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**The Sub-Saharan
Africa carbon
balance**

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The Sub-Saharan Africa carbon balance, an overview

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Abstract

This study presents a summary overview of the carbon balance of Sub-Saharan Africa (SSA) by synthesizing the available data from national communications to UNFCCC and first results from the project CarboAfrica (net ecosystem productivity and emissions from fires, deforestation and forest degradation, by field and model estimates). According to these preliminary estimates the overall carbon balance of SSA varies from 0.43 Pg C y^{-1} (using in situ measurements for savanna NEP) to a much higher sink of 2.53 Pg C y^{-1} (using model estimates for savanna NEP). UNFCCC estimates lead to a moderate carbon sink of 0.58 Pg C y^{-1} . Excluding anthropogenic disturbance and intrinsic episodic events, the carbon uptake by forests (0.98 Pg C y^{-1}) and savannas (from 1.38 to 3.48 Pg C y^{-1} , depending on the used methodology) are the main components of the SSA sink effect. Fires (0.72 Pg C y^{-1}), deforestation (0.25 Pg C y^{-1}) and forest degradation (0.77 Pg C y^{-1}) are the main contributors to the SSA carbon emissions, while the agricultural sector contributes only with 0.12 Pg C y^{-1} . Notably, the impact of forest degradation is higher than that caused by deforestation, and the SSA forest net carbon balance is close to equilibrium. Savannas play a major role in shaping the SSA carbon balance, due to their large areal extent, their fire regime, and their strong interannual NEP variability, but they are also a major uncertainty in the overall budget. This paper shows that Africa plays a key role in the global carbon cycle system and probably could have a potential for carbon sequestration higher than expected, even if still highly uncertain. Further investigations are needed, particularly to better address the role of savannas and tropical forests. The current CarboAfrica network of carbon measurements could provide future unique data sets for better estimating the African carbon balance.

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1 Introduction

The global carbon cycle is strongly linked to the climate system: CO₂ is, by far, the largest contributor to the anthropogenically enhanced greenhouse effect (IPCC, 2007a), while at the same time, a large proportion of the emitted CO₂ is absorbed by ocean and terrestrial ecosystems. Improving our knowledge of terrestrial sources and sinks of CO₂ and other greenhouse gases (GHGs), and their spatial and temporal variability is a key action to: 1) better understand and predict the global change, and 2) enhance human capacity to undertake mitigation and adaptation actions.

The role of the African continent in the global carbon cycle, and therefore in climate change, is increasingly recognised (Houghton and Hackler, 2006; Williams et al., 2007). Even if Africa contributes only less than 4% to the global anthropogenic fossil fuel emissions (Canadell et al., 2008), 20% of both global net primary production (NPP) and global land use emissions (mainly from forest degradation and deforestation), and around 40% of fire emissions have been attributed to the African continent, significantly affecting the atmospheric chemistry (Andreae, 1991; Houghton, 2003; Kituyi et al., 2005; van der Werf et al., 2006). Moreover, about 50% of interannual variability of global atmospheric CO₂ is attributed to the variability of the African carbon balance (Cao et al., 2001; Rödenbeck et al., 2003; Baker et al., 2006; Williams et al., 2007).

With low fossil fuel emissions, Africa's current continental scale carbon fluxes are dominated by uptake and release from terrestrial ecosystems (which in turn are strongly linked to climate fluctuations) as well as forest degradation and deforestation (Williams et al., 2007). In Sub-Saharan Africa the role of land use change in controlling CO₂ emissions and annual C budgets at regional and global scale may be more critical than in any other regions (Houghton and Hackler, 2006), including the basically unresolved question of natural vs. anthropogenic driven fire regime.

Human activities (agriculture, fires, pasture, logging, etc.) can alter broad scale biogeophysical processes, carbon cycling and climate through direct impact on ecosystem dynamics (particularly with enhancement of plant production through genetic breeding,

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irrigation, increased use of fertilizers and technological management of agriculture, logging and fires on natural vegetation). However, in Africa, the anthropogenic impact on these dynamics appears small (see Seaquist et al., 2008, for the Sahel region), and the NPP of cultivated ecosystems is most likely lower than natural NPP in Africa (Haberl et al., 2007). Since an increased anthropogenic pressure on African natural resources is expected, it is important to quantify the productivity of natural ecosystems, as well as its variability and trends. Much work remains to be done in trying to isolate those aspects of African climate variability that are natural from those that are related to human influence (Hulme et al., 2005).

African forests contain large carbon stocks in biomass, up to 300 Mg C ha⁻¹ in tropical rainforests (Palm et al., 2000), that appear to be particularly vulnerable, mainly due to the impact of climate change, land use change, population increase and political instability. This vulnerability is evidenced by strong sensitivity of net ecosystem productivity, soil and vegetation carbon stocks and fluxes, and fire emissions to climate fluctuations, in particular to rainfall patterns (Castaldi et al., 2006; Archibald et al., 2008; Brümmer et al., 2008; Ciais et al., 2008; Kutsch et al., 2008; Lehsten et al., 2008; Merbold et al., 2008). Africa's land use pressures will undoubtedly increase in the next years and the forecasted increase in drought and temperature (IPCC, 2007a) can lead to a significant decrease in ecosystem carbon stocks in tropical forests and savanna, at least without human countermeasures (Tan et al., 2009).

Despite the increasingly acknowledged importance of Africa in the global carbon cycle and its high vulnerability to climate change due to both ecological and socio-economic factors, there is still a lack of studies on the carbon cycle in representative African ecosystems (in particular tropical forests), and on the effects of climate on ecosystem-atmosphere exchange (Scanlon and Albertson, 2004). Up to now it is not clear whether Africa is a net carbon absorber or emitter, however Williams et al. (2007), in their comprehensive recent review on the African carbon cycle, showed that Africa's decadal scale mean carbon balance appears to be neutral, whereas latest results by Ciais et al. (2008) showed that in the last decade Africa has probably been acting as a

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net carbon sink.

Many open questions remain also on soil GHG fluxes, especially in tropical seasonally-dry areas, such as the role of termites in CH₄, CO₂ and N₂O production in African savannas and forests and the impact of land use change on such source; the magnitude and length of the GHGs pulses which follow rain events in dry areas; the impact of frequent fires on post-burning GHGs release from the soil; the extent of limitation of soil pH on N₂O and CH₄ fluxes; the role of land use in limiting/accelerating N cycle processes and N gaseous emissions from the soil.

This lack of data on African carbon budget makes the numerical models of the carbon cycle highly uncertain when applied to Africa; model simulations can provide just an approximate profile of Africa since these models are usually developed and validated for different latitudes (Chevallier et al., 2009; Ciais et al., 2008; Weber et al., 2008). Therefore there is a strong need for a denser and more representative network of carbon observation stations over Africa in order to improve the regional carbon estimates using biogeochemical models (Williams et al., 2007; Ciais et al., 2008; Weber et al., 2008).

In addition, considering the need with regards to the Climate Policy, the potential for Africa to mitigate climate change through carbon sequestration and reduction of emissions by avoiding forest degradation and deforestation is very high. It is thus important to quantify both carbon stocks and fluxes of African forests and other ecosystems, especially in the context of the UNFCCC (United Nations Framework Convention on Climate Change) mechanisms, such as the Clean Development Mechanisms (CDM) of the Kyoto protocol, and the Reducing Emissions from avoided Deforestation and forest Degradation (REDD).

As stated by Kituyi et al. (2005), the starting point for the African access to the sustainable economic development options provided by UNFCCC and its Kyoto protocol should be the development of a comprehensive national GHG inventories and the improvement of the quality and quantity of data.

As a consequences of the above arguments the project CarboAfrica, funded by the

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European Commission, was launched in 2006 in order to: 1) support a network of continued and enhanced continent-wide observations of Sub-Saharan Africa's carbon stocks, fluxes, atmospheric concentrations and ecological processes; 2) to improve biogeochemical models representing the main African ecosystem types; 3) to better understand the role of fire emissions of Sub-Saharan Africa in the global carbon cycle; and 4) to assess the potential of Sub-Saharan Africa for carbon sequestration and emission reduction.

In this paper we present some new highlights from the CarboAfrica results together with other results already published (in particular in this issue) to try to give an overview of the first results obtained by CarboAfrica in order to contribute towards: 1) a better quantification of the terrestrial carbon budget of Sub-Saharan Africa, and 2) the improvement of our understanding of the role of Sub-Saharan Africa in the global carbon cycle.

2 Methodology

Results of this paper have been obtained using both published and unpublished data of the CarboAfrica project. The study area is Sub-Saharan Africa (hereinafter called SSA). In particular, research activities are being conducted in the following SSA countries: Benin, Botswana, Burkina Faso, Ghana, Ivory Coast, Mali, Niger, Congo, South Africa, Sudan and Zambia. Other SSA countries may be considered before the end of the project.

2.1 The CarboAfrica methodology

The CarboAfrica methodology is based on an integrated multiscale and multitemporal approach. The work is divided in 6 work packages, dealing with: long term observation systems and data integration and consolidation; process understanding of carbon fluxes of SSA ecosystems; model-data integration for up-scaling to region and continent; fire-climate-carbon cycle interactions on regional and continental scale;

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evaluation of a sustainable sequestration potential in relation with CDM; communications and capacity building. More details on the project methodology is available at: www.carboafrika.net.

2.1.1 Carbon stock and fluxes

5 The observational backbone of the project is constituted by the experimental eddy covariance flux network (Fig. 1) for gas exchange measurements (carbon, water and energy fluxes) between ecosystems and the atmosphere at landscape scale¹ (see Archibald et al., 2008; Merbold et al., 2008, for details on the eddy covariance methodology). This long-term observation system integrates data from at least eighteen intensive study sites, established within CarboAfrica as well as via a number of other research projects (sixteen eddy covariance sites, of which one mobile station in three different sites and two atmospheric stations), covering a range of representative land cover, from tropical forest to desert, going through different woodland types, different savanna types, grasslands, *Eucalyptus* plantations, and different agricultural crops. 15 This network includes the first flux station in an African tropical forest, which is providing new information on the Africa's role in the global carbon cycle. Biomass samples are being taken to provide additional data for carbon estimates validation. Above ground biomass data used to produce the figures of this paper have been derived from the last IPCC report (2007a). We have used the data from Henry et al. (2009) to make an estimation of Soil Organic Carbon (SOC) for the different classes of FAO forest ecological classification (FAO, 2006). 20

2.1.2 Ecosystem processes

Intensive field campaigns at the flux sites of Fig. 1 were conducted to measure ecosystem processes in soil and vegetation, including soil and plant water relations and gas

¹In this paper positive values of carbon fluxes represent carbon sink and negative values represent carbon source.

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exchange (CO₂, but also CH₄ and N₂O), plant phenology and plant ecophysiology (see also Kutsch et al., 2008, for more details).

N₂O and CH₄ fluxes were estimated using closed chamber (PVC 31.5 cm diameter by 20 cm height, four spatial replicates per treatment) (Mosier, 1990; Smith et al., 1995). To estimate CH₄ concentration variation (four samples over one hour) within the chamber, manual sampling combined with gas chromatographic analyses was used. Pre-evacuated glass vials, sealed with butyl rubber septa and crimps, were used to store gas samples, which were analysed within two weeks from sampling by using an FID analyser (GC Fison 8000, Porapak Q column). For the analysis of N₂O, a photoacoustic analyzer (PAS) 1312 (INNOVA S.r.L. DK) was used in situ by connecting the analyzer to the chambers via an inlet and an outlet port. Air samples were driven from the chamber and analyzed every two minutes over a minimum of twenty minutes of chamber closure. This second technique was used to measure N₂O fluxes because the greater accuracy (1%) of PAS allows to detect very small fluxes of N₂O, which typically occur in the seasonally dry ecosystems during the drier periods. The same technique was demonstrated to be unsuitable for CH₄ quantification. During each campaign, soil parameters relevant to GHGs fluxes (water content, temperature, mineral N, total C and N, pH, etc.) were also analysed.

2.1.3 Modelling

In situ and remote sensing data were integrated for the model parameterisation and evaluation. Different models, from data oriented to process oriented, were used to provide a multiple constraint approach to the continental carbon cycle integration. This allows covering the model domain in terms of variable temporal scales, spatial scales and processes addressed. Data presented here were extracted from a simulation experiment on the interannual variability of Africa's ecosystem productivity (Weber et al., 2008). It is noteworthy that the models were developed mostly for other continents and are not validated against site data for the annual carbon balance of SSA. For the LPJ-DGVM model, the Pearson correlation coefficient was calculated pixel by pixel for the

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time series of NEP versus GPP and TER and nominal significances of this correlation were calculated according to (Sachs, 1996). See also Chevallier et al. (2009); Ciais et al. (2008); Seaquist et al. (2008); Sjöström et al. (2009), for more details on the models used by CarboAfrica.

5 2.1.4 Fires

The CarboAfrica fire approach considers both burned area extent and fire intensity and emission. Remote sensing based carbon emission estimates from fires were derived by combining the mapping of burned area and the fire radiative energy (FRE) technology (see also Lehsten et al., 2008; Roberts et al., 2008). The interactions of ecosystem productivity with fire patterns was studied using a combination of prescribed burned area (based on the L3JRC analysis) and the dynamic vegetation model (DVM) LPJ-GUESS with the fire model SPITFIRE included (Smith et al., 2001; Thonicke et al., 2009). Using a DVM provides a tool to disentangle the interactions of precipitation, NPP and litter production as the main drivers of fires, and to investigate whether global patterns emerge that are generally representative for savanna ecosystems.

15 2.1.5 GHGs emissions

GHGs emission data were extracted from the African countries national communication to the United Nations Framework Convention on Climate Change (UNFCCC). The following classes were considered: anthropogenic emissions (regrouping emissions from the energy, industry and waste sectors); agriculture emissions; Land Use Change and Forestry (LUCF) emissions; and removals. The base year adopted for most of the countries was 1994 except for Sierra Leone and Egypt (1990), Gambia and Chad (1993), Togo, Mali, Mauritania and Sudan (1995) and Burundi (1998). All data were converted to CO₂ equivalent on the basis of the Global Warming Potential as reported in IPCC (2007b). Some of Sub-Saharan countries were not considered due to the lack of exhaustive information. Guinea Bissau, Sierra Leone and Uganda were not included in this analysis because the data reported show inconsistency with expected

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values. Some data were removed because they were considered not reliable. South Africa's emissions by LUCF sector is zero because of intensive afforestation activities, expansion of plantations and conservation policies (as reported in its National Communication).

5 National data were regrouped in three different African regions: Northern Africa, Sub-Saharan Africa and South Africa. Northern Africa was defined as composed of: Algeria, Egypt, Libya, Morocco, Tunisia and Western Sahara. The remaining countries were considered to belong to SSA, excluding South Africa, which has been considered individually. Pro-capita data have been derived by dividing the emission values by the
10 population (UN, 2006).

3 Results and discussion

3.1 The Sub-Saharan carbon balance: an overview of current estimates

There is a great disproportion among emissions from different African regions (Table 1, Fig. 2). South Africa is the main carbon emitter, producing almost 12% of the global
15 African emissions (403 Tg eq CO₂). This result is much more evident if we compare pro-capita anthropogenic emissions: South Africa emits 8.0 Mg eq CO₂ per person, more than 4 times of both the Northern Africa and the rest of SSA.

Considering the low fossil fuel emissions, SSA carbon balance is dominated by two large fluxes: emissions from land use change and uptake by terrestrial ecosystems.
20 Emissions from LUCF and agriculture are 1894 Tg eq CO₂ and removals 4042 Tg eq CO₂. Combining all the emissions (including fossil fuel) and removals, SSA is currently a net sink of 1289 Tg eq CO₂.

According to the National Communication to UNFCCC, the whole African continent appears to be a net carbon sink of 618 Tg eq CO₂. This result is due almost exclusively
25 (99%) to SSA, with its highest removal rates by terrestrial vegetation.

However the SSA carbon balance, due to relatively small net difference between the

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two large fluxes of emissions and removals, is subjected to large interannual variability and to high uncertainties in the data used to report to UNFCCC national inventories.

The overall annual carbon balance of SSA region (CB) can be summarized into its main components as:

5 $CB = NEP - EFS - D - FD - A - LT$

Where NEP is net ecosystem productivity of terrestrial ecosystems, EFS emissions from savanna fires, D emissions from deforestation (e.g. change of land use), FD emissions from forest degradation (e.g. logging), A emissions from agriculture, LT lateral transport of carbon from the region (rivers, trade, food consumption etc.). We can neglect in a first assumption lateral transport and assume for agriculture the emission statistics of UNFCCC, and try to address more in details the other components.

3.2 Estimates of NEP of terrestrial ecosystems in the SSA carbon balance

A comprehensive analysis of the role of terrestrial ecosystem carbon contribution to the SSA carbon balance should be based on inventories of carbon pools (Henry et al., 2009) and their changes in time, direct flux measurements (as from the CarboAfrica network, see Archibald et al., 2008; Kutsch et al., 2008; Merbold et al., 2008) and process-based biogeochemical models that derive NEP from estimates of GPP and ecosystem respiration (Ciais et al., 2008; Friedlingstein et al., 2008; Weber et al., 2008). Since the current CarboAfrica network is under operation and long term data sets are not yet available consistently through all the sites, we present only few direct flux results and concentrate our analysis on existing inventory data and models derived outputs.

In broadest terms, the two dominant vegetation types in SSA are forests (ranging from tropical to mountain regions) and savannas (ranging from grasslands to woodlands).

Most of the forest biomass in Africa is localized in the Sub-Saharan region and more precisely in the Central African belt. Estimates of above-ground dry biomass in African

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tropical forests vary among authors, ranging from 30 to 255 Mg C ha⁻¹ (Brown, 1997; Palm et al., 2000; Houghton and Hackler, 2006; IPCC, 2007a). As reported in Fig. 3, mean aboveground C accumulated in humid tropical forests is 155 Mg C ha⁻¹ (IPCC, 2007a). Above ground carbon stocks decrease from tropical forest with a minimum in the mountain forests, due to limitations of climate and soil on forest productivity (Fig. 3). Tropical rain forests show the highest belowground C, both for the root (57 Mg C ha⁻¹) and the soil components (53 and 55 Mg C ha⁻¹ for 0–30 and 0–100 cm) while minimum values are shown by mountain forests. Both above ground and below ground C stocks vary between different forest management types (Fig. 4). The conversion of forest to other land use types involves significant changes in C stocks, particularly SOC. While the maximum SOC was observed in logged forest (77 Mg C ha⁻¹) the minimum SOC was observed in recent bush fallow 66 (Mg C ha⁻¹). Similar trend was observed by Houghton (1999) who estimated SOC of about 100 and 50 Mg ha⁻¹ in undisturbed closed and open forests, respectively.

From FAO statistics (FAO, 2006) and IPCC data (IPCC, 2007a) it is possible to derive an overall assessment of the C stocks in SSA forests. Above ground carbon stock for SSA forests is equal to 48 Pg C. From Henry et al. (2009) in combination with FAO and IPCC data is possible to estimate the contribution of belowground C stock, which include roots and soil organic carbon, to be equal to 179 Pg in SSA for 0–100 cm soil layer. The total C stocks for SSA can thus be considered to be 227 Pg C, of which about 80% is coming from belowground carbon.

NEP estimates from forest inventories are difficult to obtain. We can consider the current UNFCCC national communication data as an overall estimate (see Table 1) which gives a total removal (mainly forests) of 1.13 Pg C y⁻¹ for SSA. This value is comparable to recent model results from CarboAfrica that provide a new insight in NEP estimation for forests. SSA forest NEP according to several models (Weber et al., 2008) can be estimated as 0.98±0.69 Pg C y⁻¹ (see Table 2). This value can be regarded as a first approximation considering Central Africa tropical forest (as defined by Weber et al., 2008) as the main forest region of SSA.

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Tropical drought-deciduous woodlands, savannas, shrublands, thickets and grasslands form a seamless continuum which can only be divided into distinct structural types by applying arbitrary limits (Scholes and Hall, 1996). In this paper we use the term savanna to indicate the co-occurrence of trees and grasses in different proportion (Sankaran et al., 2004), ranging from grassland to woodland, and defined by Scholes and Hall (1996) as “tropical tree-grass systems”. This system covers the majority of the surface of the following African ecoregions, as defined by Weber et al. (2008): Northern Savannah belt, Horn of Africa, Southern raingreen woodlands, and South African grasslands. According to the above definition, Sub-Saharan savannas (including grasslands and open woodlands) cover an area of about 15 million km² which corresponds to more than 80% of SSA land area. However this area, and the consequent extrapolations, is overestimated because the above African ecoregions contain also other different ecosystem types.

NPP estimates of savanna ecosystems are available from a number of studies, but only few estimates are available for NEP, and they vary from a source value of $-0.25 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ (Archibald et al., 2008) to a sink value of $4.53 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ (Brümmer et al., 2008) (see Table 3). The CarboAfrica project is trying to fill in this gap and some first results are given in this issue (Archibald et al., 2008; Kutsch et al., 2008; Merbold et al., 2008) and in Table 3. The field observations deviate substantially from results presented in a modelling intercomparison reported by Weber et al. (2008) which provide an estimate of NEP across different African regions (Table 2). This shows the uncertainty in modelling as well as field estimates: the current model runs estimate an overall carbon budget of $3.48 \pm 0.67 \text{ Pg C y}^{-1}$. Whereas if we extend the average value of the field measurements on the same land surface considered as savanna for the model estimates, we obtain a smaller sink strength of 1.38 Pg C y^{-1} . Numerous processes that can impede the carbon sink are not or not adequately included in the modelling (e.g. nutrient limitation, herbivores, indirect effects of fire, etc.). The model estimates consider northern savannas, southern rain-green woodlands and grasslands, as well as horn of Africa all together as the dominant savanna like ecosystems of SSA, but do

not consider carbon emissions from fires.

According to the preliminary modelling results, forest ecosystems have much larger productivity per unit of land area (about $13 \text{ Mg ha}^{-1} \text{ y}^{-1}$) compared to NEP for savannas ($2 \text{ Mg ha}^{-1} \text{ y}^{-1}$). However the savannas are extending over a much larger area and thus they determine significantly the carbon budget of the region. As we will see below, the annual net carbon balance of SSA is dominated by savannas fires, which reduce considerably their effect as a large sink of carbon.

3.3 The role of savanna fires (EFS) in the SSA carbon balance

Africa is a continent dominated by vegetation fires; these fires contribute substantially to the total carbon emissions over large parts of the continent (Lehsten et al., 2008). Estimates of biomass burned annually in Africa are very different; however they are often around thousands of Tg of biomass (Andreae, 1993; Hao et al., 1996; Ito and Penner, 2004; van der Werf et al., 2004). Latest results published in this issue (Lehsten et al., 2008; Roberts et al., 2008) show lower values: 723 ± 70 and 855 Tg C y^{-1} , respectively, resulting into an average of 0.79 Pg C y^{-1} .

Wildfires are a prominent feature and intrinsic ecosystem component of savannas worldwide. Some theoretical models even attribute the existence of savannas, i.e. the co-occurrence of trees and grasses, to their high fire frequency (see Sankaran et al., 2004). The vast majority of African fire events occur in Savannas (Tansey et al., 2004). While the overall difference between “natural” and anthropogenically-driven fire regime is difficult to be determined, it seems clear that currently the vast majority of fires are ignited by humans, mostly due to different land management practices (Saarnak, 2001). The fire frequency determines the standing biomass, and both are ultimately determined by human activities in Africa. If fire would be prevented, a much higher above and below ground biomass could be gained (Grace et al., 2006). It is debated whether higher woody biomass could in turn lead to greater emissions from less-frequent but more intense fires.

According to Lehsten et al. (2008) fires consume around 10% of Savanna NPP annu-

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ally. Savanna systems subjected to a time-integrated relatively constant fire frequency have an almost neutral carbon balance, since the fire induced carbon losses are offset by the consequent vegetation re-growth (Saarnak, 2001). However when merging the above C loss from savanna fires (0.79 Pg C y^{-1}) with the estimated NEP of savannas (excluding the fire component) the results show a residual carbon sink variable from 0.59 (using the field measurements) to 2.69 Pg C y^{-1} (using the model estimates). Clearly, improved estimates and a more detailed analysis of all contributing processes are required to pin-point and reduce this variability and the major uncertainties.

3.3.1 Soil CH_4 emissions in burned and unburned areas

CH_4 fluxes and the impact of fire of soil net CH_4 exchange was investigated in a grassland savanna in Congo Brazzaville. Burned and unburned savannas were compared and fluxes were measured one month (dry season 2007) and seven months (end of wet season 2008) after fire. From this preliminary data the soil of the unburned savanna appeared in general a net source of CH_4 (Fig. 5). This source was more evident during the first campaign with an average CH_4 emission over 7 days of measurements of $0.8 \text{ mg CH}_4 \text{ m}^{-2} \text{ day}^{-1}$. Burning seemed to affect this net CH_4 source, which was reduced by 100% during the first campaign, one month after fire and by a 20% in the second campaign, seven months after fire. Considering that CH_4 emissions were detected at extremely low soil water contents, this CH_4 source can be attributed to belowground termite activity rather than to microbial reduction processes. Rain simulation experiments at site (Castaldi et al., unpublished) allowed to derive a relationship between CH_4 fluxes and soil water content over a wider range of soil water contents compared with those found in the field at the moment of the sampling campaigns. From these data and from recorded data at site of soil water content (A. de Grandcourt, personal communication) a rough estimate of the annual CH_4 emission from the soil in the unburned plot was derived which was equal to $2.2 \pm 0.7 \text{ kg CH}_4 \text{ ha}^{-1} \text{ year}^{-1}$. To this we should add the CH_4 emissions from the termite nests which seems, from few preliminary measurements, from 1 to 2 order of magnitude higher than those measured from

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the soil. A detailed study is ongoing at the site to quantify, over a whole year, the CH₄ source deriving from the nests and the impact of fire on such source (Castaldi and De Grandcort, unpublished). Overall these savannas might represent a significant source of CH₄ which might be strongly affected by fire both in terms of direct effect of fire on mounds and termites and in terms of reduction of the fresh plant material, litter and organic matter used by termites as source of C and CH₄. At present no comprehensive studies in African grassland are available to answer to these questions.

A confirmation of the CH₄ emitting potential of African savanna soils also come from a second set of data we collected during two campaigns in South African open savannas, at Skukuza. Two areas were investigated, presenting soils with different textures. Data indicate that the sandy soil was a source of CH₄ corresponding to about 1.2 kg CH₄ ha⁻¹ year⁻¹, to which direct CH₄ emissions from termites nest should be added. Interestingly, the heavy textured soil of the close-by site did not produce significant amount of CH₄ and was a net sink of CH₄ (-1.2 kg CH₄ ha⁻¹ yr⁻¹), in accordance with studies which indicate that subterranean termites generally prefer sandy soils over clay soils, though they will survive in many types of soil (Randal, 2000; Jackel et al., 2001).

At both sites, Congo and South Africa, N₂O fluxes during both campaigns were extremely low and in many cases no flux at all could be detected. Fire did not seem to enhance or reduce the already low measured flux. These findings are in accord with previous studies from seasonally-dry ecosystems (Castaldi et al., 2006).

3.4 The role of deforestation (D) in the SSA carbon balance

Approximately 16% of the world's forests are in Africa and around 4 million ha yr⁻¹ of forest have been lost in the period 2000–2005 in Africa (FAO, 2006). In 2005, Africa had the highest rate of deforestation with 0.62% of annual loss of forest area. Most of the forest carbon losses were reported for the Central Africa, particularly in the Congo Basin countries. The Congo Basin forest is the world's second largest tropical forest, covering 223 million of hectares in six countries, and containing a quarter of the world's remaining tropical forest (FAO, 2006). An average size of 0.805 and 0.611

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million hectares was deforested every year for the period 1900–2000 and 2000–2005 respectively (Table 4).

Africa has currently the smallest deforested area of all tropical regions (Achard et al., 2004), but shows higher forest clearing rate than South America (Achard et al., 2002) and there is a trend to intensified logging in Central Africa. Africa has been contributing up to 35% of total tropical land clearing from deforestation, with an annual carbon loss from deforestation of 0.37 Pg C y^{-1} in the last decades (Houghton, 2003). Carbon losses through deforestation tend to be “permanent” in Africa, as afforestation and reforestation rates are modest, at less than 5% of annual deforestation.

Conversion from forest to cultivation through slash-and-burn activities could decrease the aboveground C stock to 220 Mg C ha^{-1} (the rate of recovery in fallow systems depending on biomass at the start of the fallow period) (Kotto-Same et al., 1997) and the belowground C stock to $24.4 \text{ Mg C ha}^{-1}$ in humid and sub-humid tropics (Vagen et al., 2004).

On the basis of average C stocks in different Cameroon land uses (Fig. 4), which can be considered representative for SSA region, we have estimated that conversion of forest to cropland presented the highest C losses (224 Mg C ha^{-1}), while conversion of forest to vegetable cropland had lower C losses (59 Mg C ha^{-1}). On the other hand, the conversion of forest to cocoa agroforestry led to C losses of about 133 Mg C ha^{-1} .

Based on these new values we can provide an approximate estimation of the SSA deforestation related emissions in Central Africa of 101 Tg C y^{-1} (see Table 4). If we assume, for simplicity, similar rates of deforestation and land conversion for Eastern and South Africa forests the overall deforestation emission losses would be 251 Tg C y^{-1} . This estimate is lower than that by Houghton (2003), of 370 Tg C y^{-1} , which was based on the total forest area in Africa. If we correct for the total forest area of Africa (635 Mha), our estimate is 316 Tg C y^{-1} which is comparable with the estimate of Houghton (2003) and thus we can keep it as first approximation of the value of SSA emission by deforestation in our carbon balance calculation.

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3.5 The role of forest degradation (FD) in the SSA carbon balance

Deforestation and forest degradation are two different processes with different ecological consequences. Deforestation involves cutting, damaging and burning of forest and is mainly associated with slash and burn agriculture (FAO, 2006) in SSA, whereas forest degradation is mainly related to logging activities and forest encroachment by local population. Furthermore industrial operations are expanding, oil palm plantation has been expected to increase rapidly and the combination of rapid population growth and low land and labour cost put increasing pressure on the forest margins, which are already degraded.

While logging activities mostly correspond to clear-cutting practices in Asia and America, in tropical Africa selective logging is practised. Few studies have so far attempted to estimate the impact of forest degradation in SSA. Degradation is less well documented than deforestation and is also more difficult to map. While deforestation due to cropland conversion can be reported by satellite imageries, forest degradation can not be easily accounted by remote sensing tools. Moreover, estimating the logging impact on C stocks it is difficult because of the missing information on illegal logging practices and the poorly documented amount of legal logging. However, when considering the impact of logging activities on C stocks, Brown et al. (2005) reported C losses of about 10 Mg C ha^{-1} of tropical forest in Congo. By extrapolating this value using the area under forest management as reported in Table 4 for Central Africa and scaled to the overall SSA forest area, we obtain an annual emission rate for degradation equal to 772 Tg C y^{-1} .

To our knowledge, no data were available on the impact of degradation on C stocks, therefore an alternative method to derive degradation emission rates was also used by assuming that C stocks in degraded forest were close to those measured in secondary forest (Fig. 4). From the difference between carbon stock of a natural forest and a degraded one it was estimated that the conversion from forest to degraded forest led to C losses of about 98 Mg C ha^{-1} .

After logging a natural regeneration of a secondary forest takes place and can revert

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carbon losses recovering carbon stocks at a certain point in time. Very few studies report the natural capacity of African ecosystems to regenerate after perturbations. Kotto-Same (1997) reported that about 74% of aboveground C was regenerated after a period of fallow of 18 years. According to the regression between time of fallow and C stocks, the total system C would be equal to the original natural forest after a period of 24 years (Kotto-Same, 1997).

In a semi-deciduous forest of Ghana that was logged in the 1950s, inventory of forest with three types of forest management revealed that there were no significant difference in above ground biomass among a natural protected forest, a forest that was logged in the 1950s and forest that was under tree shelter-wood system in the 1950s (Henry et al., unpublished) (Fig. 6). Taking into account a recovery period of 24 years and the current projections for timber logging in the Central African belt, we can arrive to an estimate of emissions from forest degradation for SSA of 309 Tg C y^{-1} .

3.6 A first synthesis of the CarboAfrica results

Table 5 summarises the first numbers derived mainly from the CarboAfrica estimates compared to UNFCCC national reporting estimates. This attempt is still very preliminary and highlights the need for increasing field measurements and improving modelling analysis, but at least can give a relative comparison of the size of the different fluxes.

By the preliminary CarboAfrica results, the provisional carbon balance of SSA varies from around a smaller value of 0.43 Pg C y^{-1} (using in situ measurements for savanna NEP) to a large sink of 2.53 Pg C y^{-1} (using the model estimates for savanna NEP). UNFCCC estimates lead to a moderate carbon sink of 0.58 Pg C y^{-1} , but they do not consider explicitly the net ecosystem productivity of savannas. Other studies, such as Williams et al. (2007) and Ciais et al. (2008), showed a neutral balance or a small sink of 0.15 Pg C y^{-1} , respectively. Therefore SSA seems to be a carbon sink, but there is still a high uncertainty especially about the savanna role (depending on the used data: models, in situ, national communications), that leads in turn to a high uncertainty

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about this sink value. The few available annual values from in situ estimates highly differ each other, and the average model result also hides a large variability among the different model outputs, ranging from 1.3 to 3.9 Pg C y⁻¹. Moreover, terrestrial ecosystem models have not been used in-depth for savanna ecosystems up to now, and it is likely that a number of crucial processes are not yet well represented. This highlights a crucial research need as the importance of African savannas for dynamics of the African carbon balance is also seen in their large interannual variability, that seems to be strongly related to water balance. In addition, further studies are also needed to better quantify the CH₄ source value represented by termite activity in Africa and the role of land characteristics and disturbance on this source. Hence, increasing the field efforts and improving the terrestrial modelling capacity for these regions shall be a key focus in future African carbon-cycle research, in particular in the frame of the CarboAfrica project, that is producing new carbon flux data to refine and improve the above estimates.

4 Conclusions

The preliminary results of the CarboAfrica project highlighted that the SSA carbon balance is a delicate equilibrium between a number of large fluxes, that are both human and climate related, resulting in a probable carbon sink value. There is still a high uncertainty about this sink value, due to 1) the current data used which are preliminary and need validation; 2) the generalization of the Africa's land surface considered as savanna, that leads to a consequent overestimation of the total savanna NEP, 3) the lack of process representation in terrestrial models, and 4) the lack of an optimal coverage of the most representative ecosystem types (in particular tropical forests). Nevertheless, this first analysis shows that Africa could have a probable potential for carbon sequestration larger than expected, which should not be ignored for studies of global carbon cycle-climate interactions.

Savannas play a dominant role in shaping the SSA carbon balance, considering their large land cover, their fire regime, and the strong interannual variability and de-

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pendence of savanna plant productivity on climate drivers, particularly the available soil water.

The forest net carbon budget of SSA seems to be almost in equilibrium since deforestation and forest degradation are nearly balanced by forest NEP.

5 By this result a critical and urgent need for better understanding the main components of the African carbon balance have emerged, in particular for better addressing the role of savannas and tropical forests. Moreover, further studies on disturbances and plant and soil processes, including methane and nitrogen fluxes, are needed to better understand the role of CO₂ and other non CO₂ greenhouse gases in the overall
10 SSA GHGs budget. This interest is growing from the fact that agriculture is rapidly expanding also in response to biofuels demand. This rapid change in the SSA landscape has also to be considered in future projection of the carbon cycle of the region.

CarboAfrica project with its observational network can indeed provide a unique and increased dataset of field measurements for improving model parameterization and
15 validate African regional estimates. The next researches in the frame of the CarboAfrica project will try to reduce the uncertainties in order to clarify the Sub-Saharan African role in the global carbon cycle.

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Table 1. GHGs total emission estimates (above) and pro-capita values (below) for three different African regions: Northern Africa (NA), Sub-Saharan Africa (SSA) and South Africa (SA). The following sectors were considered: anthropogenic emissions (regrouping emissions from the energy, industry and waste sectors); agriculture emissions; Land Use Change and Forestry (LUCF) emissions; and removals. Data were processed from the African countries national communication to the United Nations Framework Convention on Climate Change (UNFCCC). All data were converted to CO₂ equivalent on the base of Global Warming Potential reported in IPCC (2007b). South Africa’s emissions by LUCF sector is zero because of intensive afforestation activities, expansion of plantations and conservation policies. See Sect. 2.1.5 for more details.

Region	Emissions sources					
	Anthropogenic [Tg eq CO ₂]	Agriculture [Tg eq CO ₂]	LUCF [Tg eq CO ₂]	Total [Tg eq CO ₂]	Removals [Tg eq CO ₂]	Net emission [Tg eq CO ₂]
NA	235	51	25	312	25	287
SSA	858	393	1501	2753	4042	–1289
SA	364	39	0	403	19	384
Total Africa	1458	483	1527	3467	4085	–618

Pro-capita	Emissions sources					
	Anthropogenic [Mg eq CO ₂]	Agriculture [Mg eq CO ₂]	LUCF [Mg eq CO ₂]	Total [Mg eq CO ₂]	Removals [Mg eq CO ₂]	Net emission [Mg eq CO ₂]
NA	1.7	0.4	0.2	2.2	0.2	2.0
SSA	1.4	0.6	2.4	4.3	6.4	–2.0
SA	8.0	0.9	0.0	8.9	0.4	8.5
Total Africa	1.8	0.6	1.9	4.2	5.0	–0.8

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Table 2. Global Primary Productivity (GPP), Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP) in different African ecoregions (as defined by Weber et al., 2008). Data are presented per unit of surface (a) and extended to different African regions (b). Data were extrapolated from Weber et al. (2008).

(a)	GPP g C m ⁻² y ⁻¹	NPP g C m ⁻² y ⁻¹	NEP g C m ⁻² y ⁻¹
Northern Savanna Belt	1341±474	649±184	248±50
Central Africa Tropical Forest	2558±733	1151±431	345±241
Horn of Africa	919±386	428±160	155±29
Suthern Raingreen woodland	1572±576	702±213	262±64
South African Grassland	831±348	367±111	139±32

(b)	GPP Pg C y ⁻¹	NPP Pg C y ⁻¹	NEP Pg C y ⁻¹
Northern Savanna Belt	8.83±3.12	4.27±1.21	1.63±0.33
Central Africa Tropical Forest	7.31±2.09	3.29±1.23	0.98±0.69
Horn of Africa	1.52±0.64	0.71±0.26	0.26±0.05
Suthern Raingreen woodland	7.40±2.71	3.31±1.00	1.23±0.30
South African Grassland	2.12±0.89	0.93±0.28	0.35±0.08
Sub-Saharan Savannas	19.87±3.69	9.22±1.76	3.48±0.67
Sub-Saharan Africa	27.17±3.36	12.51±1.59	4.46±0.58

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Table 3. Net Primary Productivity (NPP) and Net Ecosystem Productivity (NEP) in different savannas. When needed original data were converted to $\text{Mg C ha}^{-1} \text{y}^{-1}$. * = CarboAfrica data.

Citation	Region	NPP	NEP
		$\text{Mg C ha}^{-1} \text{y}^{-1}$	$\text{Mg C ha}^{-1} \text{y}^{-1}$
Scholes and Walker (1993)	Southern Africa	3.81	1.23
Chidumayo (2002)	Southern Africa		0.42
Veenendaal et al. (2004)	Southern Africa		0.12
Grace et al. (2006)	Africa	5.8	
Grace et al. (2006)	Global	7.2	0.14
van der Werf et al. (2006)	Africa	18.2	
Grace, unpublished in Ciais et al. (2008)	Africa	5.9	
Brümmer et al. (2008)	West Africa		4.53
*Lehsten et al. (2008)	Africa	6.3	
*Kutsch and Merbold (unpublished)	Southern Africa	16.27	0.05
*Archibald et al. (2008)	Southern Africa		-0.25
	Average	9.07 ± 5.70	0.89 ± 1.67

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Table 4. Data related to deforestation and forest degradation in the Congo Basin African countries. Source of data is specified in the footnote.

	Cameroon	Gabon	Congo	DRC	CAR	Equatorial Guinea	Central Africa
Land area (1000 ha) ^a	46 540	25 767	34 150	226 705	62 298	2805	398 265
Dense forest area	21 436	21 190	25 914	124 566	8227	1843	20 3176
Production forests	10 500	19 000	12 000	87 000	3300	1250	133 050
Area under forest management process	4348	6368	7115	9680	2994	55	30 560
Gross Deforestation (%) ^b	-0.28	-0.16	-0.12	-0.33	-0.15	-0.35	-0.27
Net Deforestation (%)	-0.19	-0.12	-0.03	-0.26	-0.07	0.41	-0.19
Net Degradation (%)	-0.02	-0.09	-0.01	-0.15	-0.02	0.52	-0.1
FAO deforestation (%)	-0.9	0.05	-0.1	-0.4	-0.1	-0.6	-0.36
C stocks (Mg C ha ⁻¹) ^c							
Average SOC (0–30 cm)	52	51	75	49	41	70	54
Average aboveground C	90	167	231	173	123	70	142
Average root C	17	32	44	33	23	13	23
Impact of deforestation (Tg) ^d							
Conversion to cropland	4.38	4.73	1.70	64.54	2.15	–	77.50
Conversion to agroforestry	1.04	1.42	0.50	19.81	0.63	–	23.40
Impact of degradation (Tg)	0.29	2.46	0.39	26.11	0.42	–	29.68
Expected C losses from logging (Tg) ^e	44.35	64.96	72.57	98.73	30.54	0.56	311.71

^a Data on land area and forest management is obtained from Nasi (2006)

^b Data from deforestation and degradation rate were obtained from CARPE (2006) and FAO (2006)

^c SOC was obtained from Henry et al. (2009), aboveground C was obtained from FAO (2007) and root C was obtained from aboveground biomass using root/shoot ration for tropical humid region (Jackson, 1996)

^d Impact of deforestation and degradation was obtained using the % of C impacted by forest conversion

^e Impact of logging was estimated using a coefficient of 10.2 Mg C ha⁻¹ obtained from Brown (2005)

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Table 5. Comparison between a preliminary carbon balance estimates for SSA, derived from this study and the UNFCCC national communication data. NEP(F) = Net Ecosystem Productivity of Forests; NEP(S) = Net Ecosystem Productivity of Savannas; D = emissions from Deforestation; FD = emissions from Forest Degradation; EFS = Emissions from Savanna Fires; A = emissions from Agriculture; CB = Carbon Balance of Sub-Saharan Africa. Data are given in Pg C y⁻¹. NEP(S) estimates are from: a) models; b) in situ measurements.

This study	Sinks		Sources			NET	
	NEP(F)	NEP(S)	D	FD	EFS	A	CB
a	0.98	3.48	-0.25	-0.77	-0.79	-0.12	2.53
b	0.98	1.38	-0.25	-0.77	-0.79	-0.12	0.43
UNFCCC	Removals 1.12		LUCF emissions -0.42			A -0.12	0.58

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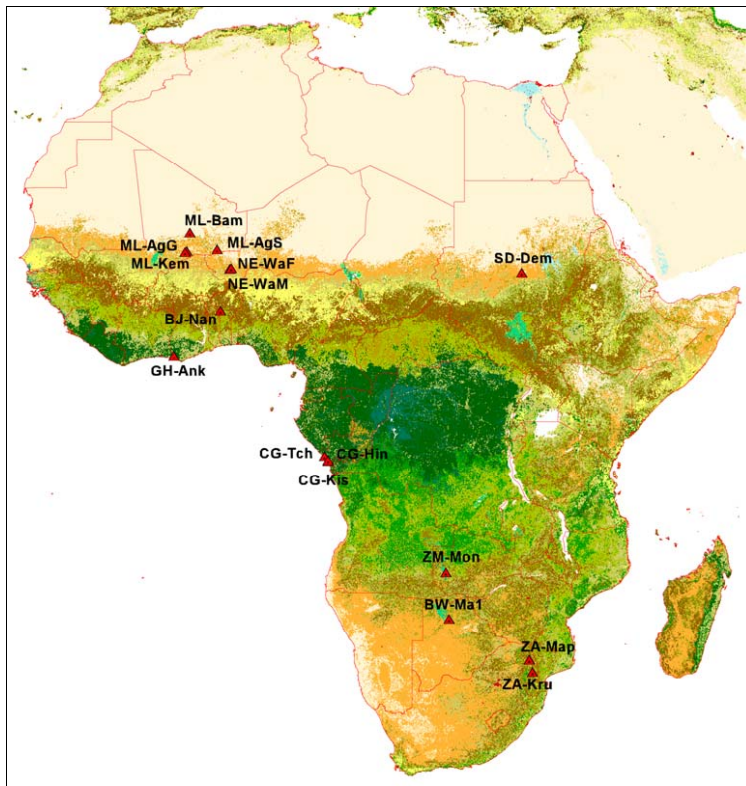


Fig. 1. GlobalCover continental map of Africa Land Cover (from ESA – European Space Agency, <http://ionia1.esrin.esa.int/index.asp>) showing the location of the sixteen eddy covariance sites that are run by or contribute data to the CarboAfrica project. The GlobCover dataset is derived from December 2004–June 2006 observations of 300 m MERIS sensor on board the ENVISAT satellite mission.

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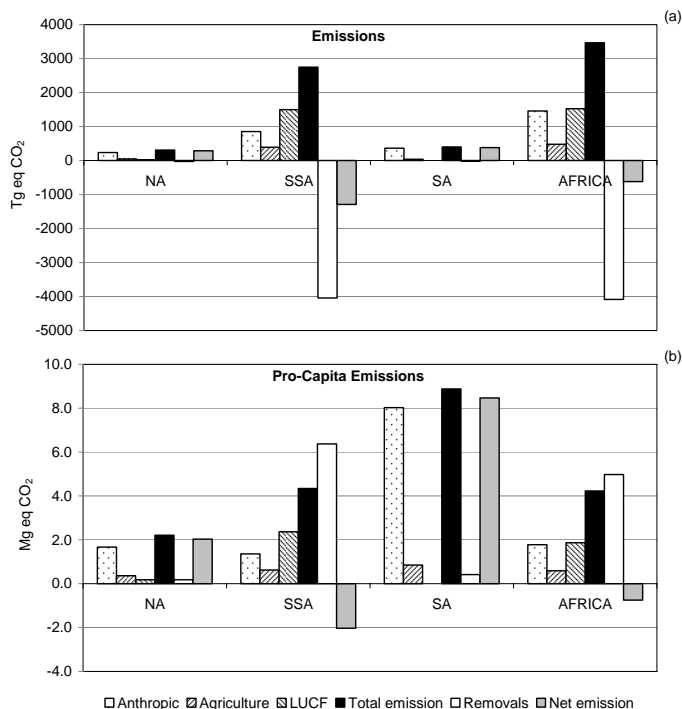


Fig. 2. GHGs total emission data (a) and pro-capita values (b) from different sectors for three different African regions: Northern Africa (NA), Sub-Saharan Africa (SSA) and South Africa (SA). Data were processed from the African countries national communication to the United Nations Framework Convention on Climate Change (UNFCCC). See also Sect. 2.1.5 and Table 1 for more details.

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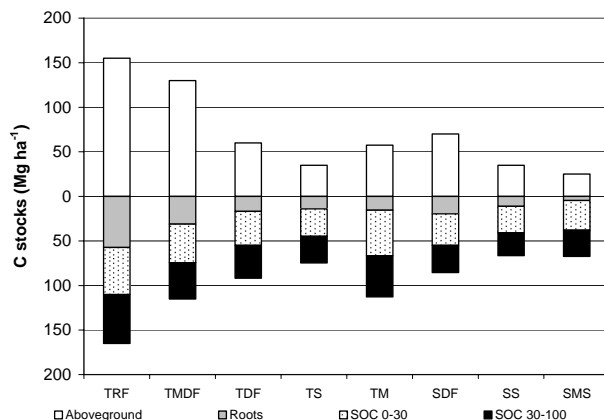


Fig. 3. Distribution of C stocks among different African forest ecosystems. TRF = Tropical rain forests, TMDF = Tropical moist deciduous forests, TDF = Tropical dry forests, TS = Tropical shrublands, TM = Tropical mountains, SDF = Subtropical dry forests, SS = Subtropical steppes, SMS = Subtropical mountain systems. Aboveground biomass and root C were obtained from IPCC (2007) and SOC was obtained from Henry et al. (2009).

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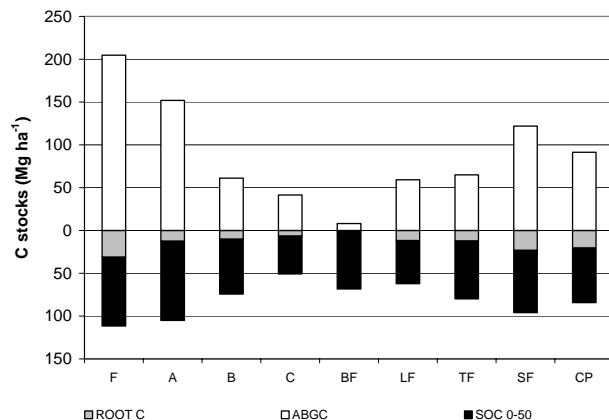


Fig. 4. Carbon stocks in humid tropical ecosystems of Cameroon under different management. F = Forest, A = Agroforest, B = Banana farm, C = Cropland, BF = Bush fallow; LF = Long fallow, TF = Tree fallow, SF = Secondary forest, CP = Cocoa plantation. Data were obtained from Kotto-Same et al. (1997) and Kanmegne (2004).

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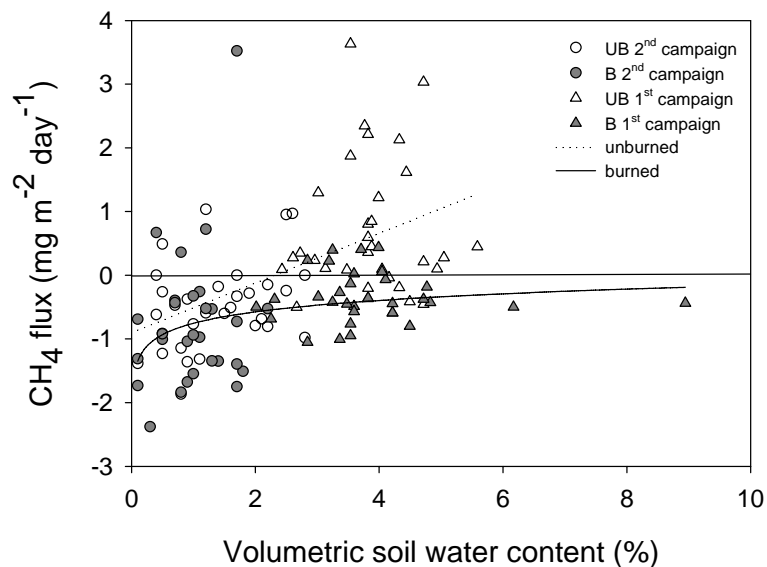


Fig. 5. CH₄ fluxes measured in a burned (B) and in an unburned (UB) grassland savanna in Congo Brazzaville during two sampling campaigns (2007–2008) plotted against soil water content measured close to the sampling chambers. Lines indicate the best fit of plotted data.

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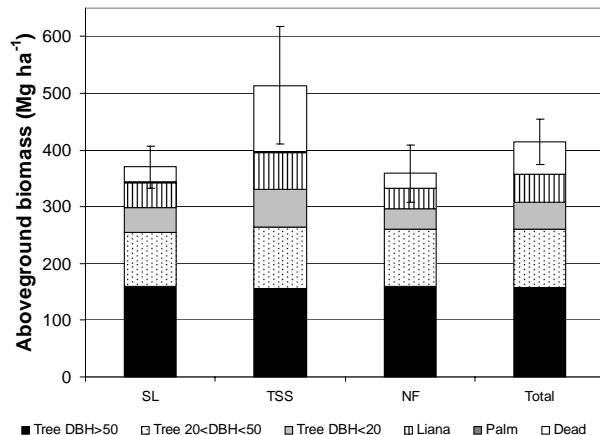


Fig. 6. Distribution of aboveground biomass in three historically different forest types in sub-humid forest zone of Ghana. Standard error is shown. SL = Selective logging, TSS = Tree Shelterwood system, NF = Natural forest. Data from Henry et al. (unpublished).

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