increasing cocoa yield.



Solid lines indicate estimated species richness and dotted lines represent the upper and lower 95% confidence intervals for each land use type. Colours represent different land use types with green indicating remnant forest, blue shaded cocoa farms and red unshaded cocoa farms.

The results also showed that increasing production intensity of cocoa leads to a drastic loss of forest biodiversity with subsequent recruitment of non-forest species. For example, shaded cocoa farms retained about 59.6% of forest plants whereas the unshaded cocoa farms retained only 7.90% of forest plants. At the same time, shaded and unshaded cocoa farms recruited 7.0 ± 2.0(S.E) and 5.0 ± 1.4 (S.E), respectively of non-forest plants. About 61.3% and 40.7%, of forest butterflies were retained in shaded and unshaded cocoa farms, respectively. An estimate of 5.05 ± 1.20 (S.E) non-forest fruit-feeding butterflies were recorded in the un-shaded cocoa farm while none was found in the shaded cocoa farm. The shaded cocoa and unshaded cocoa farms retained 76.8% and 31.6%, of forest bird species, respectively. It was found that the higher bird species richness in shaded cocoa farms compared to that in the remnant forest was due to massive recruitment of an estimated 45.45 ± 4.67 (S.E) non-forest bird species in shaded cocoa farms. The unshaded cocoa farms recruited an estimated 18.00 ± 2.45 (S.E) non-forest bird species.

The results showed that cocoa farming results in a loss of forest biodiversity and that species richness decreased in relation to increasing cocoa production intensity. This confirms the observation that shaded cocoa farms harbour significant levels of biodiversity (Reitsma *et al.*, 2001; Donald. 2004; Schroth and Harvey, 2007), although not as rich as the native forest (Ofori-frimpong *et al.*, 2005).

CONCLUSION

Our study suggests that intensively managed unshaded cocoa farms are more productive at least in the short-term compared to shaded farms but with least carbon storage potential. By considering C stocks and cocoa productivity in tandem land management strategies can be adopted to maximise benefits for both the former and the latter. Ecosystem health and biodiversity value have been found to be related to C stocks, thus providing a potential economic mechanism for wider ecosystem protection if C stocks could be traded. Currently intensive cocoa agricultural management is an attractive option to farmers because it yields higher profits, although this may not be the case in the long term. The study was limited to a small agricultural landscape and therefore comparable integrated studies within Ghana and across the entire West African region are much needed to provide baseline data.

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Land use and land cover impact on soil and vegetation carbon in Nioro area (Senegal)

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ABSTRACT

Managing carbon stocks within landscapes is a key mid-term mitigation of atmospheric and climate change. This study is based on Spot and Landsat images. The study aims to assess land use/cover changes in Nioro agro ecosystem area in the period 1990–2001 and analyze the effects of these changes in carbon sequestration in soil and vegetation. It shows major land use classifications into 7 types: low lands, fallows, plantations, cultivated areas, timbered savannah, shrubby savannah strand (“tanne”) and water plan. In the top of soil carbon is mostly sequestered in low land with 3.55 C t ha-1, involved by run off and erosion concentration. Plantation areas, essentially eucalyptus and fruit tree cultivation, shrink 91 C t ha^{-1} in biomass.

Carbon stocks were considerably reduced in the study in ten years. The average of carbon fluxes is -163.6 kg C ha^{-1} year^{-1} between 1990 and 2001. Most of the carbon flux was attributed to biomass carbon reduction due to human disturbance. Total removing of parkland involved -751 kg C ha^{-1} year^{-1}. Opportunities for carbon mitigation exist and can be integrated with practices in land management. In such area, applying agro forestry program could mitigate the depletion of the natural resources.

Keywords: Land use/cover, Remote sensing, Sub-Saharan Africa, Carbon fluxes

INTRODUCTION

Land use system is the major factor determining evolution of the ecosystems. Intensive and mining husbandries combined with the increasing demography exert a pressure on the natural resources which results in deforestation and soil degradation. Scientific research has proven that all these factors take part in the climate change causing the warming of planet due to the emission of CO_2 in the atmosphere, but also affect socio economic conditions in arid countries (Mortimore and Adams, 2001). The sequestration of carbon in

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soil and vegetation constitutes not only an effective means of reducing this phenomenon, but also it makes it possible to improve fertilizing quality of the soil for sustainable agriculture productions in semi-arid zones.

In Senegal, several studies (Niang 2004, Tschakert 2004, Kempen 2005) at a field scale are related to the effect of the production system on the carbon sequestration in soil and vegetation in different ecological zones.

However on a larger scale, where there are greater agro ecosystem complexes, some information is available on the stock of carbon and its evolution in time. To extend temporal study from the field scale to large scale, like an ecological region, geographical information systems (GIS) are useful (Rembold *et al.*, 2000).

The objective of this study was to assess land use/cover changes in Nioro agro ecosystem area in the period 1990–2001 and analyze the effects of these changes in carbon sequestration in soil and vegetation. An inventory established current soil and biomass carbon concentrations for each land use/cover unit, and calculated and then aggregated the total carbon within each unit. Values obtained from recent field measurements, a unit-specific adjustment by using Landsat images for woody biomass removal was calculated. This process allows estimating the carbon stock and potential of sequestration in soil and vegetation.

MATERIAL AND METHODS

Location, climate and soils

The study was carried out in the peanut basin of the Nioro area in Senegal (between 13° 36' and 13° 40' North and 16° 00' and 16° 30' West). The climate is classified as Soudanian. Over the last years, the average annual rainfall ranged between 700 and 800 mm (Iyamuremye 2000). The annual mean of minimum and maximum temperature is respectively 20°C and 36°C. Soils are manly sandy, mixed Haplic Ferric Lixisol, and ferrugeneous tropical Ultisol. Land management practices are mainly characterized by overgrazing, agricultural mismanagement, deforestation and overexploitation of the natural resources.

Images data assessment

Using a Spot 3 image of the year 2001, the whole zone was digitalized and great units of land use and cover were identified by supervised classification. For the year 1990, only Landsat image was available and covers 44 % of the study area. Spot image was the base for different classes' identification on Landsat image. Superposition and contours fitting for each class enabled to set areas variation and carbon change between 1990 and 2001.

Vegetation and soil samplings

After zoning the study area, samplings were carried out with two points by transect. Then each point was identified by visual interpretation. Sampling randomly consisted in an inventory of the biomass (trees, shrubs and herbaceous) and the residues on the soil in transect (R= 20 m) for different types of land use/

cover. If the diameter of the plant at 1.30 m height from soil is more less 7 cm, it is regarded as a tree. If it is less, it is a shrub. Measurements are applied on the height and the two perpendicular diameters of the canopy of each subject, in a radius of 3 m. Biomass is assigned to individual trees through allometric equations of the arid areas recommended by FAO (1997). Subplot frame of 1 m^2 sampling twice repeated of herbaceous and litter was carried out. Samples are dried at 65°C during 48 hours and then weighed. Once dried, biomass weight is assumed to contain 45 % C (Penman *et al.*, 2003).

Soil samples are collected by repeated coring from 0-20 and 20-40 cm in the biomass quadrates. Soil bulk density measurements are obtained by driving thin-walled metal cylinder of known volume into the vertical face at depths central to sampled soil horizons (0-20 and 20-40 cm). The cylinders with known volume are used for bulk density determination.

Carbon estimation

Formulas used for the calculation of the carbon contained in vegetation and soil are those recommended by Woomer (2001). Aboveground and underground biomass carbon calculation is equal to: $C\ (kg\ ha^{-1}) = (C\ trees + C\ herbaceous + C\ Residues) \times 10000\ m^2 / (20\times20\times\pi)$.

It is assumed that roots carbon of trees (C Lrac) is 0.8 C tree biomass carbon, herbaceous roots (C Hrac) C is derived by 0.15 C herbaceous' aboveground carbon. Coefficients used represent the relationship between the aboveground and underground parts of vegetable. Finally, the total vegetable carbon contained in underground (C rac) is equal to: $C\ rac\ (kg\ ha^{-1}) = (C\ Lrac + C\ Hrac) \times 10000\ m^2 / (20\times20 \times \pi)$.

Total soil organic carbon for each depth may be calculated from soil organic carbon (%) and soil bulk density: $C\ sol\ (Mg\ ha^{-1}) = 100\times100\times D\times BD\times SOC\times10000\times0.000001$. With BD= Bulk density ($g\ cm^{-3}$), D= depth of each layer (cm) and SOC= soil carbon organic (%).

RESULTS AND DISCUSSION

Land use and land cover

The total area of land use and land cover studied is 98859 ha of the department of Nioro. Digitalization and classification, carried out from Spot image of the year 2001 shows seven great types of land use and land cover. The table 1 indicates current organic carbon per hectare in vegetation and soil in different sampled classes. This study shows that on the level of the cultivated area, human activity exerts a pressure on the natural resources. Thus, 78 % of area is used for cultivation, which is due to the extensive agriculture practiced and in consequence to the increasingly growth of the population. This fact involves a degradation of the ecosystems and consequently the climatic changes with large effects on socio-economic conditions (Jenkinson 1990).

TABLE 1

Land use and land cover rate carbon in vegetation and soil per hectare

Land use/land cover	Area (ha)	Rate (%)	Vegetation (C t ha^{-1})	Soil (C t ha^{-1})	
				0-20 cm	20-40 cm
Low land	400	0.4	65	20-40 cm	3.03
Fallow	301	0.3	13	1.18	0.77
Plantation	471	0.5	91	2.10	1.70
Cultivated area	77101	78.0	13	1.32	0.88
Timbered Savannah	875	0.9	32	1.60	1.15
Shrubby Savannah	17456	17.7	21	1.40	0.87
Tannes(riversides)*	2255	2.3	0	0.88	1.56

* Bank or riversides seasonally flood by the river

Biomass carbon

Plantations and low land have the highest carbon rate with respectively 91 and 65 t ha^{-1} (Tab. 1). The plantations generally consist of orchard with fruit trees (*Mangifera indica*, *Anacardium occidentale* and others) and timber trees (*Eucalyptus sp*). The low lands vegetation tracks the hydrographic path like a forest gallery. Timbered savannahs and shrubby savannahs having respectively 32 t ha^{-1} and 21 t ha^{-1} are generally sited on soil that is inappropriate for agriculture (rock-hard and bare soil). The fallow and the cultivated area have the same carbon value per hectare, with 13 t ha^{-1}. Here the fallow seems like a cultivated area in terms of biomass. On field it is shown by observation in the likeness feature (from February to March) of the two types of land use and cover. At the period of investigation, the shrubbery of the crop zones is mainly dominated by *Guiera senegalensis*, *Combretum sp.* and *Piliostigma reticulatum* growing for 5 months.

Soil carbon

Low land is a sink of carbon of about 3.5 t ha^{-1} in layer of 0-20 cm. This result is confirmed by McCarty and Ritchie (2002), who showed the impact of the dynamics of the soil on the increasing carbon sequestration particular in the wet land. Lands covered by timber savannah, shrubby savannah and crop have more or less the same content of carbon (1.6; 1.4 and 1.3 t ha^{-1} respectively). However, soil carbon decreasing tendency is observed with the degradation of the ecosystem from forest land to agriculture land (Arrouays *et al.* 2001). Fallows with short duration do generally not present a high carbon sequestration (Masse *et al.* 2004) in semi arid areas. That could be the fact of frequent fires which follow grassy and shrubby vegetation. However soil of the land used for the plantations would be a better carbon sink with higher value than natural biomass formations.

Temporal carbon estimation

Results of this study show an increase of cultivated area from 65 to 75% in one decade that is to say 1% per year (Tab. 2). Shrubby and timbered savannah lost respectively 2% and half of areas in ten years due the extension of agriculture. Moreover it highlights the depletion of parkland which occupied 5% of lands in 1990. This comparison emphasizes the loss of the potential to sequester carbon through types of land use and land cover between the two dates. Particularly, the change of the biomass formations and the fallows into farms summarizes to an increase CO_2 in atmosphere.

TABLE 2

Land use and land cover percentage about of 46000 ha

Land use	1990	2001
Water plan	2	2
Plantation	1	1
Shrubby Savannah	20	18
Timbered Savannah	4	2
Cultivated area	65	75
Habitat	2	2
Parkland	5	0

The total average of carbon fluxes is -163.6 kg C ha^{-1} $year^{-1}$. As table 3 shows, the carbon flux is from the parkland with -751 kg C ha^{-1} $year^{-1}$. It is the fact that the total turn over of this land is used to cultivated area. This unit has been totally removing form 1990 to 2001 (Tab. 2).

TABLE 3

Estimated stock and carbon flux after adjusting land use/cover change in Nioro between 1990 and 2001

Land use	Area (ha)	Carbon stocks (t C×10^6)		C flux (kg C ha^{-1} $year^{-1}$)
		1990	2001	
Shrubby Savannah	9200	0.206	0.202	-39.5
Timbered Savannah	1840	0.06	0.059	-49.4
Parkland	2300	0.033	0.014	-751.0
Total	13340	0.299	0.275	-163.6

Shrubby savannah has the low carbon flux (-39.5 kg C ha^{-1} $year^{-1}$), however it has the largest surface with 9200 ha. Concerning the Timber savannah (1840 ha) carbon emission is about of -49.4 kg C ha^{-1} $year^{-1}$. Comparing the two units, the first is 5 times larger than the second. They have lost on the same period 2% of their area but the flux of timber savannah is 1.25 times high than the shrubby savannah. It is due to the strong concentration of carbon per hectare of timber savannah.

CONCLUSIONS

The greatest part of the landscape of Nioro area is used for agriculture (about of 78%).

A strong concentration of woody formation increases carbon content in biomass and in up layer of soil. This increase is well marked in plantations and low land, but less in soil of land covered by woody savannahs. However, natural ecosystems management particularly destroying vegetation units to farmland in ten years is favourable to increase CO_2 emission. In this zone, a grassy farm after harvest would have the same potential to sequester carbon as a fallow in short time (less than 5 years).

Carbon stocks in Nioro du Rip were considerably reduced by a combination of drought and “management” associated with survival strategies of the householders. However, it must be emphasized that opportunities for carbon gains exist and can be integrated with practices to achieve enhanced agricultural fertility and sustainability.

The study on region scale, like Nioro, estimating accuracy requires rigorous samplings strategy.

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Estimating the impact of selective logging on aboveground carbon stocks in a wet evergreen forest of Ghana

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INTRODUCTION

Deforestation is the largest contributor of tropical land use emissions (Houghton 2003), with Africa contributing 25-30% of tropical land clearing from deforestation, and as much as 0.37 Pg C yr^{-1}, in the last decades (DeFries and Achard 2002). Reducing Emissions from Deforestation and forest Degradation (REDD) is recognized as a potential option to mitigate climate change (Santilli, Moutinho *et al.* 2005). REDD is integrated into the negotiations of the United Nations Framework on Climate Change and it is highly probable that it will become eligible for the second commitment period of the Kyoto protocol. The implementation of the REDD mechanism will require estimates on the impact of forest degradation and deforestation on carbon (C) stocks, identifying baselines and monitoring forests. Ghana lost about 80% of its forest cover in the last century, and the rate of deforestation between 1990 and 2000 was 1.7% and was one of the highest in the world (International Tropical Timber Organization, 2005). The major causes of deforestation have been fires, over logging, shifting cultivation, and an ever-increasing demand for fuelwood. Nowadays, about 1.15 million ha of natural forests are under production in Ghana (ITTO 2005). The silvicultural system used in natural forests is a polycyclic selection felling system using a cutting cycle of 40 years. However, there is still no data on C stocks in forests of Ghana and on the impact of selective logging on carbon stocks. The aim of this study is to provide (1) estimates of aboveground carbon stocks in a Wet evergreen Forest Reserve of Boi Tano and (2) an estimation of the impact of logging on aboveground carbon stocks.

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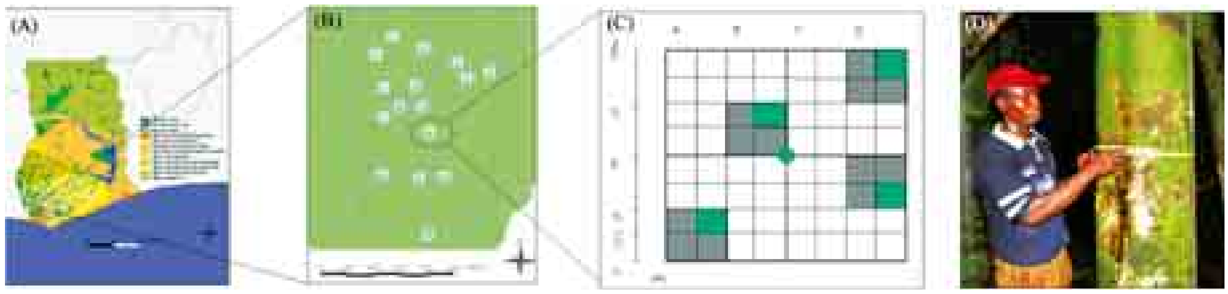
MATERIALS AND METHODS

The study is located in Boi Tano forest reserve (5°40’ N, 2°64’ W) which is situated in the wet evergreen zone of Ghana (Fig. 1). Three landscape units were identified: upper slope, middle slope and swampy area. Five vegetation classes were differentiated: (1) trees with diameter at breast height (DBH) <20cm, (2) trees of DBH between 20 and 50cm, (3) trees with DBH>50cm, (4) lianas and (5) dead plants. Sixteen plots of one hectare were randomly implemented within a 170 ha forest compartment.

All the plots were centred on a selected tree to be felled. Three plots were selected to analyze the spatial variability of biomass between ecological zones. Those three “variability plots” were divided into 10x10m plots. All the plants of a diameter at breast height above 2 cm were inventoried, the DBH was measured and 55% of plant species were identified. A niche sampling strategy was used into the thirteen other plots. While all the trees above 50cm were inventoried inside one hectare plots, the trees with diameter between 50 and 20 cm were inventoried into four randomly selected subplots of 25x25 m whereas trees with DBH <20 cm were inventoried into four randomly selected subplots of 12.5x12.5 m.

FIGURE 1

Sampling strategy: (A) ecological zones of Ghana, (B) location of the plots in one forest compartment, (C) sampling design, (D) field measurement



Biomass contained into the different vegetation classes was compared using different allometric regressions found into the literature (MacDicken 1997; Hairiah, Sitompul *et al.* 2001; Ponce-Hernandez 2004; Pearson and Brown 2005). The allometric equation presented in Pearson and Brown (2005) was preferred to estimate the aboveground biomass of the trees before logging because it does not overestimate the biomass of the big trees in comparison with the other allometric equations.

1) $$B = (\exp(-2.289 + 2.649 * \ln(DBH) - 0.021 * \ln(DBH^2))$$

Where B is the biomass of the trees (kg) and DBH is the diameter at breast height.

The biomass of the lianas was estimated using the allometric equation found in Schnitzer, DeWalt et al. (2006).

2) $$Bl = \exp(-1.484 + 2.657 \ln(\mathrm{DBH}))$$

Where Bl is the biomass of the liana (kg).

Different types of ground damage were identified: roads, logging bays, skid trails and felling gaps. While the ground area damaged by roads, logging bays were measured in the whole compartment, damages of the felling gaps were measured for eight trees and the area impacted by skid trails was estimated. The felling operations were still not finished when the study was achieved and we assumed that eight trees were harvested for each skid trail. In total 301 trees were harvested within the compartment. The impacted area by skid trails was assumed to correspond to the average distance of one tree to the road multiplied by an average width of 4.5 meters. In total, it was assumed that 38 skid trails had to be built to collect all the trees of the compartment.

The impact of logging was estimated assuming that all the aboveground biomass on the damaged area was removed when building the logging bays and the roads, while only the vegetation with diameter below 20cm was damaged when building the skid trails.

3) $$C_{losses} = A_g \times C_s$$

Where A_g is the ground area where vegetation is removed (m2) and Cs is the carbon stock density (kg m^{-2}).

RESULTS

Carbon stock measurements

Most of the plant stems belonged to the tree with DBH less than 20 cm (83%). The trees with DBH more than 50 cm represented only 1% of the stems (Tab. 1) although they represented 48% of the aboveground biomass (Fig. 3). 389 stems per ha (about 10% of the stand density) were lianas and most of the lianas were found into the upper slope ecological zone. In total, 114 species were identified. The analysis revealed that *Xylopia rubescens* was by far the species the most present (39 %), and mainly in the upper slope. The other important species were *Cynometra ananta*, *Microdesmis puberula* and *Coelocaryon sphaerocarpum*, but they represented only 7 % of the total number of trees.

TABLE 1

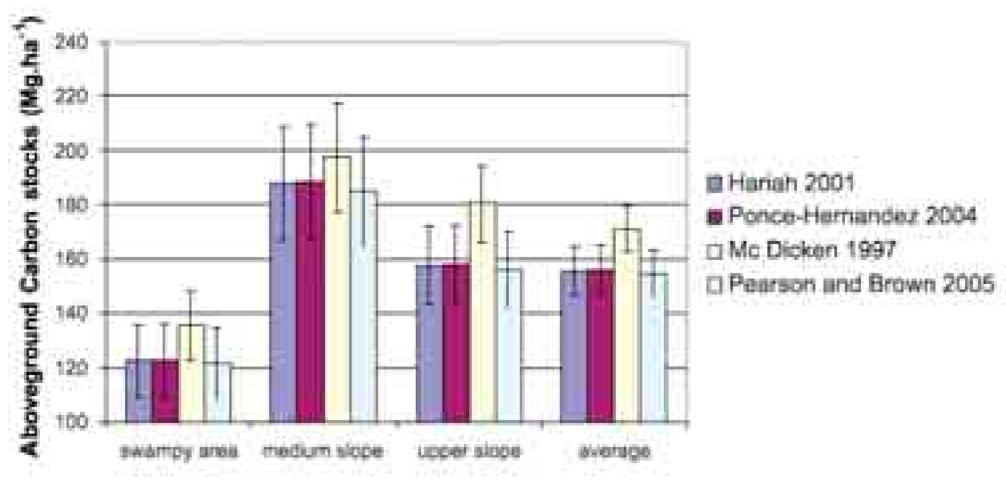
Number of plant stems and basal area (ha^{-1}) within the different stratum G is the basal area (m^2 ha^{-1})

Ecological zone	Trees>50 cm	20<Trees<50 cm	Trees<20 cm	Lianas	Dead trees	Total	G (m^2 ha^{-1})
Swampy area	23	142	2390	334	22	2911	25.5
Medium slope	36	173	2419	208	31	2867	34.9
Upper slope	39	148	4075	624	26	4912	30.5
Average	33	154	2961	389	26	3563	30.3

Estimation of aboveground C stocks ranged 154.2 – 171.1 Mg ha^{-1} using different allometric regressions (Fig. 2). The maximum C stock was obtained using the equation of MacDicken (1997) while the minimum was obtained using the equation from Pearson and Brown (2005). The allometric regression reported by Pearson and Brown (2005) was considered in our study as the more suitable mainly because it didn't over estimated the biomass of the trees with a DBH below 5 cm. Using the other allometric equations, biomass of tree with DBH below 5 cm was increasing with small diameters.

FIGURE 2

Aboveground carbon stocks in three landscape units and using different allometric regressions



Average aboveground C stocks was 154.2 (±16.2) Mg ha^{-1} (Fig. 3). Aboveground biomass was significantly different between landscape units ($P<0.05$). The most important C stocks were found in medium slope (185.2 Mg ha^{-1}) while the minimum C stocks were found in swampy area (121.5 Mg ha^{-1}). Most of the aboveground C stock was contained into the trees with DBH>50cm (48.3%), while tree with diameter at breast height (DBH) less than 50 cm represented 47.7%. Lianas and dead trees formed the rest of the aboveground C stock. The spatialisation of aboveground biomass revealed that the most important C stocks were located in the areas where the trees of DBH > 50 cm are located (Fig. 4). Using different root-shoot ratios, belowground C stocks ranged 52.6 – 114.1 Mg ha^{-1} (Fig. 5). The maximum belowground C stock was obtained using the IPCC root-shoot ratio while the minimum was obtained using the Pearson (2005) and the Brown (2005) allometric regressions. When considering the different zones, belowground C stocks ranged 42.6-137.0 Mg ha^{-1} in swampy and mid-slope area respectively.

FIGURE 3
Aboveground carbon stocks of the different stratum in three landscape units

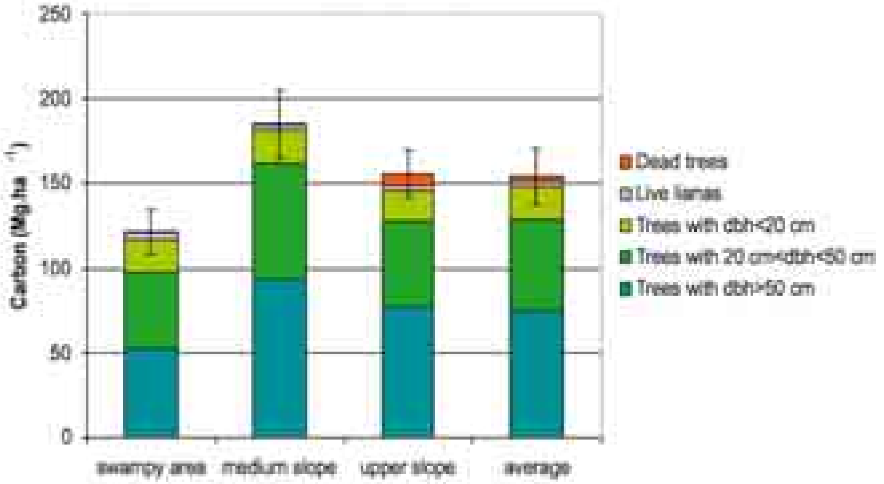


FIGURE 4
Spatialisation of aboveground biomass

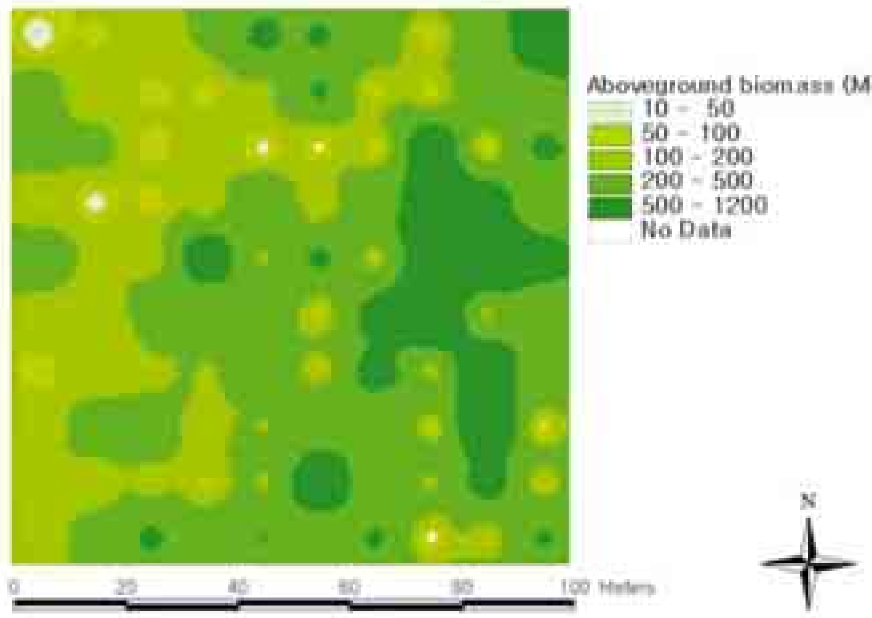
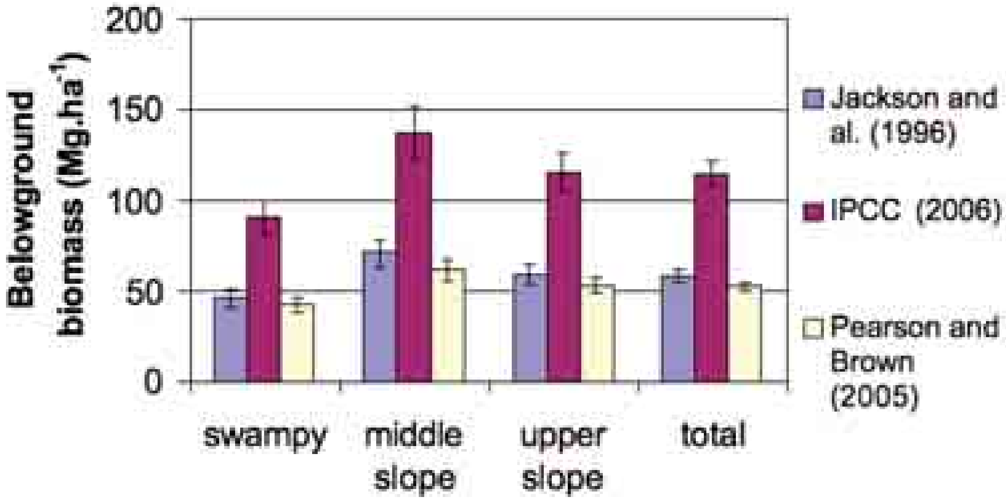


FIGURE 5

Belowground carbon stocks estimates using different root-shoot ratios



Within one hectare, the C stocks contained into 10x10 plots varied a lot and ranged 16-776, 6-1280 and 7-570 Mg ha^{-1} for upper slope, middle slope and swampy area respectively. Most of the variability was found into the middle slope ecozone. According to figure 6, 15 plots of 1 ha would have to be measured to estimate the biomass of the compartment (170 ha) with an uncertainty of 5% and 17 plots of one hectare to estimate the biomass of the Boi Tano forest reserve (12184 ha).

FIGURE 6

Number of plots required to estimate the biomass of the compartment

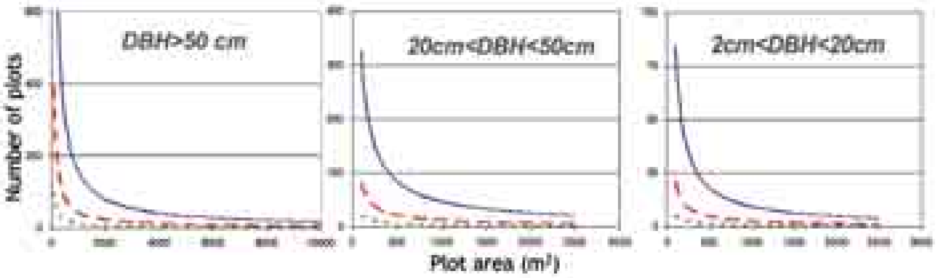


FIGURE 7

Hauling during the logging of the compartment

Aboveground carbon losses

The C losses ranged 1.8-22.5 kg m^{-2} (Tab. 1). Building roads and logging bays had the highest impact on C stocks (17.0 kg m^{-2}) while the lowest was observed for skid trails (2.4 kg m^{-2}) (Tab. 2). When considering the compartment scale, it appeared that 10.01 Mg.ha^{-1} were lost by selective logging (table 3). 20, 7, 70 and 3 % of C were lost by roads, logging bays, logging gaps and skid trails respectively. When considering the 16 plots, in average, 170 and 160 Mg ha^{-1} of C were stored in natural forests and after selective logging, respectively (Fig. 8).

TABLE 2

Carbon losses for each type of impact

Type of impact	average impact
roads and logging bay (kg m^{-2})	17.0 [12.2-22.5]
skid trail (kg m^{-2})	2.4 [1.8-3.1]
logging gap (kg tree^{-1})	8018 [1760-51670]

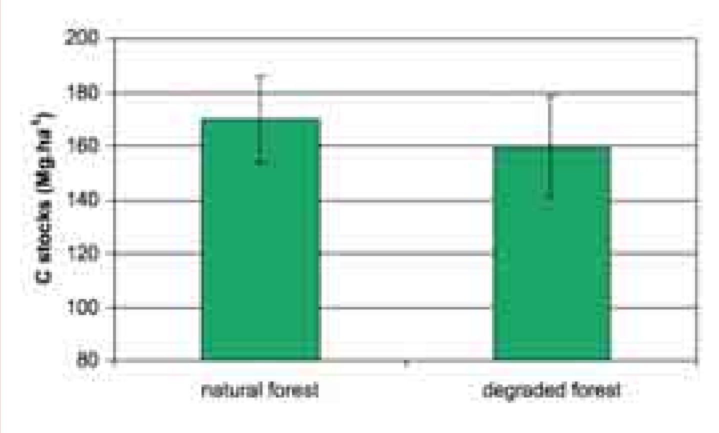
TABLE 3

Carbon losses in the whole compartment

Type of damage	Surface impacted (ha)	Mean carbon stocks losses (Mg ha^{-1})
Roads	2.00	1.96
Logging bays	0.69	0.97
Logging gaps	6.79	6.98
Skid trails	2.82	0.40
Total impact	12.29	10.01

FIGURE 8

Comparison of the C stocks between natural and selectively logged forests



DISCUSSION AND CONCLUSION

Aboveground C stocks range 138-170 Mg C ha^{-1} between stratums using the allometric regression of Pearson. However, using different allometric regressions without a good identification of the forest stratum could lead to a difference of up to 75.9 Mg ha^{-1} between the estimates. While there is still no allometric regressions for tropical forests in west Africa, there is a strong demand for further studies and improvement of the C stocks estimates in tropical forests. Aboveground C stock variability is very important between and within the stratum. It appears that 15 plots of one ha were necessary to estimate the aboveground biomass for Boi Tano forest with an uncertainty of 5%.

The impact of logging is about 10.01 Mg C ha^{-1} and represents 5% of the total aboveground C stocks. This estimate is very close to the amount of 10.2 Mg Cha^{-1} reported by Brown (2005) in a concession in the forests of the northern Republic of Congo in Central Africa. Our estimate ranges 3.7-49.0 Mg C ha^{-1} at the compartment scale. However, the estimates are still coarse and need improvement.

After substracting C losses from the total amount of C before logging, it appears that the difference between logged forest and natural forest is still not significative with 5% of error. A precision of 3% is needed to differentiate a natural forest from a logged forest, and at least 57 plots of one hectare have to be measured to identify significant difference of C stocks between the forest types.

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Run off intensity and carbon and nitrogen losses in run off water on eucalyptus plantations at Pointe Noire

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ABSTRACT

Lateral fluxes of matter through erosion and deposition processes can be the main drivers of soil horizontal and vertical distribution of nutrient pools. Near Pointe Noire, soils are deep and sandy but large gullies can happen demonstrating that risks of erosion and nutrients losses may be important. In this paper, we have been interested by the different causes of soil erosion. We focused mainly on the influence of land use and slope to run off intensity, and wanted to quantify the dissolved carbon and nitrogen losses in run off. Land cover was stratified according land use, slope and fire occurrence. We used a rainfall simulator adapted from Orstom rainfall simulator and designed to be easily transportable over the forest area. The simulated rainfall intensity ranged from 60 to 80 mm/h during 30 minutes fitting the annual maximum observed in the region. Simulations have been done on different sites for each land use and slope classes, leading to a total of 97 locations. Each time soil samples and run-off water were collected to perform analysis of soil bulk density, dissolved C and N in run off. There was a clear effect of land use on run off intensity. It was low on fire breaks and savannahs whereas it was high on skid trails. There was no effect of slope and fire occurrence. For eucalypt plantations, run-off rate was highly variable and was mainly depending on hydrophobicity which was roughly assessed by the time span between the last rainfall and the experiment. Carbon concentration in the run-off solutions was determined by the origin of the water, hydrophobicity, and also the solid matter stagnation time between simulation and water filtration. Nitrogen concentrations were not statistically different from those of the water used for the simulations. Soil chemical properties and soil textural distribution will help to improve run off model. As dissolved C and N in run off are not greater than in water used for simulation, solid matter losses by run off will be studied to complement soil degradation sensitivity evaluation of the study area.

Keywords: erosion, run off, sandy soils, rainfall simulations.

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INTRODUCTION

At the world scale, erosion is the main process of soil degradation (Robert, 2004). It takes organic matter and thin particles (like clay) out of superficial soil horizons (Roose, 1994) and can generate gullies on bare soil, or deplete soil carbon and nutrients. Tropical soils are generally resistant to drop energy but rain intensity is higher and the vegetation cover plays a role in preventing nutrient and erosions losses (Roose and de Nonni, 2004).

Near Pointe Noire, soils are deep and sandy. Their high surface permeability and hydraulic conductivity permits a rapid infiltration of rain, between 144 and 360 mm/hour (Van Caillie, 1989). Normally, erosion and run off risks should be low. However in that area, gullies can happen on bare soil like skid-trails, especially in the slope direction (Fig. 1). Furthermore, in a preliminary study on these eucalyptus plantations, Roose (2007) shown that erosion and run off risks were not negligible, almost in bare and burned areas. These risks could be mainly dependent on slope, land use and fire occurrence.

As organic matter is low and concentrated in superficial horizons in the study area (Laclau *et al.*, 2004), run off and surface erosion could also have large consequences on the biogeochemical cycles by depleting reserves of nutrient from the top soil horizons.

The objectives of this paper were: identifying causes of soil erosion, mainly studying the influence of land use and slope on run off intensity; quantifying the dissolved carbon and nitrogen losses in run off.

FIGURE 1
Gullies on trail

MATERIALS AND METHODS

Site

Eucalyptus plantations are located at 4° S, 12° E, along the Atlantic coast of the Congo (Laclau *et al.*, 2001). The study sites are located near UR2PI (Unité de recherche sur la productivité des plantations industrielles) experimental sites of Kondi and Kissoko.

The soils are Ferralic Arenosols (FAO classification) (Nzila, 2001). They are sandy (sand content >85 %), very deep (> 6 meter) and poor chemically (Tab. 1) with low spatial variation of biological and chemical content (Laclau *et al.*, 2003).

TABLE 1

Chemical properties of superficial horizon (0-5 cm)

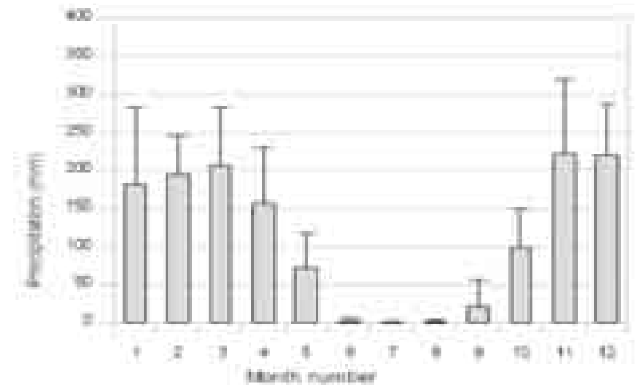
	Savannah	*Eucalyptus*
Organic matter (%)	0.91	1.14
N total (‰)	0.37	0.47
CEC (cmolc.kg^{-1})	0.43	0.53
P(‰) **(Duchaufour et Bonneau 1959)**	0.03	0.047

(Data from Laclau ***et al.***, 2000)

The climate in this region is characterized by an average annual temperature about 25 °C and a relative humidity averaging 85 % with both low seasonal variations (Laclau *et al*, 2004). The mean annual rainfall is 1200 mm with a marked dry season between May and September (Fig. 2). Maximal annual rainfall intensity in 30 min ranges between 60 and 80 mm/h (recorded from UR2PI's experimental sites).

FIGURE 2

Monthly rainfall in Kondi site. Mean and standard deviation (1998 to 2007)



The study area is located on an undulating plateau with a slope ranging between 1 % and 20 %.

The main type of vegetation is savannah annually burned by local population. Eucalyptus plantations had been planted on theses savannahs. They cover currently 40 750 ha in 2008 (data from Eucalyptus fibber Congo, in charge of the plantations).

Experimental methods

The main factors influencing run off and erosion were potentially the slope intensity, land use, and the occurrence of fires. We defined 8 types of land use and 4 classes of slopes (Tab. 2). The land use types are: firebreak, young unburned eucalyptus, young burned eucalyptus, old unburned eucalyptus, old burned eucalyptus, skid-trail, savannah and annually burned savannah. Eucalyptus plantations less than 2 years old were separated from eucalyptus older than 5 years because the mulch of litter on the soil becomes important only after two years and this may influence run-off and soil erosion.

Two different zones were chosen in the forest area (Kissoko and Kondi) because they offer a wide range of situations (land use x slope). Two experimentations per combination have been programmed in each zone. However, some cases could not be found like slopes greater than 15 % for savannahs and young eucalypts; or unburned savannahs that exist only in two experimental units of UR2PI (Tab. 2).

TABLE 2

Contingency table for the rainfall simulation (land-use × slope).

SLOPE SOIL OCCUPATION

	S					*BS*			
<5%	20	21				28	29	86	87
5-10%	31					40	41	88	89
10-15%						32	33	90	91
>15%						22	23	110	111

	YE					*YBE*			
<5%	18 -105	19 -106	84	85		12	13	103	104
5-10%	71	72	73			68	69	112	113
10-15%	74	75	79			65	66	67	
>15%									

	OE					*OBE*				
<5%	14 -108	15 -109	62	63		42	43	99	100	
5-10%	46	47	59	60		11	16	17	95	96
10-15%	58	61	64			10	24	97	98	
>15%						25	26	27	101	102

	T					*FB*			
<5%	38	39	107			36	37	92	93
5-10%	56	57	82	83		44	45	78	94
10-15%	54	55	80	81		34	35	76	77
>15%	52	53				48	49		

S=savannah; BS= annually burned savannah; T=trail; FB=firebreak; YBE=young burned eucalyptus; YE=young unburned eucalyptus; OBE=old burned eucalyptus; OE=old unburned eucalyptus.
Slope classes: (1) < 5%, (2) 5 to 10%, (3) 10 to 15% and (4) >15%. Gray intensity represents one different place studied.

In order to determine the influence of slope and land use on run off and soil erosion, we used a rainfall simulator which is a simplification of the ORSTOM simulator (Casenave, 1982) and was especially designed to be easily transportable over the forest area. The rainfall simulation is applied on 1 squared meter soil surface (Fig. 3). The system allows the comparison between situations. However, a direct inference of our results to natural rainfall effect is not possible because the energy of the rainfall drops has not been recorded. The simulated rainfall intensity ranged from 60 to 80 mm/h during 30 minutes according to the annual maxima observed in the region.

This method was chosen because:

i. The rainfall intensity is controlled leading to a better identification of the factors influencing run off and soil erosion;

ii. Studies under natural rainfall are costly and need several years of measurements before being accurate (Casenave and Valentin, 1989),

iii. We wanted to compare the different situations to assess their sensitivity to soil erosion and not a quantification of run off under natural rainfall,

iv. Many cases were to be studied over a large area so a simple and transportable material was needed.

FIGURE 3
Rainfall simulator installed in young eucalyptus plantation after a recent running fire

For each simulation, soil samples and running off water were collected for the following analysis:

Physical soil properties analyzed in Congo: bulk density.

Run off analyses in France: C and N in run off (Total organic carbon by chromatography Shimadzu TOC-VCSN, Nitrogen by colorimetry Skalar San++ System).

As run off water filtration was not possible in Congo some organic solid matter like leafs pieces remained in the water between simulation and the filtration which was performed in France. So the number of days between simulation on the field and filtration, the solid matter stagnation time (SMST) was recorded to determine its effect on the chemical analyses.

As rainfall intensity is not exactly the same in each simulation we are considering the run off rate:

1)

$$\text{run off rate (\%)} = 100 * \left(\frac{\text{run off intensity (mm/h)}}{\text{rainfall intensity (mm/h)}} \right)$$

It was then transformed to normalize its distribution and get a homogeneous variance by the following formula:

2)

$$\text{ARunOff} = 2 * \arcsin\left(\sqrt{\frac{\text{run off rate}}{100}} \right)$$

Daily rainfall data of Kondi station have also been used. The experimental period started at the end of the dry season so the last rain happened more than 140 days ago. Simulations continued in the wet season and less than 20 days separate those simulations from last rain. The variable LR (last rain) was created to distinguish these two cases.

Proc GLM procedure (SAS) was used to model run off as well as dissolved carbon and nitrogen concentration in the run-off water.

RESULTS AND DISCUSSION

Run off

The slope has no effect on run off (p-value = 0.74) but land use was found to have a great influence (Fig. 4). Run off is very high on skid trails (in average the runoff rate was 78 %) and very low on savannahs and firebreaks (respectively 1 and 3 %). Under eucalyptus plantations, run off variability was very high. As stand age and fire effect were not significant (p-value = 0.1 and 0.9), the variable land use (LU) was reduced to 4 classes: savannah, skid trails, firebreak, and eucalyptus.

FIGURE 4
Influence of land use and slope on run off rate

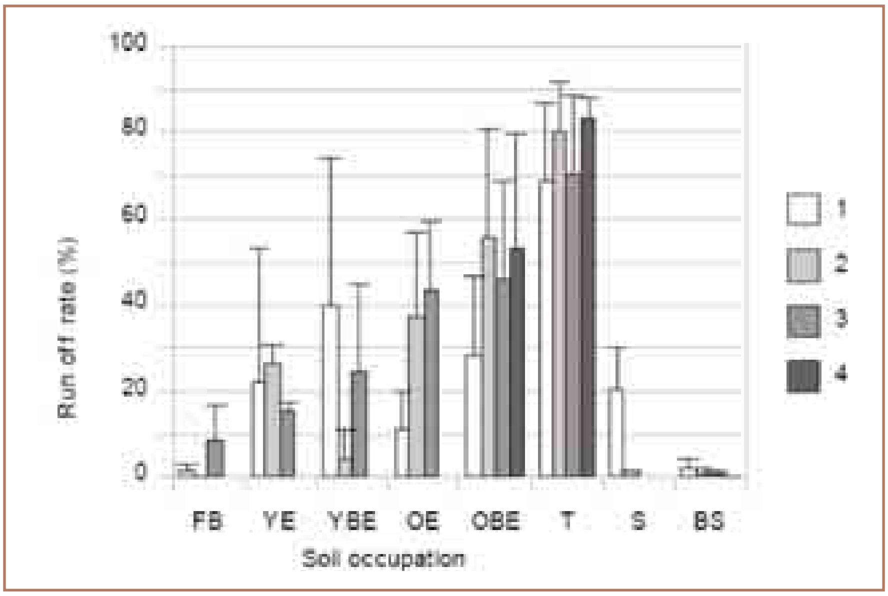
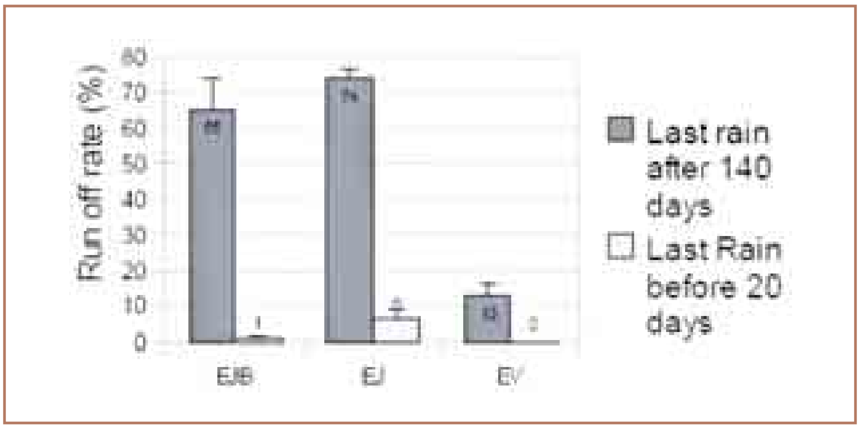


FIGURE 5
Influence of LR on run off rate, mean and standard deviation



The following model was finally obtained to explain run off intensity ($R^2 = 0.76$). It depends on LU, LR (Fig. 5) and bulk density (BD):

3) $$\text{ArunOff} = A_{(LU, LR)} - 1.84 * BD$$

Leading to the following equation for the run off rate model:

4) $$\text{Run off rate} = 100 * \sin^2\left(\frac{(A_{(LU, LR)} - 1.84 * BD)}{2}\right)$$

Values of $A_{(LU,\ LR)}$ are given in Table 3.

TABLE 3

Run-off rate model, parameter values of A depending on LU and LR

A(LU, Lr)	**Time span between the last rainfall and the experiment less than 20 days**	**Time span between the last rainfall and the experiment above 140 days**
Savannah[a]	2.27	2.93
Firebreak[a]	2.52	3.18
Eucalyptus[b]	3.49	4.15
Trail[c]	5.26	5.92

Dissolved carbon in run off water

The mean dissolved carbon concentration in run off (RunOffDC) is 23.2 ± 13.7 mg/L. Three variables explain the variability of this concentration:

WO = water origin. Because it was not possible to bring high quantities of pure water, the water used in the rainfall simulator was coming alternatively from the following sources: Kondi (K), Kissoko (KKO) and Pointe Noire (PN). Finally, there was a clear correlation between the dissolved carbon concentration in the runoff water (RunOffDC) and in the water used for the rainfall simulations (Fig. 6).

LR: If the last rain happened more than 140 days before the rainfall simulation, RunOffDC increases (Fig. 7).

SMST. The effect of SMST depends on the effect of LR. If the last rain happened more than 140 days before the rainfall simulation RunOffDC increases as SMST increases. But if the last rain was recent SMST has no effect on RunOffDC.

FIGURE 6

Carbon concentration in run off solutions and in the water used in the rainfall simulator. Influence of the water origin

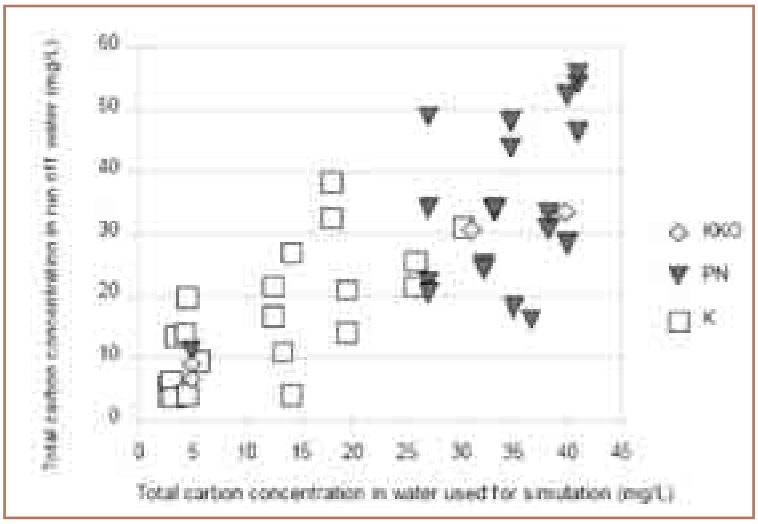
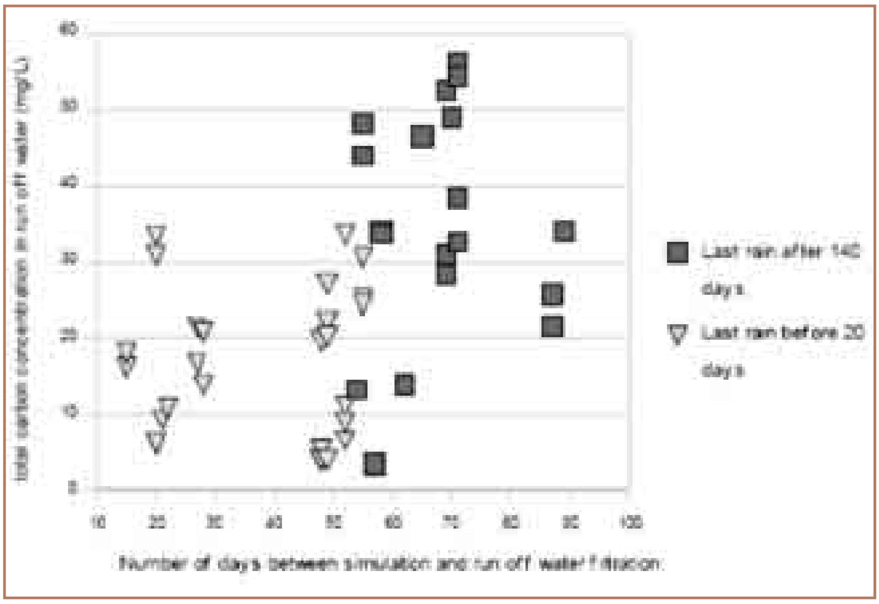


FIGURE 7

carbon concentration in run off solutions, influence of LR (time span between the last rain and the experiment) and SMST (solid matter stagnation time)



The model using these three variables explains 61 % of RunOffDC variability but it underestimated slightly the low values of RunOffDC. The final equation was the following:

$$\text{RunOffDC (mg/L)} = A_{(WO)} + B_{(LR)} * \text{SMST} \qquad 5)$$

The parameters values of $A_{(WO)}$ and $B_{(LR)}$ are given in Table 4.

TABLE 4

Model for the carbon concentration in the run-off water, parameter values of A and B

WO	A		LR	B
Ka	12.07		**last rain before 20 days**	-0.06
KKOab	23.02		**Last rain after 140 days**	0.2
PNb	27.72			

Total nitrogen dissolved in run off

The mean total nitrogen dissolved in run off is 1.53 ± 0.68 mg/L. This concentration is very close to the concentration in the simulation water (1.59 ± 1.14 mg/L). None of the studied variables helps to explain the variability of nitrogen concentration in run off.

Discussion

The main variable which drives run off intensity is land use. On skid trails run off was very high. There is an important risk of gullies on these bare and compacted soils. Conversely, run off rate was very low in savannahs even when facing regularly fires which destroy the vegetation. Savannah soils keep an infiltration capacity all over the year and are able to resist to maximum annual rain fall intensity. One explanation for this result could be due to termites: field observations show that there are a lot of termite hills in these coastal savannahs (Mboukou-Kimbatsa *et al.*, 1998) and these insects may contribute to keep soil macro porosity to high values.

Run off rate was also very low on firebreaks but simulations were done just after ploughing and this explains the great soil permeability and the low bulk density. It is necessary to redo simulations after the wet season to show if these bare soils resist well to rainfall erosivity; i.e. after the formation of the superficial crust that will reduce the permeability of the soil.

The soil of eucalyptus plantations were expected to be well protected from erosion because of (i) a quasi continuous mulch of litter (Kazotti, 2003), (ii) a modest understorey of herbaceous species (Loumeto and Huttel, 1997), (iii) a very dense root mat in medium to old stands, located at the interface litter – mineral soil (Laclau *et al.*, 2004) which could protect the soil against the aggressions of the energy of rainfalls and surface run off. However, we found that run off under eucalyptus can be high especially if the time span between the last rain and the simulation date was important. Theoretical infiltration capacity of Pointe Noire soils is about 7 m/h on soil superficial horizons (Damman, 2001). So run off is not the effect of soil saturation by water (Augeard, 2005).

Hydrophobicity could explain how the time span between the last rain and the experiment influences the run off. Strong water repellency was found under eucalyptus in dry season in the studied area (Laclau *et al.*, 2004) but also in Australia and in Portugal (Doerr *et al.*, 2000). Soil hydrophobicity is caused by a coating of long-chained hydrophobic organic molecules on individual soil particles. These hydrophobic molecules can come from the standing vegetation or from the organic matter during the mineralization or after a fire. Water repellency can increase run off from 6 to 100 times in comparison with similar soils without hydrophobicity (Doerr *et al.*, 2000).

After a long drought period soil under eucalyptus must have a strong hydrophobicity and run off is enhanced. During the first rains of the wet season, hydrophobicity decreases slowly and restores the infiltration capacity of these sandy soils. However the relation between rainfall and hydrophobicity is poorly understood (Doerr *et al.*, 2000) so it would be interesting to quantify the water repellency (Letey, 1969) under eucalyptus at the transition period between dry and wet season to confirm this result.

Run off rate decreases when bulk density increases on skid trail and on eucalyptus modalities. This result is counter intuitive because a high bulk density should result from a high soil compaction and consequently the infiltration capacity should decrease with the bulk density. The trend observed in our study is exactly the reverse. We interpret this as peculiar to sandy soils where a high bulk density can also be interpreted by a high sand content which is weightier than clay or silt resulting to a better infiltration capacity.

Slope was found to have no effect on run off intensity. This result is surprising but the slope in the forest area was not much pronounced (5 to 20%) and we can not exclude an experimental bias: the length of soil surface used for rainfall simulations could be too short (1m) to deal with propagation which is, after initiation, the second process of soil erosion. However some studies also showed that slope gradient influence on run off is not obvious (Roose and de Nonni, 2004).

Evaluating risks of carbon and nitrogen losses by dissolution in run off water is difficult because the water used to simulate rainfall had a high carbon concentration and none of the field measurements and laboratory analyses explain the variability of dissolved nitrogen in run off. The C and N concentration are not so different between run off and water used for simulation. At this step it is not possible to determine if natural rainfall water free of these two elements may increase dissolution from the soil or if anyway run off speed is too high to permit exchange between soil and water.

CONCLUSION AND PERSPECTIVES

The method used is well adapted to that kind of studies because large range of land use can be studied in a restrictive time. Around 4 to 6 simulations a day can be done if places studied aren't far each other and if a water source can be found near each experimental site. So this method is relevant to establish the influence of land use on soil erosion and soil nutrients but rain drop energy of simulated rain has to be studied to determine to what extent it reflects real rain.

There was a clear effect of land use on run off intensity. It was low on fire breaks and savannahs whereas it was high on skid trails. There was no effect of slope and fire occurrence. For eucalypt plantations, run-off rate was highly variable and was mainly depending on hydrophobicity which was roughly assessed by the time span between the last rainfall and the experiment. Carbon concentration in the run-off solutions was determined by the origin of the water, hydrophobicity, and also the solid matter stagnation time between simulation and water filtration.

Nitrogen concentrations were not statistically different from those of the water used for the simulations. Chemical soil properties and soil textural distribution will help to enhance understanding of land use effect to run off intensity. As it seems to be one of the main process influencing run off under eucalypt plantation correlations between hydrophobicity, climate seasonality and run off intensity has to be studied. Then in complement of dissolved elements losses, both physical and chemical analyses of solid mater losses by run off will help to evaluate soil degradation sensitivity of the study area.

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Helping small scale tree farmers in Africa participate in carbon trade

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ABSTRACT

On-farm tree planting projects in Africa can lead to sustainable development and at the same time contribute to the global effort to stabilize Greenhouse Gases (GHG) levels in the atmosphere. Trees can provide sinks of atmospheric carbon dioxide and the carbon credit accruing from such programs can be used to offset carbon emissions in industrialized countries whose emission levels have been capped. Many countries in Africa have met the requirements under the United Nations Framework Convention on Climate Change (UNFCCC) for hosting forestry projects under Clean Development Mechanism (CDM). A study was carried out in Kenya to assess whether the smallholder tree farmers are capable of participating in carbon-offset projects. The study established that opportunities exist for smallholder tree farmers to incorporate carbon offset as a tree product and participate in CDM and Voluntary Carbon Offset (VCO) markets. Currently farmers have been able to stock on average 11.23 tons of carbon per farm with a market value of US$ 224.. There exist networks in form of co-operatives and farmers groups which farmers can use to market their carbon stock.

Keywords: Climate change, Carbon credits, Carbon stock

INTRODUCTION

Carbon dioxide, a major component of greenhouse gases, is reported to be accumulating in the atmosphere at a rate of about 3.5 billion tons per annum as a result of fossil fuel combustion and tropical deforestation. In light of the potential negative socioeconomic and environmental consequences likely to visit the global community, the 1992 United Nations Conference on Environment and Development (UNCED) agreed to a convention on climate change to stabilize GHG levels in the atmosphere at a level that would not cause dangerous changes in the global climate (FAO, 2001). The UNFCCC was conceived to coordinate the programmes to stabilize GHG levels.

At the third conference of the parties to the UNFCCC in 1997 in Kyoto, Japan, (Kyoto Protocol), a set of nationally differentiated emission targets of greenhouse gases were agreed, subject to ratification, for industrialized economies for the first commitment period between 2008 and 2012 (IPCC,

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2001). Signatory nations agreed to reduce green house gases emissions to an overall average of 5.2 % below 1990 levels. No emission reduction targets were assigned to developing countries.

In Africa, on-farm tree planting can be an important carbon sequestration strategy due to its huge carbon storage potential in plant materials and its applicability in agricultural lands. By planting trees on farm, farmers can raise their land productivity through the added sale of the tree crop and improved productivity of associated crops. Trade in carbon credits from carbon sequestered in the tree crop can provide an extra benefit to farmers.

There are many parts of Africa that consists of fragile ecosystems and are generally inhabited by poor households. Some of these areas are currently characterized by poor and erratic rainfall that leads to poor crop productivity. Continuous cropping in these fragile ecosystems and extensive vegetation clearing has resulted in severe land degradation. Addressing the problem of the high poverty level, declining crop yields and wanton environmental degradation requires exploration of all opportunities to raise land productivity, ecosystem restoration and improvement of the livelihoods of the inhabitants. Tree farming presents an appropriate opportunity to raise land productivity and arrest land degradation in these areas. Carbon sequestered by growing trees is a recognized tradable environmental output among other tree products and can be used to boost income levels from the tree component of farm forestry systems. However, information on the amount of carbon available for purposes of exploiting opportunities presented by CDM is scanty to guide both farmers and investors willing to participate. Requisite information on the abilities of farmers to participate in carbon trading is very crucial but is lacking to guide participating governments and policy makers. This information is important as the process is governed by rules that both host governments and investors must conform to.

MATERIALS AND METHODS

Study area

The study was carried out in Siakago division in Mbeere district, Eastern Province of Kenya. The district falls mainly within the Lower Midland 5 (LM5) agro ecological zone (Jaetzold and Schmidt, 1983). The average annual rainfall is 700 mm and the mean temperature is 21^{0}C. Small scale crop farming and rearing of livestock are the main pre-occupation of the farmers (Ministry of Planning, 2002). The division has a population average density of 95 persons per km^2. There is high level of poverty that characterizes the division with 60% of the population living below the poverty line (Ministry of Planning, 2002).

Data sources

Both primary and secondary data were used with the secondary data being obtained from government offices, local non-governmental organizations and local leaders. Primary data was obtained through interviews of farmers and key informants. Observation walks were carried out. Semi-structured interviews were used to collect data from household heads and key informants. For purposes of assessing the amount of carbon resources within the farm, actual measurements of trees on farm were carried out to determine biomass accumulation. A total of 250 farms were sampled for the administration of the questionnaire. This number formed the basis for which the attributes to the community and land holdings as a whole were estimated. Twenty six farms were further randomly sampled to estimate the amount of above and below ground carbon sequestration under different on-farm tree planting methods.

Carbon sequestration was determined by calculating the biomass of different tree species and ages within the farm holdings and under different tree planting methods. Individual tree parameters that were collected in the field included tree species, diameter at breast height (DBH), tree height and root collar diameter for seedlings below 5 cm. The number of trees under each farm forestry technology was also collected. Tree biomass was calculated using established allometric equations that rely on empirical relationship between the tree diameter and above ground biomass developed by Brown *et al.* (1989). The constants and coefficients used are those developed for areas with rainfall less than 1500 mm per annum. The above ground biomass was calculated using the formula:

$$Y=34.4703-8.0671DBH+0.6589DBH^2$$

Where Y= biomass in kg per tree

DBH= diameter at breast height

This method was applicable for tree of DBH of 5 cm or more. The above ground tree carbon was estimated at 50% of the total above ground biomass as recommended by MacDicken (1997). Below ground biomass was estimated at 10% of above ground biomass as recommended by Hamburg (2000) for tropical ecosystems. Once the total biomass and carbon amounts were calculated for individual farm holdings, the quantities were divided by the area of the farm holdings to get the production per acre. For purposes of valuation, a value of US $20 per ton of carbon that is normally used in World Bank calculations was employed. This value is rather high for CDM projects, perhaps it will fit to voluntary markets?

RESULTS AND DISCUSSIONS

To be rigorous with CDM one should deduct **emission** generated by planting activities if any (Synthetic fertilizers, fuel consumption) from total amount sequestered by trees.

Available carbon stocks within the farms

All the farm holdings sampled can be classified as smallholder afforestation and reforestation project activities within the CDM definition. This makes them eligible for the simplified assessment and monitoring procedures awarded to low income smallholder carbon producers under CDM in view of their subsistence nature, low individual carbon stocks and the need to provide a mechanism to reduce transaction costs that go with the process. The combined accumulated carbon stock within the 26 sampled smallholder farms was 291.96 tons (Tab. 1). Using the upper end market price of $20 per ton of sequestered carbon, the market value of the carbon sequestration resources within the sampled farm holdings is equivalent to US$ 5,825.2. The average carbon sequestration level per farm holding is therefore 11.23 tons with a market value of US$ 224.

TABLE 1
Carbon sequestration levels in the sampled farm holdings in Siakago division

Number of farms.	Above ground Biomass (Kg)	Above ground carbon (Kg)	Below ground carbon (Kg)	Total carbon (Kg)	Total carbon (Tons)
26	530,840.48	265,421.24	26,542.12	291,963.37	291.96
Average	20,416.94	10,208.51	1,020.85	11,229.36	11.23

Smallholder tree planting project activities, as defined within CDM, are expected to result in net anthropogenic GHG removal of less than 8 kilotonnes of carbon dioxide per year and implemented by low-income communities and individuals. This allows them to enjoy simplified assessment and monitoring procedures (IPCC, 2001). Average annual carbon sequestration per hectare within the farm holdings studied is about 2.08 tons per hectare which compares well with the Watson *et al.* (2000) average carbon sequestration rates range of 1.5 to 3.5 tC per ha for smallholder farm forestry systems in the tropics. Based on average tree age and carbon sequestration values within the farms, it was found that average annual sequestration for each farm holding within the study area was 1.39 tons valued at US$ 27.8. In an area where extreme poverty levels have been estimated at 60%, carbon sales are then likely to boost family incomes by providing an extra output from the trees.

Further analysis revealed that a maximum of 712 smallholder farmers would be required to achieve the 8,000-ton threshold carbon. This provides an opportunity to the farmers to jointly participate in the programme and reduce the transaction costs. To put the figures in perspective, between 10 and 15 small-scale farm forestry projects would be required to cover the whole of Siakago division. This may result in high transaction costs (Roshetco *et al.*, 2002; Cacho, 2003). The challenge therefore is to develop bundling mechanisms to reduce the costs. It may be necessary to identify intermediaries for carbon trading and to decide how to share costs and benefits.

Carbon Sequestration within different tree planting designs

Boundary planting was reported to be the most preferred option for tree establishment in the study area (Tab. 2). With a total of 175 tons of carbon sequestered under this system and a total carbon value of US $ 3,500, boundary planting represents 61% of the total carbon resources sequestered within the farm holdings in Siakago division. Inter-planting of trees with food crops and establishing woodlots are also popular tree planting methods in the area where there is a combined total carbon stock of 78.54 tons valued at US$ 1570.8. Other tree planting methods practiced in the study area include windbreaks and homestead planting. The tree species that is most popular in the area is *Grevillea robusta* and has sequestered 52.25% of the total carbon stock. It is a fast growing species making it highly preferred by farmers.

TABLE 1

Carbon sequestration levels in the sampled farm holdings in Siakago division

Tree planting method	Number of Trees	Total carbon (Tons)	Price per Ton(US$)	carbon value (US$/ technology)
Boundary planting	3,793	175.00	20	3,500
Homestead planting	560	23.14	20	462.8
Inter-planting	819	43.93	20	878.6
Windbreak planting	318	14.37	20	287.4
Woodlots	949	34.61	20	692.2

Other tree species grown include *Senna siamea* and *Melia volkensii*. They are also fast growing and have superior wood quality for timber, poles and fuel wood. They are also becoming popular with farmers but the main problem with *Melia volkensii* is seed germination.

CONCLUSIONS

Farmers in Siakago division are eligible to participate in small-scale CDM project. This would allow them to enjoy simplified baseline and monitoring methodologies and make their participation in the CDM process easy and cheaper. This methodology will also allows bundling of project activities and thus enables farmers within the area to participate as a group for further reduction in individual costs and easy access to education materials. Tree species selections, as currently done by smallholder farmers for incorporation within the agricultural systems, are suitable for raising overall land productivity and do not compromise food security. *Grevillea robusta*, *Senna siamea*, *Melia volkensii* and other trees species that are promoted within the area are appropriate for incorporation into the farmlands as they are fast growing, easily coppice, enhance overall land productivity and promote positive ecological and economic interactions within the farming system. Within the UNFCCC under which CDM activities would operate, the tree species satisfy the definition of a tree as contained in the Kenyan communication, promote biodiversity conservation and possess important attributes for sustainable development.

Tree planting, as practiced in the area, fulfils the additionally requirement of CDM projects by providing verifiable carbon credits beyond those achieved by original land use while, at the same time, encouraging carbon credits that are secure over a long time. On-farm tree planting is also unlikely to result in any significant project leakage as it puts emphasis on diversification and sustenance of household incomes.

Significant carbon stocks exist within the small holder farms and have accumulated mainly after year 2000 with average carbon sequestration level per farm holding at 11.23 tons with a market value of US$ 224.6. These stocks could be used as residue stock for purposes of initiation of carbon offset projects for participation within CDM. Under the current rules for small-scale carbon offset projects, tree-based carbon stocks do not form part of the baseline scenario and would therefore qualify for issuance of Certified Emissions Reductions (CERs). These stocks can act as incentives for more investment in on-farm tree planting.

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Demonstration projects and developing capacities in Africa

Adapting with tropical forests to climate change in Sub-Saharan Africa

Nkem, J. N.[1]

ABSTRACT

This paper discusses the importance, and the use of tropical forests for climate change adaptation and the implications of tropical forest management for achieving both mitigation and adaptation to climate change. The paper uses research activities of the Center for International Forestry Research on the role of forests for climate change adaptation in West and Central African regions. As an ecosystem providing multiple forest goods and services to multiple stakeholders, prioritization of what should be the focus for adaptation, was found to be crucial in building consensus among the stakeholders for planning adaptation in shared resource systems especially when undertaken through a participatory approach. The results point to the need for prioritization in approaching climate change adaptation using forest which should be conducted with the participation of the stakeholders. The pattern of tenure systems in the region require their integration in the planning of adaptation using forest goods and services. The different tenure systems have their comparative advantages in the provision of goods and services, besides the development of a co-existence framework that reduces vulnerability. The predominant public ownership of forest require institutional and policy evaluations to guide reforms that improve flow and accessibility to essential resources to reduce vulnerability. There are limited household benefits noted in trade revenues from forest commodities in market systems managed by the local communities following the distribution of the revenue in the market chain of some non-timber forest products (NTFPs). In encouraging synergy between mitigation and adaptation in forest ecosystems, a combination of approaches involving financial incentives and community asset bases held in forest ecosystems will need to be considered in the planning.

Keywords: erosion, run off, sandy soils, rainfall simulations.

INTRODUCTION

The severity of climate change impacts in Africa is well established (IPCC, 2007) especially on the poorest majority of the population. Tropical forests constitute an inseparable resource-base for both national development and household livelihoods in Sub Saharan Africa (Belcher *et al.*, 2005). The dependency on forests is only likely to soar in the region as climate change impact other sectors

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e.g. agriculture, water resources, hydro-electricity, medicinal products etc increasing the dependency of local communities on their safety nets in forests (Dudley *et al.*, 2008). Forests are also experiencing large scale changes through expanding human population and livelihood activities, economic growth and changes in consumption patterns which are affecting both their integrity and resilience (Polasky *et al.*, 2008) that could amplify their vulnerability to climate change impacts especially under certain management practices. Forests in Sub Saharan Africa for example, are experiencing deforestation rates of more than 1% annually in some place (FAO, 2007), which further diminishes the potential in achieving the global goal for the stabilization of greenhouse gas emission (UN, 1992).

As capital assets (Daily *et al.*, 2000) under proper stewardship, forests will generate the flow of multiple goods and services often shared by many individuals, communities and nations. Like in any coupled human-environment system, climate impacts are likely to generate some feedbacks in the system that could potentially affect the flow of ecosystem goods and services (Chan *et al.*, 2006; Lamb *et al.*, 2005; Tallis *et al.*, 2008). Some of the feedbacks could lead to mal-adaptation. Typical examples are 'slash-and-burn' agricultural practices that often lead to the loss of other resources held in the forest.

Land tenure is crucial for African adaptation to climate change not only as a cause of conflict, but also in the role of government in forest-based adaptation as the predominant landlord. The type of ownership, rights and access to resources can contribute to the vulnerability of communities who depend on forest resources (Sunderlin *et al.*, 2008).

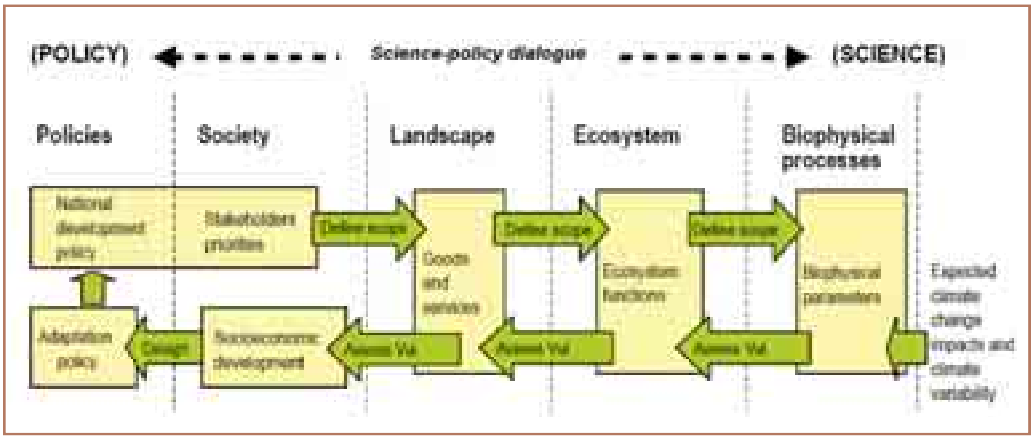
There is urgent need for adaptation measures following the scientific establishment of the severity of climate impacts on Sub Saharan Africa (IPCC, 2007). Response actions are required and should entail all available means and opportunities for adaptation those building on local skills and knowledge-base of communities in managing natural resources familiar to them. This is important in minimizing new risks and complexity in the process of responding to the new challenges with adaptation measures. The objective of the paper is to highlight the importance, and the use of tropical forests for climate change adaptation and the implications of tropical forest management for achieving both mitigation and adaptation to climate change.

MATERIALS AND METHODS

This paper is based on the research activities of the Center for International Forestry Research (CIFOR) on tropical forests and Climate Change Adaptation in West Africa (Mali, Burkina Faso, Ghana) and in the Congo Basin Forests of Central Africa (Cameroon, Central African Republic, Democratic Republic of Congo) using a common methodological framework approach. The methodological framework is designed to capture the interactive and dynamic coupled human-environment system which is commonly the case with ecosystem-based adaptation approach used in the research. The design is characterised by a science-policy dialogue process as the platform for stakeholders' engagement for participatory actions throughout the implementation process. As a dynamic feedback process, the design represents a collection of inter-connected activities along the project implementation chain in a cyclical pattern (Fig. 1).

FIGURE 1

The framework for the implementation of the project



The research commenced with the identification of potential stakeholders and partners. This was followed by engagement and consultations of the stakeholders to firstly introduce and explain the objectives of the research and the potential relevance to the household, local communities, and at the national and regional levels. This enabled the constitution of a list of stakeholders in establishing a science-policy dialogue forum.

The participatory approach was used in setting up the agenda and planning the implementation activities with the stakeholders. This guided the process of identifying and prioritizing the sectors or areas of regional interest, following their relevance to livelihood, national development and perceived by the stakeholders to be highly vulnerable to climate change. The scope of the prioritised sectors was defined by the ecosystem goods and services linked to the sectors across the landscape, and how the state and functioning of the ecosystem will affect the provision of these ecosystem goods and services. Biophysical parameters were used in characterising the biophysical processes underlying ecosystem functions and these were evaluated under current and expected climate impacts and climate variability taking into consideration uncertainties.

Expert judgement and analyses were also used throughout the project. Questionnaires were used in conducting local market survey and collecting data on the trade of non-timber forest products (NTFPs) trade in two provinces (Equateur and Bandundu) of the Democratic Republic of Congo. A matching analysis of the corresponding market activities in non timber forest products (NTFPs) and the prioritized development sectors for adaptation was carried out.

RESULTS AND DISCUSSION

The prioritized sectors for adaptation linked to the forest turn out to be the same (Tab. 1) in West and Central Africa. These sectors included woodfuel, potable water, and NTFP for food for human and livestock, and medicinal plant parts. These were all provisioning ecosystem services. Although the prioritization referred to development sectors linked to the forest, corresponding ecosystem services were identified (Tab. 1) using the Millennium Ecosystem Assessment (MEA, 2005). Forest ownership was predominantly by the government. In the Congo Basin Forests for example, there is just below 1% of designated forest land to the community, 10% as protected area, and 36 % as concession area primarily for logging (Fig. 2). The role of markets following trade in five NTFPs (Charcoal, Gnetum spp., caterpillar (larvae), mushroom and kolanuts) showed significant variations in the prices of the farmer, wholesale and retail of all the NTFPs surveyed. The farmers' price was the lowest for the NTFPs and almost twice as low for some of the products.

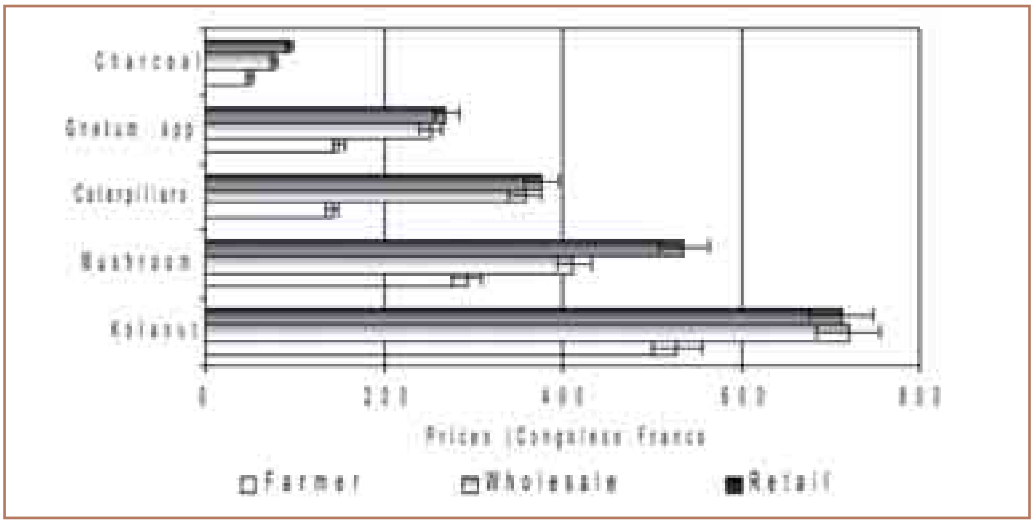
TABLE 1

The prioritized sectors in West and Central African regions and their corresponding ecosystem services (MEA, 2005)

Regions	Prioritized Sector	Ecosystem Services	Type of services
West and Central Africa	a. Water	Fresh water	Provisioning
	b. Wood fuel	Fiber (wood fuel)	Provisioning
	c. Non-timber forest products		
	- Foods	Foods	Provisioning
	- Medicinal	Biochemicals, natural medicines & pharmaceuticals	Provisioning

FIGURE 2

Comparison of farmer earnings to wholesale and retail prices of five top NTFP sales at the local market in two provinces of DRC



Planning adaptation using participatory approach and a science-policy dialogue forum requires common understanding by the multi-stakeholders with multiple disciplinary backgrounds. Having matching equivalences of the key messages and terminologies is crucial in the science-policy spectrum. Some stakeholders of policy and development backgrounds relate to, and regard ecosystem services as, sectors related to livelihoods. Some sectors could actually represent an ecosystem service (MEA, 2005) and in other cases, could be surrounded by a number of ecosystem services. Thus, making their connections evident or defining their equivalence is important in using ecosystem services for planning adaptation strategies and keeping the stakeholders at the same level of comprehension. Besides communicating, conducting an assessment of the sectors this is feasible using the ecosystem services especially quantitative assessments.

The preferences of the two regions for provisional ecosystem services for adaptation fall along the same line of the development challenges in sub-Saharan Africa some of which are related to the Millennium Development Goals. In West Africa for example, the long history of drought and desertification with significant impacts on water and food explains the emphasis on provisioning ecosystem services especially fresh water. The implication is that adaptation in Sub Saharan Africa has more to do with coping with resource degradation that is affecting human development and community resilience to climate change even of low impacts. Following the results, the ecosystem-base adaptation approach of this study, is the more applicable adaptation approach for sub-Saharan Africa in addressing the main sources of vulnerability amplifying climate impacts even when the impacts might be low. Although the approach puts people and the community as the central focus, environmental aspects are also addressed as a coupled human-environment system.

Understanding community preferences in ecosystem services is crucial in designing and undertaking forest-based activities including climate change responses like REDD, that garner the support of the community. The sectors prioritized for adaptation to a certain extent, represent asset bases of the community as the motivation for their selection rather than simply sources of income. Therefore, cash incentives might not easily substitute community preference for these ecosystem services since that was never a motivation in the first place.

The role of market revenue from forest products for adaptation to climate change needs to be carefully reviewed prior to integration into adaptation planning. Following the analysis of the markets in NTFPs connected to the sectors, none of the prioritized sectors were market-driven sectors that primarily depended on revenue generation for their use. The sectors mostly represented need-base sectors crucial for adaptation rather than their monetary values although some get to the market place. The market prices for farmers was the lowest compared to the wholesale and retail prices which raises doubts of the potential impacts of market instruments for community based adaptation. Market use by local communities is a challenge (Scherr *et al.*, 2003). This will have major implications for REDD even if local communities rather than government were directly responsible in managing the scheme.

From a policy perspective, the ecosystem approach of this study has provided a platform to facilitate engagement between government and local community groups which is not always necessarily present in some of the regions. Planning the future in partnership improves the likelihood of fostering the resilience and adaptive capacity of the eco-social systems. Furthermore, it emphasizes the role of stakeholders in the process, which falls in the category of 'participation by consultation' as described by Walker *et al.* (2002). The approach however depends on the specific national forest policies, institutions, ownership structures, ecosystems, laws, and other national circumstances to enhance the process.

The ecosystem approach of this study also provides the opportunity for integrating human and ecological priorities into development programmes that require comprehensive strategies for the utilization of forest systems in pragmatically addressing multiple developmental goals such as poverty reduction, food, energy security and community resilience to shocks.

CONCLUSIONS

Forest has a central place in African response to climate change by safeguarding the lifeline for the weakest links in the community. Under state ownership of forestland with custody over the principal resources, African governments owe an obligation and special responsibility in ensuring the adaptation of forest-dependent communities to climate change impacts since state ownership limits the intuitive space and flexibility for reactive or proactive responses. Entrusting and empowering local communities with the responsibility for their adaptation would require policy and institutional reforms that facilitate accessibility to forest resources in a coordinated fashion.

In the phase of rapid resource degradation, adaptation urgently needs mitigating climate change impacts on the forests for the continuous provision of ecosystem goods and services required for adaptation. However, under limited regional case studies, there is need for caution in the implementation of mitigation schemes such as REDD, because there is no assurance that the beneficial effects of the revenue from the scheme, will be transferred to the household level adaptation.

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Sustainable production intensification in Africa — a climate change perspective

Friedrich T.[1]

ABSTRACT

Over the next few decades food production will need to be doubled in response to increasing food demand by a growing population. On the other hand the natural resource base for agricultural production is showing increasing signs of degradation. These problems are even more pronounced in Africa. In the past highly intensive agricultural production took a heavy toll on the environment, which was accepted as unavoidable collateral damage, while agriculture which was less damaging to the environment was less productive. The new paradigm of "sustainable production intensification" is recognizing the need for a highly productive agriculture which at the same time positively contributes to environmental services as an element of sustainability.

With regards to climate change this refers to the reduction in the contributions of agricultural production systems to greenhouse gas (GHG) emissions. Adequate agricultural production techniques, based on minimum disturbance to the soil (no-till) and enhancement of aerobic conditions in soils can reduce emissions and eventually lead to the sequestration of carbon in soils reaching 0.25-2.5 bill t/year. The reduction in GHG emissions results from enhanced efficiency that reduces losses of production inputs and carbon, without sacrificing high production levels. Sustainable production intensification, based on concepts such as Conservation Agriculture, provide opportunities for adaptation to climate change. With these perspectives, Conservation Agriculture has a particularly high potential in addressing the problems of African agriculture. Harnessing the potentials of conservation agriculture for carbon sequestration and reduction of GHG emissions through the payment of environmental services to farmers, would provide further incentives to farmers in changing to this new way of agriculture.

Keywords: Climate change, Conservation Agriculture, Sustainable Agriculture, Carbon Sequestration, Adaptation

INTRODUCTION

By 2030, food production has to double in order to satisfy the increasing food demand of a growing world population in qualitative and quantitative terms (FAO 2002). In addition to this demand for food, there is an increasing demand for the production of renewable resources, including bio-energy, using the same

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natural resources as food production. So far food production in Africa has only grown at half the rate as the demand. This has direct impacts on rural livelihoods, since over 65% of Africa's population still lives in rural areas depending on agriculture. Presently, the farming systems in Africa are mostly unsustainable. Yield levels by small farmers are very low yet there is an over exploitation of the natural resources, leading to land degradation as one of the major limiting factors for agricultural production in Africa.

The principal element for the unsustainable use of natural resources leading to soil degradation is the destruction of soil organic matter by burning, uncontrolled grazing and intensive soil tillage. This under climate change scenarios leads to increased vulnerability resulting in either increasing incidence of drought periods on the one hand or extreme precipitations on the other (Shaxson et al. 2008).

SUSTAINABLE PRODUCTION INTENSIFICATION THROUGH CA

The new paradigm of "sustainable production intensification" recognizes the need for highly productive agriculture which at the same time does not only conserve the natural resource-base and the environment, but also positively contributes to environmental services as an element of sustainability. One of the most promising technical options to achieve such sustainable production intensification is Conservation Agriculture (CA). CA is currently defined by the UN Food and Agriculture Organization (FAO) as follows (FAO 2008):

CA is a concept for resource-saving in agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. CA is based on enhancing natural biological processes above and below the ground. Interventions such as mechanical soil tillage are reduced to an absolute minimum, and the use of external inputs such as agrochemicals and nutrients of mineral or organic origin are applied at an optimum level and in a way and quantity that does not interfere with, or disrupt, the biological processes.

CA is characterized by three principles which are linked to each other in a mutually reinforcing manner, namely:

1. Continuous no- or minimal mechanical soil disturbance (i.e. direct sowing or broadcasting of crop seeds, and direct placing of planting material in the soil);

2. Permanent organic-matter soil cover, especially by crop residues and cover crops; and

3. Diversified crop rotations in the case of annual crops or plant associations in case of perennial crops, including legumes.

While the principles of CA are not new at all, the simultaneous application is creating the above mentioned synergy effects by strengthening the advantages and reducing the downsides of each single technology. In this way the simultaneous application of the principles of CA results in benefits greater than the sum of the single technologies. Zero tillage reduces the mineralization of soil organic matter (Reicosky 2001). In addition to this, the soil habitat remains undisturbed and soil life can develop in quantity and quality better than on tilled soils. Vertical continuous macro pores as created by earthworms or roots are not destroyed and remain as drainage channels for rainwater into the subsoil. By not disturbing the soil, the weed seed bank in the soil does not receive the stimulation for germination. This can be perfected even during the seeding process by furrow openers with minimum soil movement allowing the "invisible seeding". The permanent soil cover protects the soil surface from wind, rain, sun and from drying out. In addition the mulch suppresses the germination and growth of weeds, provides habitat for beneficial fauna and feed for the soil life and hence the substrate for the creation of soil organic matter. Allelopathic or other repellent effects of specific covercrops can be used for weed and pest management. The treatment of the mulch cover therefore is part of the weed management under CA. Crop rotation is of particular importance with regard to zero tillage and permanent soil cover. Different crop species with different root systems explore different soil horizons and hence increase the efficiency of the use of soil nutrients. In addition to this a diversified crop rotation is beneficial for avoiding pest and weed problems (Anderson 2005). When designing the crop rotation it is important that the entire growth period is used by growing some crop, if only for cover.

The synergy effects resulting from the simultaneous application of the CA principles have positive impact on productivity, efficiency of input use as well as on environmental effects and economic profitability of the production system. Soil erosion is reduced to a level below the regeneration of soil. In some cases the soil is literally growing. Under humid temperate conditions soil growth rate can be up to 1 mm/year within 30 to 50 years, during which the soil organic matter level reaches a new balance (Crovetto 1999). Under humid tropic conditions the input of organic matter in the system will need to be higher to achieve comparable increases in organic matter, but also under those conditions carbon sequestration is possible (Bayer *et al.* 2006). Depending on the supply of organic matter and climate conditions the increase in soil organic matter content can reach 0.1-0.2% /year mainly in the top 20 cm soil layer. Soil structure is improved, soil volume available to root growth is increased, providing access to more soil nutrients and improving the fertilizer efficiency (Bot and Benites 2005).

While Conservation Agriculture is reducing farm power requirements in general, this implies that for a farmer working manually, there is a potential to save 30 – 50 % of the time normally spent for farming. Labour intensive activities such as hoeing and weeding are significantly reduced or even eliminated. With this CA is providing the weak with a chance for farming in maintaining their livelihoods. Although CA cannot fight against HIV/AIDS, it can enable the affected people to mitigate the impact of the disease on their farming income (Bishop-Sambrook 2003). In general CA makes agriculture less unattractive, as it removes the drudgery and improves farm profit. Since it improves the options for diversification of the farm enterprises, CA has also the potential to revert the migration to urban centres by providing the young generation with new opportunities.

The availability of extra time allows investing into more profitable occupations other than agriculture. This is particularly important for small farmers who cannot make sufficient profit from their farm for a comfortable life. The extra time might also be used for value adding and processing activities within the agricultural production and food chain. The overall income of CA farmers increases and allows for the purchase of household goods or even better houses which improves their lives significantly. In many rural areas where CA has been introduced this is an important factor of empowerment for the rural women. Last but not least, the extra time might allow sending children to school that would normally have to work on the farm (Lange 2005).

The long term results on the production side are a steady increase in the yields with reduced need for inputs. In some cases, spectacular yield increases could be observed from the first year (FAO 2001). Technologies, although not always readily available in Africa, exist for CA at any farm size and mechanization level, from manual hand held equipment through animal traction to fully motorized tractor driven equipment.

CA is spreading in many areas of Africa and particularly in eastern and southern Africa, where it is promoted by FAO and the African Conservation Tillage Network. Building on indigenous and scientific knowledge and innovative equipment design from Latin America, farmers in at least 14 countries are now practicing CA (in Kenya, Uganda, Tanzania, Zambia, Swaziland, Sudan, Madagascar, South Africa, Zimbabwe, Mozambique, Ghana, Burkina Faso, Morocco and Tunisia). In Zambia alone, between 70 000 and 100 000 smallholder farmers are practicing CA (Rumley and Ong, 2007). In the specific context of Africa (where the majority of farmers are resource-poor and rely on less than 1 ha, and there is food insecurity, degradation of soil fertility, drought and irregular rains, shortage of human power for agricultural labour) CA systems are very relevant for addressing the old as well as the new challenges of climate change, high energy costs, environmental degradation, sustainable intensification paradigm other than the standardized tillage-based "green revolution" types relying on the inefficient use of purchased inputs of agro-chemicals. In Africa CA should respond to growing food demand by increasing food production while reducing negative effects on the environment and energy costs, and develop locally adapted technologies that are consistent with CA principles. (Kueneman *et al.*, 2007). A huge potential exists for the adoption of CA in the moist savannah areas. No-tillage systems have also been promoted in Northern Africa under arid conditions, particularly in Morocco and Tunisia. In Tunisia the promotion and development was farmer centred and the area under No-tillage increased from 27 ha on 10 farms in 1999 to nearly 6000 ha on 78 farms in 2007 (Baccouri, 2008). Officially there are several organizations promoting CA in Africa, such as the African Conservation Tillage Network (ACT), the Alliance for a Green Revolution in Africa (AGRA) and others. In 2005 Kenya hosted the 3rd World Congress on Conservation Agriculture.

AGRICULTURE AND CLIMATE CHANGE

Agriculture is both, a significant contributor to climate change with a share of nearly 30% of the global green-house gas emissions (including those from deforestation and land use change). On the other side managed soils are among the largest carbon stocks on earth and can be harnessed for further carbon sequestration and climate change mitigation through adequate agricultural practices (IPCC 2007). Of the 5 bill ha in total of managed land (crop and pasture) with a potential to sequester 0.25-2.5 bill t C/year, 20 % are in Africa.

In addition to carbon sequestration, CA can reduce the emissions of fossil fuels compared to conventional agriculture by up to 60% (Doets *et al.* 2000). Furthermore, the use of fertilizer and agrochemicals can be reduced in the long term by 20%. Even the capital investments in heavy machinery such as tractors can be reduced by 50% (Baker *et al.* 2007; Bistayev 2002). This would also reduce the emissions resulting from the production of these inputs. However, the largest contribution to mitigate climate change with CA can be obtained from carbon sequestration and the storage of atmospheric carbon in the soil. The levels of carbon to be captured in the soil vary depending on climate and production system. The above mentioned increase of organic matter by 0.1 to 0.2% in the top 20 cm result in an amount of organic carbon capture in the soil of 0.1-0.5 $t.ha^{-1}.y^{-1}$ on average under humid temperate conditions,. Under semi arid or tropical, including humid, conditions, these levels decrease to about 0.05-0.2 $t.ha^{-1}.y^{-1}$ (Baker *et al.* 2007). This process continues for 25-50 years before a new balance is reached (Reicosky 2001). Even the emissions of other greenhouse gases such as methane and nitrous oxides can be positively influenced by a change in the cropping practices to CA. These gases occur as traces but have much stronger effect as greenhouse gases than carbon dioxide. Methane for example is emitted from rice fields under anaerobic conditions. CA would change the rice soils into a more aerobic environment without permanent flooding, which would reduce the methane emissions (Belder 2005; Gao 2006). Similar effects can be achieved for nitrous oxides as a result of changes in the nitrogen fertilization and the soil water management. Suitable selection of fertilizers and placement in the soil can reduce the emissions under conditions of zero tillage (Izaurralde *et al.* 2004; Gao 2006).

A Conservation Agriculture Carbon Offset consultation in West Lafayette, USA, organized jointly by FAO and the Conservation Technologies Information Centre (CTIC) with technical assistance from the secretariat of the UNFCCC came to the conclusion that agricultural production following the principles of CA could sequester carbon and significantly reduce other GHG emissions (FAO-CTIC 2008).

Climate change is becoming increasingly a problem for agriculture. Extended drought periods and heavy rainstorms are becoming common features of the weather not only in the tropics (Met Office 2005). CA can help to adapt to these changing and less stable climatic conditions. The increased water infiltration allows soils to absorb most of the rain water even during extreme rainfall events, reducing the risk of erosion and flooding (Saturnino and Landers 2002). Increased organic matter levels and a better rooting environment in the soil improve water holding capacity of the soils and the ability of plants to survive during drought periods. Yield variations between dry and wet years are less pronounced under CA than under conventional farming practice (Shaxson and Barber 2003, Bot and Benites 2005). Continuous macro pores in the soil increase the water infiltration and hence the absorption capacity of soils during heavy rainstorms. This can be instrumental for the reduction of flood risks (DBU 2002). The increased water infiltration contributes also to a recharge of the aquifer which is of particular importance for regions with falling ground water tables (PDCSR 2005). The increased organic matter levels under CA also provide for better water retention capacity of the soil. For each percent of soil organic matter 150 m^3ha^{-1} of water can be stored in the soil. Loss of soil water is further reduced and in general water savings of 30% under CA are reported compared to conventional cropping systems under similar climatic conditions (Bot and Benites 2005).

CONCLUSIONS

Conservation Agriculture as defined by FAO is a base element for the sustainable intensification of crop production. It addresses also many problems faced in African agriculture. At the same time CA allows to include agricultural crop production into the instruments for climate change mitigation since it results in carbon sequestration into soils and it provides the conditions for a reduction of other agricultural green house gas emissions. In addition, CA is a useful tool for adaptation to climate change, making agricultural production systems more resilient to extreme drought, rain and temperature conditions. With these characteristics, agriculture could not only provide for food security and better livelihoods, but also for better environmental services.

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Fostering shifts from existing fire behaviour patterns to more environmentally-friendly ones: Challenges and approaches

Mammino L.[1]

ABSTRACT

The use of fires (biomass burning) is more extensive in sub-Saharan Africa than anywhere else. Both the environmental impact of the emissions (including greenhouse gases) and the loss from the waste of materials that could be otherwise utilised suggest the need to find effective ways to foster behaviour-patterns changes.

Fostering behaviour changes is not easy. The difficulties are greater for habits that are long-established, transmitted through generations and believed or proved to bring some benefits. Attempts to foster changes require delicate combinations of approaches aimed at building conviction and active involvement of the communities concerned, so as to prevent the development of perceptions viewing the proposed changes as outsiders' interventions without links to immediate needs. This implies the design of approaches to illustrate the motivations for changing behaviour patterns, and to encourage the participation of communities in the search for alternative options that can be considered viable and bring sufficient benefits to compensate or outweigh the ones that would be lost.

The preliminary steps need to consider two major tasks: the dissemination of information on the effects of biomass burning (pursuable through the preparation of suitable material and through the identification of viable dissemination chains) and the collection of information on current points of views and perceptions from persons close to the type of community-life that would be the major target of change-fostering initiatives (pursuable mainly through careful listening-attention and through personal interactions, and providing essential information also for the design of dissemination material and pathways).

The paper considers options, based mostly on preliminary investigations for the preparation of resource material meant for science students and other persons with adequate science background, identified as optimal first link in a dissemination-of-information chain meant to ultimately outreach to communities.

Keywords: Biomass burning, Dissemination of information, Fires, Greenhouse emissions, Sub-Saharan Africa

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INTRODUCTION

Biomass burning is more extensive in sub-Saharan Africa than in any other continent. It is a practice transmitted traditionally through generations and generally unquestioned within communities. Fires are utilised for many purposes: disposing of agricultural wastes; clearing overgrown grass when it is sufficiently dry, or disposing of cut grass and bushes in gardens and other areas before the end of the dry season; "cleaning" agricultural areas before the sowing season; clearing often-extensive areas nearing streets and roads or other areas not devoted to agriculture (including areas that – not being devoted to any particular human-determined purpose – would be expected to be allowed natural cycles). In summary, fires are used as the major or only option for disposing of any unwanted material of plant origin, often on substantially large scales. The option is fast, labour-inexpensive and equipment-inexpensive. It is also believed to bring some benefits, like enhancing soil fertility for grass growth, or helping control some insects' population. On the other hand, fires produce a variety of combustion products, including aerosol particles and greenhouse gases (Seiler and Crutzen, 1980; Helas *et al.*, 1995; Rudolph *et al.*, 1995; Scholes, 1995; Scholes, Ward and Justice 1996; Li *et al.*, 2003; Swap *et al.*, 2003), besides having other types of impacts, like posing a threat to biodiversity in some areas. In the current global environmental situation, reducing emissions is an urgent priority. This would imply a substantial reduction in the use of fires, i.e. substantial behaviour-patterns changes.

Fostering changes in behaviour patterns is not easy, whether it refers to individuals or to communities. The difficulties are greater for habits that are long-established, transmitted through generations, believed or proved to bring some benefits and/or generally accepted as the obvious way of doing things. Besides the generalised inertia towards behaviour pattern shifts, shifts to environmentally-friendly behaviour patterns may encounter additional hampering factors, determined by inadequate awareness (diagnosed often even among persons with higher education) of the importance of the attention to environmental issues, or of the environmental impacts of certain actions. The biomass burning practice falls within the cases for which these difficulties are greater, because the motivations for behaviour shifts pertain to science-based information, requiring adequate science literacy for real understanding and appreciation, and refer to large-scale phenomena and concerns, not easily perceivable at individual or small-community level.

Attempts to foster changes require a delicate combination of approaches, aimed at building conviction and active involvement of the communities concerned, so as to prevent the development of perceptions viewing the proposed changes as outsiders' interventions, unmotivated interventions, or interventions without links to the immediate needs of the communities. This implies the design of approaches for the dissemination of information in a way apt to convincingly illustrate the motivations for changing behaviour patterns, and to encourage the communities participation in the search for alternative options that can be considered viable and can bring sufficient benefits to compensate or outweigh the ones that would be lost. The identification of viable channels for the dissemination of information, and the quality (clarity and effectiveness) of the communication resources through which it is realised, become key factors. The modes of communication need to be tuned to the targets and need to comprise options that enable the communication of science-based information in a way that is understandable even in the absence of prior science literacy.

OBJECTIVES AND METHODS

The viability of options for the dissemination of information on a specific issue strongly depends on the nature of the issue. Given the science-based character of the information about the impact of fires, a viable dissemination sequence needs to initially target persons with adequate science background: tertiary level science students, science teachers of all levels and experts with science preparation working in administrative bodies. Thanks to their specific preparation, they are more ready to appreciate the value of documented evidence and can, therefore, evaluate and understand the motivations of proposed shifts in a clear, analysis-based way. This will enable them to act, in turn, as sources for the dissemination of information to other persons/groups, first of all the communities from which they come from. Moreover, they will be in an ideal position to contribute valuable suggestions for the subsequent preparation of resource materials that do not assume prior science literacy, because of their familiarity with the communities' backgrounds and attitudes. Such second stage material would thus be apt for diverse dissemination channels: schools, media (first of all, TV, that reaches practically everywhere), and for initiatives in which experts encounter communities.

The form chosen for the resource material meant for persons with adequate science knowledge is that of a collaborative book with contributions from different Africa contexts (Mammino, 2008). The choice follows students' positive comments on a resource material with a similar set-up, meant to disseminate information about green chemistry (Tundo and Mammino, 2002). The option contributes to underline that the themes considered are actually relevant to the African reality and are investigated and debated in African institutions and responds to a students' diffuse need for materials made in the continent.

The main objective of the study was that of collecting information for a viable design of the approaches in the planned collaborative book, to maximise its communication effectiveness by ensuring that it is "tuned to the target". To pursue this objective, one needs extensive prior familiarization with the current views and perceptions of the persons/groups for which the material is meant, as well as their modes of approaching written material and their possible expectations from it. A parallel objective was that of collecting information that might be relevant for the design of materials for the subsequent steps.

Since the needed/sought information is clearly of a qualitative type, the investigation was conducted in an informal way, mostly through exchanges of views with students during the 2007-2008 academic years. The informal character was considered essential to ensure that the information about current opinions, perceptions, expectations and possible responses is spontaneous, since spontaneity (and, therefore, genuinity) makes it valuable for designing purposes (design of materials). Additional information was collected by careful attention to casual/random discussions in whichever context or occasion, to attain better familiarization with common perceptions as well as with anticipated/possible responses (or expressions of concerns) to interventions suggesting changes in fires-related behaviour patterns.

RESULTS AND DISCUSSION

Because of the qualitative, open-target features of the approach utilised, the information collected expands into a comparatively broad picture, providing interesting indications for the design of the planned resource material and for subsequent steps. The most significant will be outlined in the next paragraphs.

First of all, it appears necessary to assume no prior knowledge about fires (whether in terms of emissions, or environmental effects, or the mere possibility of considering alternative options). The use of fires is generally unquestioned. Therefore, resource materials need to provide very clear and convincing motivations to highlight the importance of shifting to different practices. The material meant for the first step (targeting persons with adequate science background) needs to provide data and also their interpretation, to ensure that the reader will not encounter difficulties in identifying interpretations and implications.

Since a resource material is not envisaged as a prescribed textbook, the need to stimulate and maintain interest is paramount (the book will not be read unless the reader's interest is stimulated). The impact is expected to be greater when the information is not only accurately documented, but also complemented by proposals for implementable options. Communication effectiveness is generally enhanced by concrete examples. All this suggests the opportunity of proposing and motivating initiatives for a gradual reduction of the extent of biomass burning through time-sequences identifying intermediate objectives. Non-agriculture-related practices are more viable as first targets for shifts in fires behaviour-patterns, as there is no perception of associated benefits (except labour-saving – what is, however, not specifically perceived as a benefit in contexts with high unemployment rates among unskilled labour). Therefore, the use of fires for clearing areas not devoted to agriculture can be proposed as an apt target to make a first move towards fires-behaviour shifts – a move whose feasibility and economic viability are easier to envisage. Since, for areas of this type, government or local offices are the bodies that can more frequently take decisions, the importance of shifting to alternative practices can be motivated through the provision of science-based or statistics-based information, like:

- the extent of the areas concerned with non agriculture-related fires, in a given region;
- the overall emissions from biomass-burning in those areas during a year;
- other undesirable consequences or features that might be identified for specific areas (e.g. the simultaneous burning of plastic refusals in areas close to high population-density places);
- a predictive evaluation of the feasibility of alternative options to attain the "clearing/cleaning" purposes;
- a predictive evaluation of the reduction of emissions and of other losses, achievable by shifting to those alternative options, and of possible benefits (e.g., by finding viable uses for the grass that would otherwise be burnt).

In order to broaden readability and to ensure communication effectiveness, it is also necessary to clearly and thoroughly explain the contextual meanings of terms and expression, above all in view of the probable non-familiarity of a number of readers (including students taking other science disciplines) with the terms and expression typical of environmental sciences. For instance, it unexpectedly turned out that the concept that "biomass is wasted" through the fires requires clarifications to ensure that the reader/listener associates the concept of "wasting" to that of "physical destruction", and to avoid the risk of interpretations perceiving that the "wasting" concept is extended to all traditional uses of grass (like e.g.

making mats). This instance actually constitutes an important reminder about the delicacy of discourses referred to traditionally established behaviour patterns - even simply at the level of dissemination of information - as the weight of historical factors (traditional behaviours having being often looked down) is unavoidably conditioning many perceptions. Ignoring its possible impacts might jeopardise the efficacy of communications meant to stimulate individuals/communities' awareness, interest and active participation. It becomes extremely important to combine the provision of documented evidence with careful attention to the wording through which interpretations, inferences and objectives are expressed. A priory prediction of possible ranges of interpretations of specific terms, expressions, considerations or recommendations may not be easy. A perspective option is that of allowing some (selected) tertiary students to read the material in advance, as representative of a large group of target readers, and, if the opportunity arises, also some persons from other categories (science teachers, persons working in administrative bodies). The option has already proved effective in the preparation of textbooks, where it had the objective of testing readability and understandability (Mammino, 1993) and, therefore, can be considered viable.

The diversification of communication forms and dissemination channels has an important role both in the initial and in subsequent steps, because of the enhanced effects from the combination of different forms and different channels and because specific forms or channels may have greater impacts on different target groups:

- Information within formal instruction can attain a dissemination-range far beyond the students directly involved, through well-known mechanisms, as children relate to adults (families, communities) what they have learnt. The nature and role of formal instruction facilitates students' conviction and this, in turn, can foster pioneering roles of the younger generation towards behaviour-patterns shifts.

- The inclusion of information and appeals in the media and in official messages provides important dissemination vehicles. The way in which the media realise large-scale communication is particularly apt to foster opinions and perceptions. Official messages have great outreach-effectiveness (through media) and are generally extensively discussed in relation to what they mean for everyday life.

- The use of art-forms may effectively complement other communication options, as they communicate more immediately to the emotional sphere. Traditionally honoured forms of communication (verbal/narrative or other forms honoured in a community) are able to attain communication effectiveness independently from the education or science-literacy levels of individuals/communities and can have a relevant role in fostering active participation.

- The use of indigenous languages for at least some of the communication options is of paramount importance to foster interest, conviction and participation, just as it is for mass education and for development in general (Prah, 1993 and 1995).

CONCLUSIONS

The active participation of individuals and communities that would be concerned with shifts from traditionally-inherited fire behaviours to more environmentalfriendly ones is *conditio sine qua non* for the shifts to be possible. The participation needs to involve all the aspects of interest, first of all the search for alternative options that can be perceived as viable and perspectively interesting. The dissemination of information is the necessary pre-requisite to attract attention and stimulate participation. The design of options for effective dissemination of information is a necessary preliminary step.

The preparation of resource material meant for persons with good science background (science students, science teachers and specialists in administrative bodies) is viewed as an optimal initialization step, capable of fostering the subsequent viability of other dissemination channels, targeting the general public (without requiring science literacy).

The dissemination of information within the frameworks of formal instruction can stimulate new dissemination approaches, as the youth can often find novel ways to effectively communicate to other young people. It can also stimulate students' involvement in the search for viable alternative options - an interesting possibility, as students combine sharing the experience of their communities and being more ready to innovation and changes - and may foster their taking pioneering roles.

Because of the need to reach as broad range of targets as possible, the dissemination of information needs to act at many levels and use diversified communication vehicles: formal instruction, outreach from teaching/learning bodies, inclusion into official messages, media, art and traditionally honoured forms of communication.

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Appendix 1

Agenda

CarboAfrica

Open Science conference on

Africa and Carbon Cycle: The CarboAfrica Project

Accra (Ghana), 25-27 November 2008

PROGRAMME Tuesday, 25 November 2007

08.00-08.45 – Registration

Welcome address *(Chair Anastasios Kentarchos)*

08.45 – Welcome from European Commission (A. Kentarchos)

09.00 – Welcome from Ghana
(E. Obeng Dapah – Honourable Minister for Lands, Forestry & Mines)

09.15 – Welcome from FAO (M.H. Semedo)

09.30 – The CarboAfrica Project (R. Valentini)

10.00 – Coffee Break

Keynote speeches on Africa and Global Carbon Cycle *(Chair Robert Scholes)*

10.15 – Dynamics of the African carbon cycle: a continent of flux and variation (R. Scholes)

10.45 – Greenhouse gas inventories in Africa: constraints and perspectives (M. Khouma)

11.15 – Round Table on Africa and Global Change *(Chair Riccardo Valentini)*
Participants: A. Kentarchos, J. Nkem, R. Scholes, L. Thiombiano, N.A. Kotey

12.30 – Lunch

Terrestrial Carbon Observations in Africa and Ecosystem fluxes *(Chair D. Papale)*

14.00 – Vegetation heterogeneity, does it matter? (L. Merbold)

14.20 – Estimation of Net Ecosystem Exchange at the Skukuza Flux Site, Kruger National Park, South Africa (A. Kirton)

14.40 – Effect of burning on soil-atmosphere greenhouse gas exchange in African grassland savanna in Congo Brazzaville (A. de Grandcourt)

15.00 – Semi-arid afforestation and its effect on land-atmosphere interactions (E. Rotenberg)

15.20 – Coffee Break

15.40 – LAMTO, Ivory Coast: A new station for monitoring CO2 and CH4 in the atmosphere (M. Ramonet)

16.00 – Ground-based remote sensing of atmospheric trace gases in the tropics (L. Amekudzi)

Soil and Vegetation: Carbon and GHGs emissions in Africa *(Chair M. Bonsu)*

16.20 – Seasonal and inter-annual variations of LAI in a Sahelian environment, Gourma, Mali (E. Mougin)

16.40 – West Africa´s savannahs under change: a holistic synthesis of positive and negative effects of agriculture and land cover changes on carbon cycling and trace gas emission (H. Nacro)

17.00 – Close of the first day

19.00 – Conference Dinner

PROGRAMME Wednesday, 25 November 2007

Soil and Vegetation: Carbon and GHG emissions in Africa *(continuation)*

08.00 – Understanding soil carbon dynamics for sustainable land management (E. Yeboah)

08.20 – Seasonal dynamics of soil carbon dioxide efflux in a restored young mangrove plantation at Gazi bay, Kenya (B. Yebei)

08.40 – Estimates of CO2 emissions from soil organic carbon for different land uses (M. Bonsu)

09.00 – Soil respiration in a semi-arid ecosystem in Mali (V. Le Dantec)

09.20 – The effect of cattle manure and nitrogen fertilizer amended wetland cropping on nitrous oxide emissions into the atmosphere (J. Masaka)

09.40 – Coffee Break

Biogeochemical Modelling *(Chair N. Hanan)*

10.00 – The CA model intercomparison - review and outlooks (U. Weber)

10.20 – African Carbon Exchange II: A systems approach (N. Hanan)

10.40 – Towards an African carbon budget from data-oriented modelling (M. Jung)

11.00 – Land cover change, biogeochemical modeling of carbon stocks, and climate change in the Sahel/West Africa (L. Tieszen)

11.20 – Assimilation of land-surface temperature in the land surface model JULES over Africa (D. Ghent)

11.40 – Evaluation and improvement of the representation of Sahelian savannah in the vegetation model ORCHIDEE (P. Brender)

12.00 – Lunch

Impact of vegetation fires on African GHG budget *(Chair H. Balzter)*

13.30 – Remote sensing methods for monitoring fire related biophysical parameters (H.Balzter)

13.50 – Analysis of satellite imagery to map burned areas in Sub-Saharan Africa (I. Palumbo)

14.10 – Modelling tree - grass balance in savanna ecosystems: the importance of different factors (V. Lehsten)

14.30 – An enhanced estimate of pyrogenic carbon emissions from Africa using a synthesis of polar orbiting and geostationary active fire products (P. Freeborn)

14.50 – Synchronizing Fire Emission Measurements with Land Use Patterns in Zambia (B. Mhango)

15.10 – Coffee Break

15.30 – Poster Session
(Poster authors are requested to stay close to their posters)

17.00 – Close of the second day

PROGRAMME Tuesday, 25 November 2007

Carbon sequestration and reduced emissions potentialities in Africa *(Chair S. Adu-Bredu)*

08.00 – Ghana as a case study for CDM and REDD Africa's potential (M. Henry and collaborators)

08.30 – Carbon stock under four land-use systems in three varied ecological zones in Ghana (S. Adu-Bredu and collaborators)

09.00 – Carbon storage and the health of cocoa agroforestry ecosystems in Ghana (A. Asase)

09.20 – Above-ground biomass in Gabon (D. Maniatis)

09.40 – Helping small scale tree farmers in Africa participate in carbon trading: a case in central Kenya highlands (J. Kungu)

10.00 – Coffee Break

Carbon sequestration and reduced emissions potentialities in Africa *(continuation)*

10.20 – Carbon fluxes and deforestation (W. Kutsch)

10.40 – Potential for Carbon Sequestration in Terrestrial Forests of Zambia (A. Siampale)

11.00 – Promoting carbon sequestration through participatory land use planning by poor resource farmers in arid communal areas of Zimbabwe: a case study (R. Mugandani)

11.20 – Finding on Integrated Land use Asessment Projet (ILUA), Biomass and Carbon stocks (J. M. Mukosha)

Demonstration projects and developing capacities in Africa *(Chair L. Thiombiano)*

11.40 – Tropical Forests and Climate Change Adaptation (J. Nkem)

12.00 – Lunch

Demonstration projects and developing capacities in Africa *(Chair L. Thiombiano)*

13.30 – SHARE: Soil Moisture for Hydrometeorologic applications in the SADC (Southern African Development Community) region (C. Pathe)

13.50 – TerrAfrica partnership; potential for climate change adaptation and mitigation in Sub-Saharan Africa (L. Thiombiano)

14.10 – Sustainable Production Intensification in Africa - a climate change perspective (T. Friedrich)

14.30 – Fostering shifts from existing fire behaviour patterns to more environmentally-friendly ones: challenges and approaches (L. Mammino)

14.50 – Cooperative Community Carbon Offsetting with Biodiversity and Social Co-Benefits: a case study of trees for global benefits programme in Uganda (P. Mwima)

15.10 – Local strategies of adaptation to climate change: 6 case studies in Burkina Faso (F. Bationo)

15.30 – Final remarks

16.00 – Conference closure

UNIVERSITÀ DEGLI STUDI DELLA Tuscia

WWF

FAO FIAT PANIS

CAMPBELL SCIENTIFIC AFRICA

Appendix 2

List of Participants

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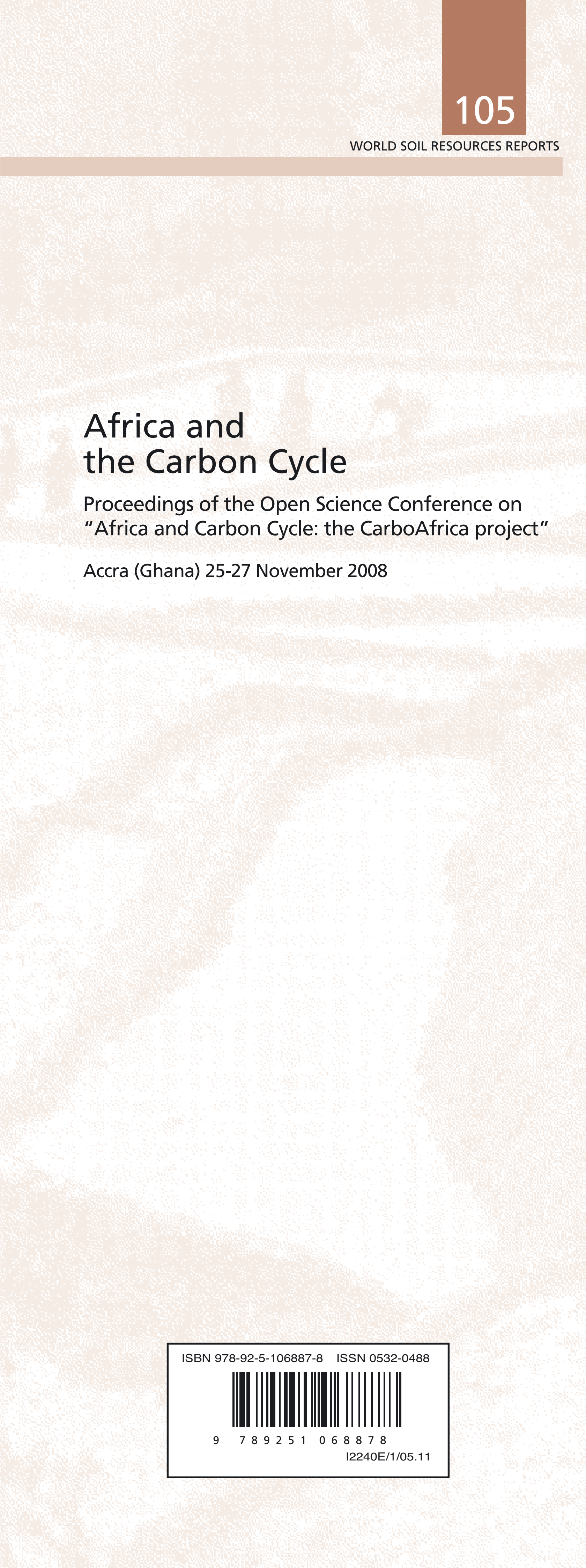

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