

Anthropogenic CO₂ emissions in Africa

J. G. Canadell¹, M. R. Raupach¹, and R. A. Houghton²

¹Global Carbon Project, CSIRO Marine and Atmospheric Research, Canberra, ACT 2601, Australia

²Woods Hole Research Center, Falmouth, MA 02540, USA

Received: 1 September 2008 – Published in Biogeosciences Discuss.: 19 November 2008

Revised: 9 March 2009 – Accepted: 9 March 2009 – Published: 20 March 2009

Abstract. An understanding of the regional contributions and trends of anthropogenic carbon dioxide (CO₂) emissions is critical to design mitigation strategies aimed at stabilizing atmospheric greenhouse gases. Here we report CO₂ emissions from the combustion of fossil fuels and land use change in Africa for various time periods. Africa was responsible for an average of 500 Tg C y⁻¹ for the period 2000–2005. These emissions resulted from the combustion of fossil fuels (260 Tg C y⁻¹) and land use change (240 Tg C y⁻¹). Over this period, the African share of global emissions from land use change was 17%. For 2005, the last year reported in this study, African fossil fuel emissions were 285 Tg C accounting for 3.7% of the global emissions. The 2000–2005 growth rate in African fossil fuel emissions was 3.2% y⁻¹, very close to the global average. Fossil fuel emissions per capita in Africa are among the lowest in the world, at 0.32 t C y⁻¹ compared to the global average of 1.2 t C y⁻¹. The average amount of carbon (C) emitted as CO₂ to produce 1 US\$ of Gross Domestic Product (GDP) in Africa was 187 g C/\$ in 2005, close to the world average of 199 g C/\$. With the fastest population growth in the world and rising per capita GDP, Africa is likely to increase its share of global emissions over the coming decades although emissions from Africa will remain low compared to other continents.

ical trends. The two main anthropogenic CO₂ fluxes are emissions from the combustion of fossil fuels and net emissions from land use change, the latter being largely driven by deforestation in tropical regions (Canadell et al., 2007; Houghton, 2007). Knowledge of these fluxes and their characteristics is essential for the design of regional and global agreements aimed to stabilize greenhouse gas emissions over the coming decades.

Much of the focus on anthropogenic CO₂ emissions has been on the developed world and emerging economies in Asia which together account for over 80% of the cumulative CO₂ emissions and growth (Raupach et al., 2007).

With a population of 943 M (UNSD, 2008), Africa's economy is dominated by Least Developed Countries (LDCs) and Developing Countries (DCs), and accordingly its contribution to global fossil fuel emissions (8.2 Pg C y⁻¹ in 2005; Canadell et al., 2007) is smaller than the global per-capita average. However, there is an upward trend to African emissions as national economies undergo rapid development. In addition, CO₂ emissions from land use change (largely deforestation of tropical forests) globally contribute approximately 1.5 Pg C y⁻¹ (Canadell et al., 2007); Africa's contribution is poorly constrained. With the fastest population growth in the world, some economies rapidly developing, and new pressures on land to meet food and bioenergy demands, Africa is set for a growing influence on the global CO₂ balance.

Here we report a regional and temporal analysis for the continent of Africa on i) CO₂ emissions from the combustion of fossil fuels, and their underlying drivers and trends; and ii) the net CO₂ emissions from land use change and forestry, with historical trends. We place the findings in the global context and compare Africa with other major regions in the world.

1 Introduction

The wide acceptance of the existence of human-induced climate change, together with the dominant role of CO₂ as an anthropogenic greenhouse gas, has led to increasing interest in characterizing the regional contributions of anthropogenic CO₂ emissions, their underlying drivers, and their histor-



Correspondence to: J. G. Canadell
(pep.canadell@csiro.au)

2 Methods and datasets

2.1 Emissions and drivers from fossil fuel

We analyze CO₂ emissions from the combustion of fossil fuel for all countries in Africa for the period 1980–2005, using emissions data from the Energy Information Administration (EIA, 2008). In this data set, total fossil fuel emissions includes the consumption of solid, liquid and gas fuels, together with flaring of natural gas. Analyses were done for all African countries together, for Northern African and Sub-Saharan countries as separate groups, and for DCs and LDCs also as separate groups (according to the United Nations Statistics Division). We single out South Africa and Ethiopia as examples of a DC and LDC, respectively.

Northern Africa Countries: Algeria, Egypt, Libyan Arab Jamahiriya, Morocco, Sudan, Tunisia, and Western Sahara.

Sub-Saharan Countries: Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe.

Developing Countries (DCs): Algeria, Botswana, Cameroon, Egypt, Gabon, Ghana, Kenya, Libya, Malawi, Mauritius, Morocco, Namibia, Nigeria, Reunion, Seychelles, Somalia, South Africa, Sudan, Swaziland, Tunisia, Western Sahara, Zimbabwe.

Least Developed Countries (LDCs): Angola, Benin, Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Cote d'Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Mali, Mauritania, Mozambique, Niger, Republic of the Congo, Rwanda, Sao Tome and Principe, Senegal, Sierra Leone, Tanzania, Togo, Uganda, Zambia

We used a simplified form of the Kaya identity (Yamaji et al., 1991; Raupach et al., 2007) to analyze the drivers and trends of fossil fuel emissions:

$$F = Pgh,$$

where F is fossil fuel emissions, P is population, g is per-capita Gross Domestic Product, GDP/population, and h is the C intensity of the economy, as F/GDP .

Population data was obtained from the United Nations Statistics Division (UNSD, 2008) and GDP from the International Monetary Fund (IMF, 2008) based on Purchasing Power Parity. All GDPs are expressed in 2000 US dollars. The C intensity of the economy is the C emitted to produce 1 US\$ of GDP. This measure is the product of the energy

consumed per dollar of economic activity (the energy intensity of the economy) and the C emitted per unit of energy (the C intensity of the energy). We acknowledge that a significant economic activity in Africa might rely on traditional and non-market energies such as biomass.

A more extensive description of the datasets and an extended Kaya identity can be found at Raupach et al. (2007).

2.2 Emissions from land use change

C emissions from land use change and forestry were determined with data and a C tracking model as described in an earlier analysis of Sub-Saharan Africa (Houghton and Hackler, 2006). The model is a bookkeeping model based on a series of response curves that track the carbon in living vegetation, dead plant material, wood products, and soils for each hectare of land cultivated, harvested, or reforested. The present analysis updates the previous one in three ways. First, this analysis updates the earlier one to 2005 with data from the UN Food and Agriculture Organization's (FAO) 2005 Forest Resource Assessment (FRA) (FAO, 2006). Second, rates of deforestation for the 1990s were revised downward by 18% (FAO, 2006). Third, 16 countries in North Africa were also included in this analysis. For recent years (1980–2005) the approach used rates of deforestation and average biomass values reported by repeated FRAs by the UN (FAO, 1995, 2001b, 2006) and annual changes in land use reported since 1960 by FAOStat (FAO, 2001a) to determine annual net changes in the areas of forests, plantations, croplands, pastures, and shifting cultivation.

The rate of deforestation for shifting cultivation was obtained by the difference between the total deforestation rate of natural forests (1980–2005) and rate of increase in area of croplands. The estimate assumes that both of these reported rates are accurate, whereas, they are quite uncertain (Lanly, 2003). The percentage of deforestation attributed to shifting cultivation by this estimate, however, is similar to the percentages reported by Lanly (2003).

Rates of wood harvest were obtained from FAOStat (FAO, 2001a). Before 1960 rates of land-use change were assumed to have increased linearly from zero in 1900 to the rates given by FAOStat (FAO, 2001a). Rates of change were variable before ~1900, as lands abandoned from agriculture during periods of wars, epidemics, and famines were cleared again in subsequent years. In contrast to these variable changes, after 1900 both demographic and global economic incentives combined to increase the production of agricultural commodities (Kimble, 1962).

The net flux of C from industrial wood harvest, including C emissions from the decay of harvested products and C uptake from the recovery of harvested forests, were included in this analysis. Industrial wood accounted for ~10% of total harvests; fuelwood, for 90%. We did not explicitly include fuelwood in the analysis because most of the emissions would be offset by C accumulation in forests recovering from

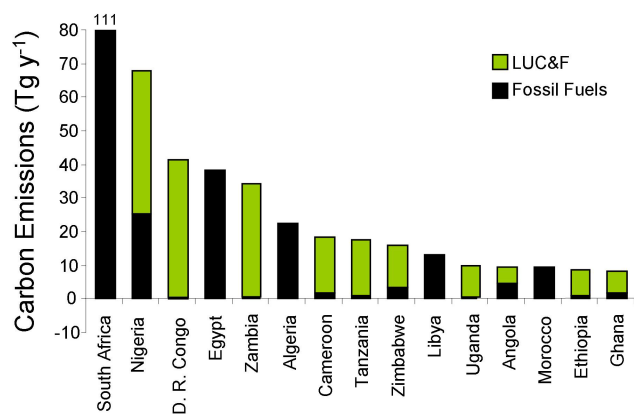


Fig. 1. Annual emissions of carbon (Tg C y⁻¹) from the combustion of fossil fuels (FF) and land use change and forestry (LUC&F). Top fifteen African countries averaged for the period 2000–2005.

harvest. Only in regions where fuelwood harvest exceeded regrowth, or vice versa, would there be a net C flux. Furthermore, more wood was burned annually as a result of conversion of forests to croplands and to shifting cultivation than as a result of fuelwood production, and some of this burned material would have been used for fuel. Thus, the net flux of C determined in this analysis includes most of the C emitted from use of fuelwood.

3 Results

3.1 Emissions and drivers from fossil fuel

Africa was responsible for 2.5% of the global cumulative CO₂ emissions from fossil fuel for the period 1980–2005, while accounting for 13.8% of the global population in 2005. Average annual emissions were 260 Tg C for the period 2000–2005 of which 77 Tg C y⁻¹ occurred in Northern Africa (7 countries) and 183 Tg C y⁻¹ in Sub-Saharan countries (48 countries). Categorized by economic status, 22 DCs were responsible for 93% of total African emissions (240 Tg C y⁻¹) and 33 LDCs were responsible for the remaining 7% (19 Tg C y⁻¹).

South Africa was the highest emitter in Africa with an average of 110.1 Tg C y⁻¹ for the period 2000–2005 followed by Egypt (38.2 Tg C y⁻¹), Nigeria (25.1 Tg C y⁻¹) and Algeria (22.4 Tg C y⁻¹) (Fig. 1). For the last year reported in this study, 2005, Africa emitted 285 Tg C accounting for 3.7% of the global emissions and 3.6% of global emissions growth (Fig. 2).

Emissions per capita in African countries are among the lowest in the world. In 2005, emissions per capita were 0.32 t C y⁻¹ averaged for the whole of Africa, 2.43 t C y⁻¹ for South Africa and 0.02 t C y⁻¹ for Ethiopia. For comparison, the global average was 1.2, USA was 5.5 and Europe was 2.5 (Fig. 2).

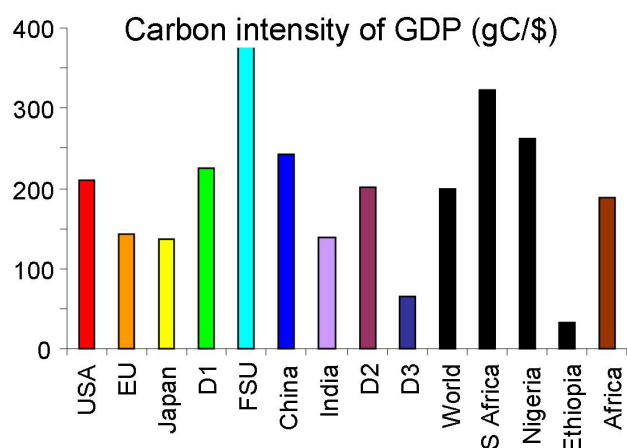
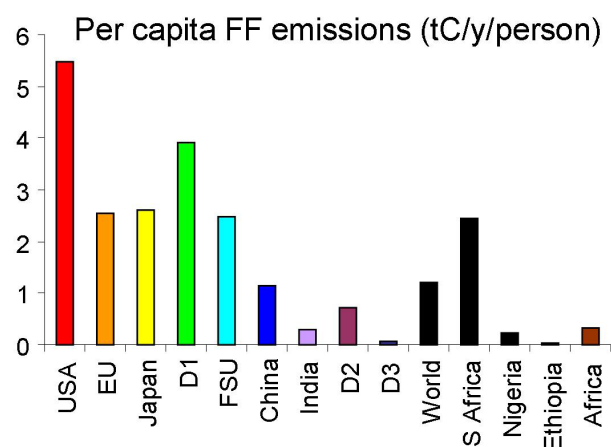


Fig. 2. Per capita gross domestic product (US\$) and carbon intensity of the economy (g C/US\$) for several regions and countries in 2005.

The C intensity of the African economy in 2005 (or the amount of C emitted as CO₂ to produce 1 US\$ of GDP) was 187 g C/\$ close to the world average of 199 g C/\$. South Africa and Ethiopia had C intensities of 321 and 31, respectively. For comparison, the C intensity of the Former Soviet Union was 464 g C/\$, USA was 210 g C/\$, Europe was 143 g C/\$ and Japan 136 g C/\$ (Fig. 2).

Figure 3 shows the trends of fossil fuel emissions and the drivers of those emissions for the period 1980–2005 as per the Kaya identity: population, per capita GDP (US\$), and C intensity of the economy (g C/US\$). Emissions from Africa have grown at a faster pace than global average and tightly followed population growth. The coupling between emissions and population was strong for DCs and weaker for LDCs where C emissions outpaced population growth due to a simultaneous strong growth in per capita GDP.

The C intensity of the economy in most African countries increased (worsened) between 1980 and the early 1990s and declined (improved) thereafter, with most of the improvement driven by DCs.

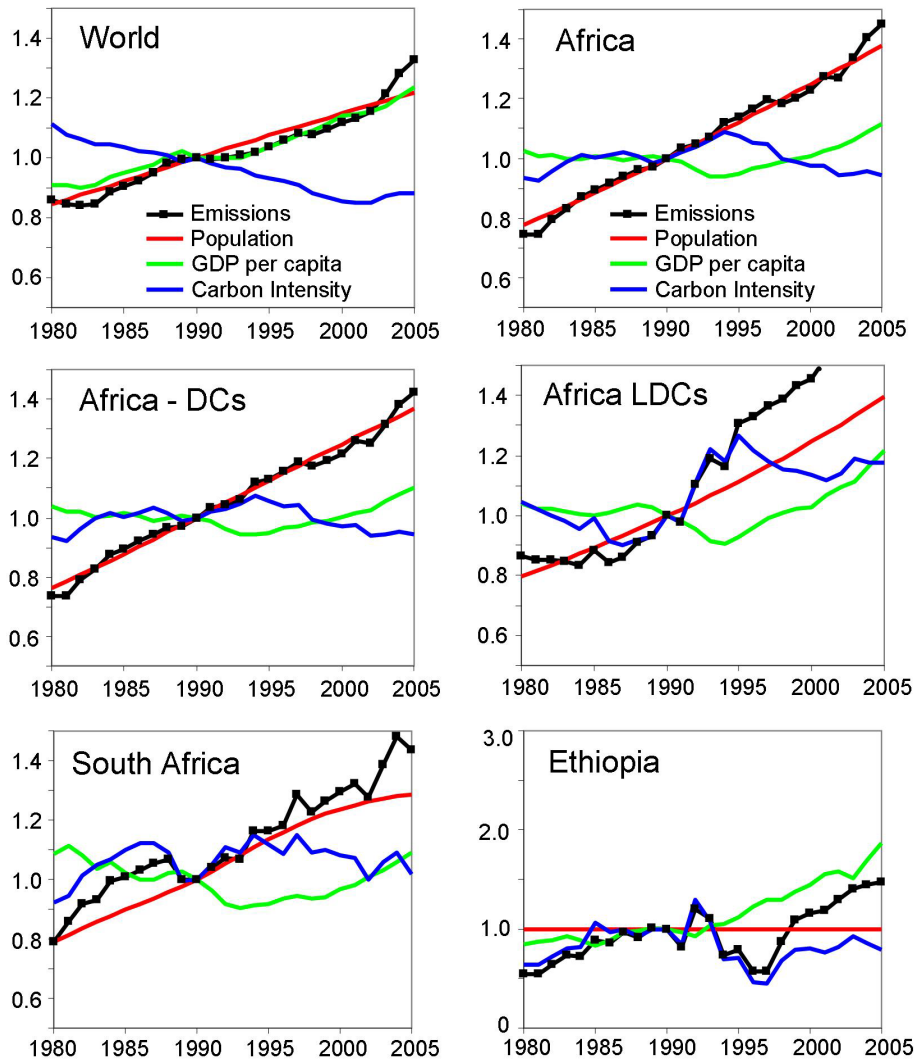


Fig. 3. Drivers of fossil fuel emissions as per the Kaya identity for the period 1980–2005. Emissions = Population \times Gross Domestic Product (GDP)/Population \times Emissions/GDP. All quantities were normalized to 1 in 1990 for the purpose of comparing trends, therefore the figures provide no information on the absolute values which are shown in Figs. 1 and 2.

South Africa showed a rapid growth in emission tightly coupled with population growth and more recently also with increased per capita GDP. In contrast, Ethiopia's rapid growth in emissions was driven largely by the growth in per capita GDP while population and C intensity remained steady.

3.2 Emissions from land use change

Rates of deforestation in most parts of Africa increased between 1900 and 1990 (Fig. 4), and thereafter have leveled off (average of 4.47×10^6 ha y^{-1} in the 1990s and 4.13×10^6 ha y^{-1} during the first half decade of the 2000s). The fraction of deforestation for shifting cultivation decreased from $\sim 70\%$ for the years 1975–1997 to only 3% for the period 2000–2005. The reduction is sharper than that reported by Lanly (2003), who compared the years around

1980 (64%) with the period 1988–1997 (14%). The establishment of plantations ($\sim 0.067 \times 10^6$ ha yr^{-1} over the period 1990–2005) has offset little of this forest loss. Net C emissions from deforestation and afforestation, together, averaged $240 \text{ Tg C } y^{-1}$ over the period 1990–2005. Most of the emissions were from deforestation for agriculture (41% for permanent croplands; 48% for shifting cultivation). Industrial wood harvest accounted for 11% of the total net flux in this period.

Individual regions within Africa show small differences in both the historical pattern and the magnitude of emissions (Fig. 4). Only in North Africa, where the establishment of plantations has recently exceeded deforestation, has the flux of C been a net sink recently ($3 \text{ Tg C } y^{-1}$), small in comparison to the sources from the other regions ($40\text{--}72 \text{ Tg C } y^{-1}$).

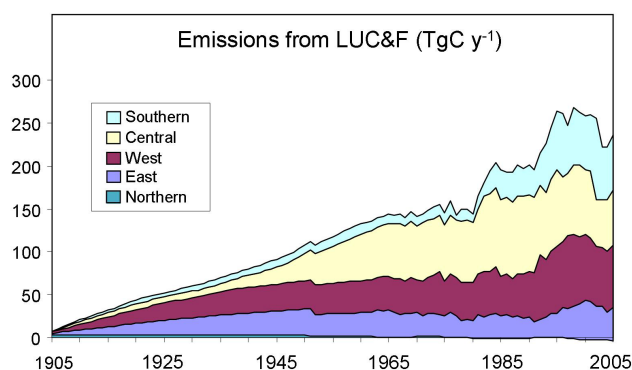


Fig. 4. Annual emissions of carbon (Tg C y⁻¹) from changes in land-use change and forestry in four African regions during the period 1900–2005.

The regional net C emissions determined in this work were divided among countries based on (1) rates of deforestation (FAO, 2006) and (2) average forest biomass for each country (FAO, 2001). Countries with higher rates of deforestation and/or higher average biomass were assigned a greater proportion of the regional emissions than countries with low rates of deforestation and low average biomass. According to these calculations, 15 countries accounted for about 90% of the emissions from land-use change (Fig. 1).

4 Discussion

Average total anthropogenic C emissions in Africa were 500 Tg C y⁻¹ for the period 2000–2005: 260 Tg C y⁻¹ from the combustion of fossil fuels and 240 Tg C y⁻¹ from land use change. Emissions from land use change thus accounted for 48% of total anthropogenic emissions, giving Africa a unique emission profile in the global context: significant emissions from deforestation and relatively low emissions from fossil fuel burning given the size of its population.

At the national level, however, we often observe a negative correlation between emissions from fossil fuel and land use change: countries with high fossil fuel emissions have low emissions from land use change (e.g., South Africa, Egypt, Algeria, Libya) and vice versa (e.g., D.R. Congo, Zambia, Cameroon, Tanzania) (Fig. 1).

Fossil fuel emissions were dominated by South Africa and Northern African countries, while emissions from land use change were dominated by the central African countries such as Nigeria, the Democratic Republic of the Congo and Zambia (Fig. 1).

Emissions varied among countries: 10 countries were responsible for 90% of all fossil fuel emissions while 15 countries accounted for 90% of all emissions from land use change (of 55 African countries and dependencies reported in this study) (Fig. 1). Six countries are in both lists of top emitters: Nigeria, Angola, Zimbabwe, Sudan, Cameroon, and

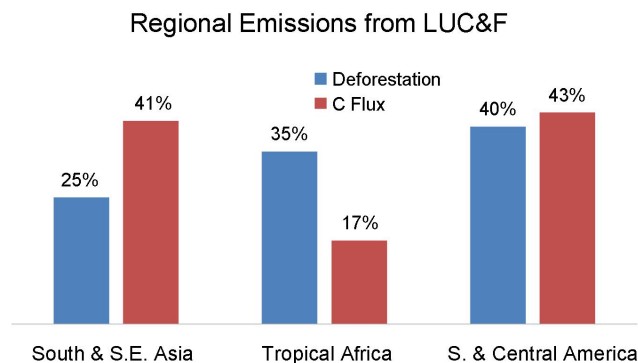


Fig. 5. Percent of total tropical deforestation and total carbon emissions for each region during the period 2000–2005.

Ghana. Nigeria ranks in the top three in both lists with a total combined emissions of 67.7 Pg C y⁻¹, second in total anthropogenic CO₂ emissions after South Africa.

The African share of global emissions from fossil fuel was 2.3% and per capita emissions were among the lowest in the world. However, the observed growth rate of emissions (above the world average), caused by rapid growth in per capita GDP and the fastest population growth in the world, will likely lead to increased emission over the next decades. Nevertheless, emissions per capita will remain low by comparison with other continents.

Improvements in the C intensity (decline) remain a challenge for African countries particularly for LDCs whose C intensity has stalled or worsened (increased) since 2000. This latter trend was also found at the global level driven largely by China's strong economic performance coupled with increased C intensity of its energy sector (Raupach et al., 2007). Improvements in the C intensity of the economy results in decreased pollution and increased energy efficiency, characteristics to which all nations aspire.

Although rates of deforestation in Africa were higher than those in tropical Asia and nearly as high as those in Latin America, the resulting net annual CO₂ emissions from Africa were lower than from the other regions (Fig. 5). Africa accounted for a third of tropical deforestation between 2000 and 2005 (FAO, 2006) but only 17% of the CO₂ emissions from land-use change (0.24 Pg C y⁻¹ out of a total of 1.47 Pg C y⁻¹) (Canadell et al., 2007). The difference suggests that a greater proportion of deforestation in Africa is of dry forests with low biomass. A recent study of deforestation in humid tropical forests supports this observation. Hansen et al. (2008) reported that the rate of deforestation of humid forests in Africa accounted for only 5.4% of the total rate for humid forests. The much higher rates reported by FAO (2006), in contrast, include dry (lower C stocks) as well humid forests.

Anthropogenic CO₂ emissions of 0.5 Pg C y⁻¹ (500 Tg C y⁻¹) in Africa are the smallest of all inhabited continents but

not insignificant compared to global emissions of 8 Pg C y⁻¹. The rate of growth in emissions, however, is above the world average, and Africa's share of global emissions is likely to increase in the coming decades. Opportunities exist to leverage regional and international support for development pathways that reduce deforestation and embrace cleaner and more efficient energy systems consistent with regional and global sustainability goals (Canadell and Raupach, 2008; Gullison et al., 2007; IPCC, 2007).

Acknowledgements. This paper arose from the partnership of the Global Carbon Project (GCP) with CarboAfrica, specifically from a joint meeting in Kruger National Park, South Africa, in 2007. We thank Navin Ramankutty for constructive suggestions for the manuscript. Support for RAH was from the US National Science Foundation (grant number DEB0639950). This paper is a contribution to the "Global Carbon Budget and Trends" activity under the umbrella of the GCP of the Earth System Science Partnership. Support for the GCP from the Australian Climate Change Science Program is appreciated.

Edited by: F. Joos

References

- Canadell, J. G. and Raupach, M. R.: Managing Forests for Climate Change Mitigation, *Science*, 320, 1456–1457, doi:10.1126/science.1155458, 2008.
- Canadell, J. G., Le Quéré, C., Raupach, M. R., Field, C. B., Buitenhuis, E. T., Ciais, P., Conway, T. J., Gillett, N. P., Houghton, R. A., and Marland, G.: Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks, *Proceedings of the National Academy of Sciences*, 104, 18866–18870, doi:10.1073/pnas.0702737104, 2007.
- EIA: Energy Information Administration, <http://www.eia.doe.gov/environment.html>, 2008.
- FAO: FAOSTAT DATA, Food and Agriculture Organization, <http://apps.fao.org/>, 2001a.
- FAO: Global Forest Resources Assessment 2000. Main report. Food and Agriculture Organization, Forestry Paper 140, Rome, 2001b.
- FAO: Forest Resources Assessment 1990. Global Synthesis, FAO Forestry Paper 124, FAO, Rome, 2005.
- FAO: Global Forest Resources Assessment 2005, FAO Forestry Paper 147, Rome, 2006.
- Gullison, R. E., Frumhoff, P. C., Canadell, J. G., Field, C. B., Nepstad, D. C., Hayhoe, K., Avissar, R., Curran, L. M., Friedlingstein, P., Jones, C. D., and Nobre, C.: Tropical forests and climate change, *Science*, 316, 985–986, 2007.
- Hansen, M. C., Stehman, S. V., Potapov, P. V., Loveland, T. R., Townshend, J. R. G., DeFries, R. S., Pittman, K. W., Arunarwati, B., Stolle, F., Steininger, M. K., Carroll, M., and DiMiceli, C.: Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data, *Proceedings of the National Academy of Sciences*, 105, 9439–9444, 2008.
- Houghton, R. A.: Balancing the global carbon budget, *Annu. Rev. Earth Planet. Sci.*, 35, 313–347, 2007.
- Houghton, R. A. and Hackler, J. L.: Emissions of carbon from land use change in sub-Saharan Africa, *J. Geophys. Res.*, 111, G02003, doi:10.1029/2005JG000076, 2006.
- IMF: World Economic Outlook Database, International Monetary Fund, <http://www.imf.org/external/data.htm>, 2008.
- IPCC: Climate Change 2007: Mitigation of Climate Change, contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer, L. A., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 851 pp., 2007.
- Kimble, G. H. T.: Tropical Africa: Land and Livelihood, vol. 1, Doubleday, New York, 1962.
- Lanly, J.-P.: Deforestation and forest degradation factors. Proceedings of the XII World Forest Congress, Quebec, Canada, <http://www.fao.org/docrep/article/wfc/xii/ms12a-e.htm>, 2003.
- Raupach, M. R., Marland, G., Ciais, P., Le Quere, C., Canadell, J. G., Klepper, G., and Field, C. B.: Global and regional drivers of accelerating CO₂ emissions, *PNAS*, 0700609104, 2007.
- UNSD: Demographic Year Book 2006, United Nations Statistics Division, <http://unstats.un.org/unsd/demographic/products/dyb/dyb2.htm>, 2008.
- Yamaji, K., Matsuhashi, R., Nagata, Y., and Kaya, Y.: An Integrated System for CO₂/Energy/GNP Analysis: Case Studies on Economic Measures for CO₂ Reduction in Japan, Workshop on CO₂ Reduction and Removal: Measures for the Next Century, 19 March, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1991.