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Discussions

The carbon balance of South America: status, decadal trends and main determinants

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Abstract

We attempt to summarize the carbon budget of South America and relate it to its dominant controls: population and economic growth, changes in land use practices and a changing atmospheric environment and climate. Flux estimation methods which we consider sufficiently reliable are fossil fuel emission inventories, biometric analysis of old-growth rainforests, estimation of carbon release associated with deforestation based on remote sensing and inventories, and finally inventories of agricultural exports. Other routes to estimating land-atmosphere CO_2 fluxes include atmospheric transport inverse modelling and vegetation model predictions but are hampered by the data paucity and the need for improved parameterisation. The available data we analyze suggest that South America was a net source to the atmosphere during the 1980s (~ 0.3–$0.4\,\mathrm{Pg\,C\,yr^{-1}}$) and close to neutral ($\sim 0.1\,\mathrm{Pg\,C\,yr^{-1}}$) in the 1990s with carbon uptake in old-growth forests nearly compensating carbon losses due to fossil fuel burning and deforestation. Annual mean precipitation over tropical South America measured by Amazon River discharge has a long-term upward trend, although over the last decade, dry seasons have tended to be drier and longer (and thus wet seasons wetter), with the years 2005 and 2010 experiencing strong droughts. It is currently unclear what the effect of these climate changes on the old-growth forest carbon sink will be but first measurements suggest it may be weakened. Based on scaling of forest census data the net carbon balance of South America seems to have been an increased source roughly over the 2005–2010 period (a total of $\sim 1\,\mathrm{Pg\,C}$ of dead tree biomass released over several years) due to forest drought response. Finally, economic development of the tropical forest regions of the continent is advancing steadily with exports of agricultural products being an important driver and witnessing a strong upturn over the last decade.

1 Introduction

We review the carbon balance and trends over the last decades, as well as their determinants, for South America as part of a catalogue of similar regional syntheses covering the globe for the RECCAP ("REgional Carbon Cycle Assessment and Processes") effort. South America as a region has attracted the attention of global carbon cycle and climate researchers mainly because of the very large amount of organic carbon stored in its rainforests. Amazonia contains on the order of 95–120 Pg C in living biomass and additional 160 Pg C in soils (Gibbs et al., 2007; Malhi et al., 2006; Saatchi et al., 2011; Jobaggy and Jackson 2000; Appendix 2). To place this in perspective in total this is approximately half of the amount of carbon contained in the atmosphere before the beginning of the industrialization in the 18th century. A substantial fraction of these carbon pools is thus amenable to release to the atmosphere on short timescales (decades) by deforestation. On the other hand, because of their vast size the forests also have the potential to slightly moderate the global carbon problem by taking up carbon and thereby mitigating some emissions due to the burning of fossil fuels. However, this effect will eventually saturate. Hence two main factors will likely dictate future changes in forest biomass. Firstly, the current fast demographic and economic development (e.g., Soares-Filho et al., 2006), and secondly changes in forest biomass and biome boundaries caused by changes in atmospheric gas composition and any associated climate change (e.g., Phillips et al., 2009; Marimon et al., 2006).

The development of the region is associated directly with forest destruction mainly for agricultural use (e.g., DeFries et al., 2010), while changes brought about by altered climate and atmospheric composition on forests are subtler. Specifically, increases in carbon dioxide concentration and/or changes in direct light may stimulate tree growth and in turn rainforest biomass gains (Lloyd and Farquhar, 1996; Mercado et al., 2009). There is strong evidence for such a process having occurred over the last decades and is still ongoing (Phillips et al., 1998, 2009; Lewis et al., 2009). In contrast the changing climate has also been hypothesized to have adverse effects on tropical rainforests. As for other parts of the globe, warming of the Earth's surface is predicted to result in an increase in climate variation in South America (Held and Soden, 2006) including likely increased frequency and intensity of dry periods. Such increased variation, together with a general global warming, may possibly lead to forest decline through enhanced water stress, and drought induced forest loss may be further amplified by fire (White et al., 1999; Cox et al., 2000; Poulter et al., 2010; Nepstad et al., 1999; Aragão and Shimabukuro, 2010). Altogether it is the interplay between the very large area covered by high carbon density intact forests, and the very fast economical and demographic development and a changing climate, which make South America of particular interest for its role in the contemporary carbon cycle and, in turn, to climate over the decades to come.

The purpose of this study is to give a state of the art assessment of South American carbon stocks, fluxes and time trends, and their dominant controls. Further, we will assess the role of South America in the carbon cycle over the last decades in order to provide an indication for what to expect in the decades to come. The paper is structured as follows. We start with a characterization of main biomes, stocks, mean climate, climate trends, demography and economic development. We then present and discuss stocks and carbon fluxes associated with different processes and estimated using complementary methods. Dominant processes, in a loose sense, fall into the categories of fossil fuel emissions, deforestation, agriculture and trade, and rainforest tree growth trends. We then also discuss inferences from atmospheric greenhouse gas concentration patterns on carbon sources and sinks using atmospheric transport inverse modelling and vegetation model estimates, whilst recognising these two methods are still in stages of development.

2 Main determinants of large-scale land surface changes and future energy consumption

2.1 Geography, population density, demography

Among South American countries, Brazil is by far the largest, occupying ∼ 49 % of the total area of 17.8×10^6 km^2, followed by Argentina (16 %), Peru (7 %), Colombia (6 %) and Bolivia (6 %). Brazil is also the dominating economy of the continent, accounting for ∼ 50 % of the continent's Gross Domestic Product in 2009 (e.g. IMF 2009).

The primary geographical pattern of the continent's population distribution is the large void in the tropics which includes the Amazon Basin and covers an area of $\sim 8 \times 10^6$ km^2 or nearly half the continent (the area of the basin drained by the Amazon River is $\sim 6 \times 10^6$ km^2 and ∼ 6.4 km^2 if the Tocantins Basin is included (based on SRTM3 data, see Callède et al., 2010), and the area of the humid tropical forest biome $\sim 6.7 \times 10^6$ km^2 (Achard et al., 2002); the areas combined cover $\sim 8 \times 10^6$ km^2). The area of the Brazilian state Amazon, the "legal Amazon", is 5.08×10^6 km^2 (e.g., Perz et al., 2005).

Population density in South America is high along the coastal arc stretching counter-clockwise from Venezuela, the Caribbean Sea and along the Pacific down to the South of Peru and similarly clock-wise along the South Atlantic coast from the easternmost tip (around Recife, Brazil) to Argentina including the mega-cities Rio de Janeiro, São Paulo and Buenos Aires (Fig. 1a).

South America has witnessed very fast population growth as well as urbanization over roughly the last 70 years (Fig. 2). Current growth is still substantial but is decreasing and anticipated to stabilize by approximately the mid of the 21st century at approximately half a billion inhabitants according to UN projections (Population division of the Department of Economic and Social Affairs, UN, 2008). An important aspect of demography is also a general trend of rural population moving to cities.

A key region for the global carbon cycle is the Amazon Basin and its rainforests. A very large fraction of the Amazon Basin and the South American forests is part of

Brazil (62 %), with most of the remaining fraction belonging to Peru (7 %), Bolivia (6 %), Colombia (6 %), and Venezuela (6 %). It hosts not only the rainforests but also many not yet exploited resources like oil, gas and metal ores (e.g., Killeen, 2007; Finer and Orta-Martinez, 2010). Development has been and still is paralleled by large-scale land use change of both forests and savannahs (Cerrado) mainly for purpose of cultivation and pasture. Opening to global markets thereby plays an important role (e.g., Nepstad et al., 2006a; DeFries, 2010; Butler and Laurance, 2008; Finer and Orta-Martinez, 2010).

2.2 Biomes and their transformation over the last decades

Main vegetation and land cover types of South America, with fractional estimates based here on the remote sensing estimates of Eva et al. (2004), include tropical forests (45.24 % by area, $\sim 8.04 \times 10^6\,\text{km}^2$), savannah and scrub-lands (25.07 %) and agricultural land (24.06 %), (Appendix 1, Fig. 1b). Percentage land-cover numbers refer to the time-window 1995–2000. The remaining land is covered by deserts (Atacama, easternmost region of South America), water bodies and urban areas. Forest vegetation is predominantly located in the tropics of which large parts are located within the Amazon Basin. Savannah type vegetation (Cerrado), if unaltered by agricultural use, would stretch along a wide belt to the South of the Amazon forests from north-east to south-west (Eva et al., 2004) with temperate forests to the east. Regions further south are used for agriculture including sugar cane plantations in São Paulo state for purpose of ethanol production and still further south for cattle grazing (Argentina).

From a carbon cycle perspective, it is of interest that unlike the temperate and boreal regions, tropical ecosystems have not been “reset” by glaciations and thus their soils have developed on the same substrate over very long periods (millions of years). As a consequence for large parts of the Amazon, the weatherable phosphorus pool in the soils is highly depleted and thus phosphorus is a limiting element for forest growth (Vitousek, 1984; Quesada et al., 2009; Aragão et al., 2009).

Parts of the Savannah (Cerrado) and the rainforest biomes have undergone substantial transformation over the last few decades mainly for agricultural use. Brazilian Cerrado (both within and outside the legal Amazon), covering originally $\sim 2 \times 10^6\,\text{km}^2$, has decreased to ~ 43 % of its original area by 2004 and will be entirely converted to agricultural use by around the year 2030 if annual conversion rate stays at its current level of 22 000–30 000 $\text{km}^2\,\text{yr}^{-1}$ (Machado et al., 2004). The rainforests have been reduced in size at a fast pace since the early 1970's as well for similar reasons (for the Brazilian Amazon at a rate of ~0.4 %, Appendix 4 or also Fearnside (2005)). Major forest transformation occurred and occurs in the so-called "Arc of deforestation" along the steadily northwards retreating southern rim of the forests. According to Fearnside (2005) by the year 2003 "16.2 % of the originally forested portion of Brazils $\sim 5 \times 10^6\,\text{km}^2$ legal Amazon region had been deforested". Thus compared to the Cerrado a much larger percentage, 83.8 % of the forests, remained intact. This is partially likely because the forests are more remote from economic centers. In addition measures to protect Brazilian Cerrado are also much less far-reaching than measures to protect Brazilian rainforest (e.g., Fearnside, 2005).

Some insight about causes of deforestation can be gained from land use statistics. Specifically for the Brazilian legal Amazon (the states Rondonia, Mato Grosso, Amazonas, Acre, Roraima, Par, Amap and Tocantins combined) Brazilian government statistics (AGROPECUARIA) show that in 2006 approximately 60 % of land converted has been used for pasture, 15 % for cultivation and the remainder is degraded or managed forest (Fig. 3). The fraction of cultivated land in the legal Amazon has approximately doubled from 1995 to 2006 and so has its area (Fig. 3) and it matches approximately the time course of the area of forest destruction (Fig. 7 and Appendix 4).

Quantitative data on deforestation in the other countries sharing the tropical forests, Peru, Colombia, Bolivia, Guyana, French Guiana, Suriname, Venezuela are more sparse. Remote sensing data covering the period from 1984 to 1994 indicate a similar relative deforestation rate for Bolivia as for the Brazilian Amazon (Steininger et al., 2001) ($\sim 0.4\,\%\,\text{yr}^{-1}$). Deforestation rates for Peru have been lower with rates between

0.1–0.28 % yr^{-1} (Appendix 4). The deforestation rate of 0.1 % yr^{-1} applies to recent years (Oliveira et al., 2007). Although we have not found reliable data on deforestation for the remaining countries with tropical forests, a pan tropical study for 1990–1997 based on a combination of 1 km^2 and higher resolution ($100 \times 100\,m^2$, Landsat, Achard et al., 2002) remote sensing data, indicates similar decrease rates across the entire Amazon Basin as compared for just the Brazilian Amazon. For both Brazil and Peru deforestation rates have decreased over the last few years (Regalado, 2010; Oliveira et al., 2007) which seems to be a result of enhanced government attempts to protect the forests (see also Nepstad et al., 2006b).

Outside the tropics there have been even higher deforestation rates: specifically in Paraguay, Argentina, Chile. For these regions some forest areas are now nearly entirely converted to agricultural use (Gasparri et al., 2008; Huang et al., 2009; Echeverria et al., 2006). These forest areas are small compared to the tropical forest area (Appendix 4).

2.3 Climate and climate trends

With South America stretching from approximately 10° N to 55° S the continent's weather and climate can be partitioned broadly into three zones following the atmospheric controls. The tropical zone with climate determined by the westerly direction of the atmospheric circulation, the monsoonal circulation during austral summer and the influence of the Andes on lower tropospheric flow. The subtropic's climate is controlled by semi-permanent high pressure cells (~ 30° S), and finally the mid-latitudes by cyclones and anticyclones associated with the polar front in a generally westerly air flow (e.g., Fonseca de Albuquerque et al., 2009).

Because the Amazon Basin is the most significant South American region from a carbon cycle perspective, we describe its climate in slightly greater detail. The basin's climate is characterized by large annual mean precipitation amounts (between 2 and 3 m yr^{-1}) and quite constant daily mean temperatures of 24 to 26 °C (e.g., Nobre et al.,

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2009; Marengo and Nobre, 2009). The main element of the seasonal variation of the Amazon Basin climate is the austral summer monsoon, which occurs roughly during the period from early October to end of March. For the relatively small Northern Hemisphere part of the basin the seasonal cycle is out of phase with the rest of the basin by approximately 6 months. Associated with the (austral) summer monsoon is the rainy season followed by the dry season from approximately April/May onwards. The dry season is not dry in the sense of the Northern Hemisphere mid-to-high latitudes but rather "less wet", typically defined as a month with less than 100 mm of rainfall.

The main mode of inter-annual variation over recent decades is associated with the El Niño and La Niña oscillation, collectively the El Niño/Southern Oscillation (ENSO). El Niño phases are associated with drier conditions in the North of the basin and vice versa (Costa and Foley, 1999). Not all variation is controlled by ENSO (i.e. Pacific sea surface temperature variations). Cross-equatorial Atlantic sea surface temperature differences influence the ITCZ location and thereby precipitation patterns as well (e.g., Yoon and Zeng, 2010). Also, on multi-decadal scales dominance of Pacific and Atlantic influence vary (e.g., Yoon and Zeng, 2010; Espinoza et al., 2011).

Historically Amazonian droughts occur fairly regularly, sometimes with large negative effects on human life. During droughts, dry season precipitation is even lower than usual. A particularly intense drought occurred in 1926 (Williams et al., 2005). Further severe droughts in the 20th century, mostly associated with El Niño occurred in 1935–1936, 1966–1967, 1979–1980, 1983 and 1992 (Marengo and Nobre, 2009). In more recent years there have been strong droughts in parts of the Amazon in 1997/1998, 2005 and 2010, with the latter two apparently related to Atlantic SST anomalies (Yoon and Zeng, 2010).

Similar to global land temperature trends, the Amazon region has warmed by approximately 0.5–0.6 °C over the last few decades (1960 to 2000, e.g. Victoria et al., 1998; Malhi and Wright, 2004). There is a particular requirement to understand how anthropogenic climate change and any associated global warming will alter precipitation patterns for the Amazon region. Analysis of precipitation trends by various authors differ in the periods chosen, and climatologies or station data used (Espinoza et al., 2009). Nonetheless the following patterns emerge when analysing trends in Amazon River discharge at Obidos (Callède et al., 2004, Fig. 5). Obidos is located approximately 800 km inland from the estuary of the Amazon River and drains a basin of $\sim 4.7 \times 10^6$ km^2 or roughly 77 % of the Amazon Basin. River discharge is a good diagnostic of the hydrological cycle as it acts as an integrator of the basin-wide precipitation. However it cannot differentiate whether water has been recirculated via evapo-transpiration or not. River discharge at Obidos (Fig. 5) over the last ~ 100 yr reveals firstly an increasing trend (approx. 10–15 % over the 20th century) indicating a similar trend in annual mean net precipitation (although possibly with a contribution from glacial melt, e.g., Mark and McKenzie, 2007). A positive trend in river discharge is expected given that the main air-flow enters the basin from the Atlantic and Atlantic sea surface waters have been warming (e.g., Held and Soden, 2006). The second main noteworthy feature is that seasons have become more pronounced over roughly the last two decades: dry seasons tend to become drier/longer while wet seasons become wetter (Fig. 5).

A third remarkable trend of the South American troposphere water balance over the last few decades is a gradual increase trend in precipitation in the La Plata River catchment and La Plata River discharge into the Atlantic at Buenos Aires (e.g., Milly et al., 2005 and references therein). This is very likely the result of an increasing trend in water vapour outflow from the Amazon Basin towards the South (Rao et al., 1996).

2.4 Potential vegetation responses and feedbacks with climate

One widely cited hypothesis states that the anticipated increase in frequency and intensity of anomalously dry periods in a warming climate may lead to a large reduction in tropical forest vegetation and replacement by savannahs by 2100 (White et al., 1999; Cox et al., 2000; Oyama and Nobre, 2003). This hypothesis has amongst others also been suggested by the first fully coupled climate – carbon cycle modelling results (Cox et al., 2000). However more recent versions with the meanwhile further evolved coupled climate-carbon cycle model from the same institution (Hadley Centre UK) do not show such a biome switch for the Amazon region (C. Jones, personal communication, 2011). A data-oriented analysis by Malhi et al. (2009) which corrects for the fact that climate models are predicting a too dry contemporary climate finds much lesser effect of a future changing climate on tropical forest vegetation, and a climate ensembles approach suggests that the likelihood of a change from forest to savannah vegetation is low (Poulter, 2010). Thus although the possible risk of large-scale climate-change induced forest "die-back" remains a concern and requires on-going analysis and research, not all climate models predict this possibility. For contemporary periods, there is evidence from ground-based inventory studies that the forest is currently gaining carbon.

Inventory data is especially of use for analysis of year-on-year features, and in some instances can give indications of what the Amazon response might be in a future climate state (for instance, warm years might show features that become prominent in a continually warmer greenhouse gas-enriched world). As mentioned above, there is an increasing trend in dry season length and in 2005 the effect of particularly dry conditions in parts of the Amazon Basin on trees have been examined by Phillips et al. (2009) based on tree growth and mortality data of a pan-tropical forest census network. Phillips et al. (2009) reported an increase in mortality compared to the long-term pre-2005 mean rate indicating the potential sensitivity of forest dynamics and carbon storage to any tendency to more frequent or intense droughts that some climate models suggest might occur for raised levels of atmospheric greenhouse gas concentrations.

Besides climate alone, the 40 % increase in atmospheric CO_2 today over its pre-industrial concentration could in principle affect functioning of vegetation, specifically decreasing stomatal density and conductance, leading to higher water use efficiency (e.g., Woodward, 1987). Although stomatal conductance decreases, this is counter balanced by the higher carbon dioxide concentrations enhancing internal CO_2. Furthermore, higher atmospheric CO_2 should favour the C_3 photosynthesic pathway (mainly trees) over the C_4 pathway (e.g., Ehleringer and Cerling, 2002). There are indications

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based on trends in $^{13}C:^{12}C$ ratio of wood and leaf cellulose (the carbon isotopic ratio of wood is a strong function of stomatal conductance (e.g. O'Leary, 1988)) that there has indeed been down-regulation of net flux of CO_2 and H_2O through stomata in parts of the Amazon (Hietz et al., 2005) although unambiguous attribution to mechanisms remains difficult (Seibt et al., 2008). Amazon River discharge and basin-wide precipitation seem not having increased at the same rate, consistent with a trend in down-regulation of stomatal conductance (i.e. reduced evapo-transpiration) (Gedney et al., 2006). Finally numerous studies document forest moving into savannah at the Southern border of the Amazon forest-to-savannah transition zone (so-called Cerradão) with a speed on the order of 50 m yr^{-1} over the last 3000 years, attributed to a shift in the ITCZ, and still higher rates over the last decades (e.g., Marimon et al., 2006; Pessenda et al., 1998; Mayle et al., 2000).

3 Flux estimates

3.1 Fossil fuel and ethanol production and use

Currently (data available up to 2007) total fossil fuel emissions from South America are estimated to be 0.26 Pg C yr^{-1} or approximately 3 % of the global total fossil fuel emissions (Boden et al., 2011). The increase since the 1950s has been approximately exponential with annual increase rate of about ~ 8 % yr^{-1} from 1950–1980 but falling back to 3 % yr^{-1} during the period from 1980–2008 (Figs. 6 and 12). Per capita use of fossil fuels in 2005 was 0.65 Mg C yr^{-1} compared to a global average of 1.22 and 4.9 Mg C yr^{-1} in the USA.

An interesting aspect of fuel use in Brazil is that a substantial part used for running engines (~ 40 %) is ethanol (C_2H_6O) produced by fermenting sugar cane and subsequent distillation (Macedo et al., 2008), although it is important to note that biofuel usage does not contribute to the fossil fuel totals above. Compared to other crops the ratio (renewable energy of ethanol)/(fossil fuel energy used to produce ethanol) = 8.3

is high (Macedo et al., 2008). Ethanol utilization in Brazil in 2006 was 14.1×10^9 l. To put this into perspective the C flux to the atmosphere from burning ethanol in 2006 amounts to ~ 5.8 Tg C (density of ethanol 0.789 kg l^{-1}) which is ~ 5 % of the total fossil fuel emissions from Brazil.

Ethanol production from sugar cane in Brazil goes back to the 1920's as a means to utilize sugar cane overproduction. Currently the main region where sugar cane is planted is Sao Paulo state in the southeast of Brazil (Sao Paulo State ~ 66 %, Parana ~ 9 %, Minas Gerais ~ 9 %) (UNICA, Brazil, 2011). Production of ethanol and export of ethanol has risen strongly over the last decade (production from 11.5×10^9 to 27.5×10^9 l and export from 0.2×10^9 to 5.1×10^9 l in the years 2000 and 2009, respectively (UNICA Brazil, 2011)). Although the area used to cultivate sugarcane (in 2008/2009 6.8×10^6 ha, UNICA 2011) is currently not large in comparison to pasture (approx. 200×10^6 ha in 2008/2009, UNICA, Brazil, 2011) there is strong concern and evidence that if exports are permitted to drive expansion of sugar cane plantations it will contribute to move the deforestation frontier further north (e.g., DeFries et al., 2010, and Figs. 3 and 4).

3.2 Deforestation

Historically, global deforestation carbon emissions have been based on the pioneering study of Houghton et al. (1983). The data used for land use change related carbon fluxes in this study are from the Food and Agriculture Organization of the United Nations (FAO) with the data provided to FAO by country's governments. More recently independent land use change area estimates – particularly those caused by deforestation – based on remote sensing data and various statistical scaling approaches have become available (PRODES, Brazilian government– see Morton et al., 2005; Hansen et al., 2008; Achard et al., 2002). An advantage of these latter estimates is that they are more easily reproducible than the FAO data. Based on area change rate data, it is then possible to estimate land use change related fluxes based on spatially explicit forest biomass estimates e.g. from the RAINFOR forest census network (e.g., Malhi et al., 2002; Phillips et al., 2009), fraction of biomass combusted, and estimates of lagged carbon release and uptake due to decomposition of dead organic carbon and recovery after deforestation, respectively (Houghton et al., 1983).

To progress along similar lines in this study, we first compare several estimates of the time course of forest area change (Fig. 7) based on FAO and independent remote sensing based estimates using sensors of various spatial resolutions, in some cases following a hierarchical approach using increasingly spatially resolving sensors to first identify "deforestation hotspots" and then zoom in to hotspot areas using higher accuracy (Achard et al., 2002; Hansen et al., 2008). Figure 7 includes also estimates of changes in agricultural land use from the Brazilian government, which permits some test of consistency of the deforestation numbers. Although not a new insight, it is apparent that compared to the various independent remote sensing-based estimates (the numerical data are given in Appendix 4) the FAO area deforested numbers are substantially larger, even when considering that the different estimates are not for exactly the same regions. The independent remote sensing based estimates are quite consistent amongst each other and also consistent with the estimates of changes in agricultural land use in Brazil provided by the Brazilian government as discussed in Sect. 2.2. We therefore base our further attempt to estimate carbon fluxes associated with forest clearing on the published remote sensing estimates of forest area change rates (i.e. independently from the deforestation numbers of FAO). However we note that the data we use here may miss some forest degradation after deforestation.

The deforested area provides an upper bound on carbon release to the atmosphere, when assuming that all forest carbon (including roots and necromass) and soil carbon fraction lost after deforestation is immediately released to the atmosphere. A more accurate estimate is obtained by taking into account the time lags between the decomposition of dead organic material after deforestation and similarly gradual replacement of the deforested area by a new (or similar) vegetation type (Houghton et al., 1982). Below, we implement a simplified version of the so-called "book-keeping" procedure with simple conceptualization of the time lags in decomposition and time-course of spin-up to a new vegetation cover. The purpose is to bracket likely values of deforestation fluxes, reflecting the uncertainties of lags in carbon release and recovery using published remote sensing based deforested area estimates. Specifically, we assume exponential decay of dead organic material left over from a deforestation event (i.e. $\Delta\mathrm{C}=-\lambda_{\mathrm{resp}}\mathrm{C}\Delta t$ with C carbon, Δt a discrete time interval (here one year), and λ_{resp} a decay constant); spin-up to new vegetation is assumed to approach steady-state carbon content following

$$\mathrm{C}(t)=\mathrm{C}_{\mathrm{steady}}(1-e^{-\lambda_{\mathrm{rgrwth}}t})$$

where C is carbon and $\lambda_{\mathrm{rgrwth}}$ is the inverse of the time-scale to reach a new steady state. The total flux to the atmosphere in year t caused by deforestation during year t and decomposition of dead organic material remaining from deforestation events in previous years is

$$F^{\mathrm{tot}}_{\mathrm{ld}\rightarrow\mathrm{at}}(t)=\sum_{t_{\mathrm{def}}=-\infty}^{t}F_{\mathrm{ld}\rightarrow\mathrm{at}}(t,t_{\mathrm{def}})$$

where $F_{\mathrm{ld}\rightarrow\mathrm{at}}(t,t_{\mathrm{def}})$ is the flux from land ("ld") to the atmosphere ("at") in year t due to deforestation in year t_{def} in the past. Similarly the total flux from the atmosphere to land due to re-establishment of either forest or another vegetation type (we distinguish cultivation, secondary forest and pasture) is given by

$$F^{\mathrm{tot}}_{\mathrm{at}\rightarrow\mathrm{ld}}(t)=\sum_{t_{\mathrm{def}}=-\infty}^{t}\sum_{\mathrm{lu}}\alpha_{\mathrm{lu}}F_{\mathrm{at}\rightarrow\mathrm{ld}}(t,t_{\mathrm{def}})$$

where $F_{\mathrm{at}\rightarrow\mathrm{ld}}(t,t_{\mathrm{def}})$ is carbon uptake in the wake of deforestation in year t_{def} and is the fraction of originally deforested land being replaced by land use type lu (for details see Appendix 5). Main uncertainties of the approach arise because of uncertainties in forest biomass density (i.e. forest tree biomass per area ($\mathrm{t\,ha^{-1}}$)).

Our estimates indicate a flux to the atmosphere on the order of 0.5 Pg C yr^{-1} due to deforestation and land use change in South America over the last two decades or so (Figs. 7 and 8). This is true also over the last few years, despite the remarkable decrease in deforestation in the Brazilian Amazon, because of lagged fluxes caused by earlier deforestation.

3.3 Amazon forest censuses

Forest carbon storage and its trends are being monitored since several decades using forest plots by keeping track of the diameter of all living trees within each forest plot of the network. Two measurement strategies have been followed. One strategy samples a few (3 in Americas) plots of comparably large size 16–50 ha (Chave et al., 2008). The other (the RAINFOR network, Phillips et al., 2009) currently samples 136 1 ha plots covering the main axes of forest growth variation (El Niño, soil fertility, dry season length, O. Phillips personal communication, 2011). The censuses from the RAINFOR network have revealed a positive trend in above ground biomass stocks (dry matter, in units MgC ha^{-1} yr^{-1}) in the Amazon reported first by Phillips et al. (1998) and recently summarized in Phillips et al. (2009). The measurements do not include soil carbon. This inventory data is a significant step forward in understanding the evolution of carbon content in the rainforest. Given its labour-intensive requirement, then inevitably it remains relatively sparse, and of course is only available for the length of the project so far (a few decades). Thus, there is some concern that the biomass accumulation (NEP) estimates are biased toward high estimates, because rare large-scale disturbance events are not captured. However, an examination of this concern (Gloor et al., 2009) concluded that using a realistic (observed) disturbance severity and return time distribution, the results of a positive forest biomass gain trend based on the existing census network remain statistically significant. Other criticisms like the uncertainty induced by using allometric equations for biomass estimation have been assessed and have also been demonstrated to have only minor impact on the regional sink estimates

(Lewis et al., 2009). The results from a similar analysis based on the large forest plots confirmed a pan-tropical biomass increase trend although of lesser magnitude (Chave et al., 2008). Here we do not use the results from this latter study though because only one plot is located in tropical South America.

We extrapolate the biomass changes reported by Phillips et al. (2009) to intact forests in tropical South America assuming a carbon content of wood of 50 % by mass. Furthermore we follow the compilation of Lewis et al. (2009) (Supplement, their p. 30) for estimating intact forest area in the year 2000 using a value of $703.3 \pm 142 \times 10^6$ ha (values used: 630.5×10^6 ha from GLC 2000 (Global Land Cover Mapping for the Year 2000) (if dry and flooded tropical forest would be included total tropical forest area would be $8.03 \times 10^6\,\mathrm{km}^2$ instead), $8.58 \times 10^6\,\mathrm{km}^2$ from FRA CS (FAO Forest Resource Assessment, 2000), $7.80 \times 10^6\,\mathrm{km}^2$ from FRA RS (FAO Forest Resource Assessment, 2000, remotely sensed values) and $544 \times 10^6\,\mathrm{km}^2$ from WCMC (World Conservation Monitoring Centre)). The first forest area estimate is based on the remote sensing instrument SPOT-VEGETATION (1km spatial resolution), the second "based primarily on available information provided and validated by national authorities" (Mayaux et al., 2005), the third estimate based on "117 multi-date Landsat TM scenes covering approximately 10 % of tropical forest" (Mayaux et al., 2005) while it has not become clear to the authors what the last estimate is based on. From the four estimates the first three for all tropical forest are similar, while the fourth estimate is quite different.

We scale the tropical intact forest carbon sink $f(\mathrm{yr})$ in units of $\mathrm{Mg\,DW\,C\,ha^{-1}}$ (DW: "Dry Weight") from Phillips et al. (2009), their Fig. 1, to carbon flux F ($\mathrm{Pg\,C\,yr^{-1}}$) using

$$F(\mathrm{yr}) = (1 + r_{\mathrm{BG:AGB}}) \times r_{\mathrm{C:DW}} \times (1-\lambda)^{(\mathrm{yr}-1970)} A_{\mathrm{trop.forest}}(1970) \times f(yr)$$

$r_{\mathrm{C:DW}} \sim= 0.5$ is the ratio of carbon to dry weight of trees, $A_{\mathrm{trop.forest}}(1970) \sim= 8.17 \times 10^6\,\mathrm{km}^2$ is the area of intact tropical forest in the Amazon before intense deforestation started, $\lambda \approx 0.005\,\mathrm{yr}^{-1}$ using (i.e. approx 0.5 % forest area lost per year, estimated from INPE deforestation numbers based on PRODES). We also assume a belowground to aboveground tree biomass ratio $r_{\mathrm{BG:AGB}} = 0.2$ based on Malhi et al. (2009).

The resulting flux numbers are listed in Table 1 and shown in Fig. 11. The main features are a long-term (1980–2004) carbon sink of 0.39 ± 0.26 Pg C yr^{-1} in the mean (the uncertainty includes the contribution from area estimate variation) interrupted in 2005 by a presumably short-term reversion to a source of 0.66 Pg C yr^{-1} due to the drought in that year. The cause for the reversion was primarily an increase in tree mortality (Phillips et al., 2009). The carbon associated with dead trees (~ 1 Pg C) will not be released to the atmosphere immediately but rather gradually over a several year period.

3.4 Inferences from atmospheric CO_2 and atmospheric transport

The effect of a carbon flux between land and the atmosphere is to either increase or deplete the CO_2 concentration in the overlying air column, depending on whether the land is a source or a sink. By keeping track of an air parcel's path over a region of interest and by measuring the air column CO_2 increase/decrease along the air parcel path it is thus possible, in principle, to estimate integrated net fluxes along the path. More generally, spatio-temporal concentration patterns in the troposphere contain information on surface fluxes, which theoretically can be extracted, by inverting and un-mixing the effect of atmospheric transport and dispersion. This is done in practice using 3-D atmospheric transport models in an inverse mode. For tropical South America, and the tropics generally, two obstacles make such an approach unreliable. Primarily, the troposphere around and inside the continent is highly under-sampled. Inverse methods can potentially provide information from remote observations in the tropical marine boundary layer or in the temperate latitudes. However, both transport modelling shortcomings and the inherent atmospheric dispersion that occurs over transport times of weeks from the tropical land surface to remote sites hamper that approach. As Stephens et al. (2007) showed for the tropics as a whole, tropical land flux estimates derived from CO_2 observations at remote sites may reflect biases induced (propagated) by misfits in other regions of the globe. Furthermore, even with a single inversion model (in which transport is assumed to be perfectly known), the formal statistical uncertainties are very large, which reflect the loss of information during transit on the way to the remote observation sites. The flux estimates based on classical atmospheric transport inversions in Fig. 9 reveal large scatter in the estimates among models, confirming our assessment of bias. Given that the estimates may largely reflect noise we disregard them for this study.

A new development with atmospheric sampling over South America is that recently joint efforts by IPEN (Sao Paulo, Brazil), NOAA-ESRL (Boulder, USA), University of Leeds (Leeds, UK) and University of Sao Paulo (USP) have led to regular vertical aircraft based greenhouse gas sampling, with one/two stations (Santarem, Manaus) operating since approximately the year 2000 and four aircraft sites from end of 2009 onwards. These data provide the necessary information to apply an atmospheric approach to estimating Amazon Carbon sources and sinks. An air parcel back-trajectory based column integration technique applied to the Santarem data covering the period 2000–2009 reveals a moderate net carbon source of the land region upstream of Santarem and when fire related fluxes are subtracted on the basis of CO column enhancements, an approximately balanced land surface is found (Gatti et al., 2010). The region upstream Santarem covers only 10–20 % of the basin and includes not only forests but also forest converted to agricultural use as well as savannah and grasslands. It is thus quite likely that the balance of the entire basin differs from this result.

3.5 Estimates from Dynamic Global Vegetation Models (DGVM's)

For this study modelling results from five DGVMs have been made available to us (TRENDY project, Sitch personal communication). The models (DGVMs) were applied globally with common climate forcing, and atmospheric CO_2 concentrations over the historical period 1901–2009. Global atmospheric CO_2 comes from a combination of ice core and NOAA annual resolution (1901–2009). A 6-hourly, 0.5° resolution global climate dataset was constructed based on merging the observed monthly mean climatology from the Climate Research Unit (CRU) and NCEP reanalysis. The models were forced over the 1901–2009 period with changing CO_2, climate and land use according to the following simulations: varying CO_2 only, varying CO_2 and climate (S2), and varying CO_2, climate and land use and land cover change (S3, optional). Herein we present results from simulation S2.

Main features of the simulation results (Fig. 10) are as follows. Inter-annual and decadal variability of the model predictions are similar, nonetheless differences become apparent when fluxes are cumulated over time. With regards to cumulated changes in pool sizes, simulation results can be grouped intro three sets. One model (LPJ) predicts a balanced land vegetation, three models a moderately carbon gaining vegetation (SDGVM, TRIFFID and ORCHIDEE) and the last model substantial carbon gains (HYLAND). With exception of the LPJ model results, all predictions indicate a regime shift around 1970 towards an increase in carbon gains. Overall on longer time-scales there is substantial divergence in the predictions indicating that processes relevant to longer term changes may not be properly captured/represented by the models yet thus we do not include them in a synthesis with estimates based on more direct methods here.

3.6 Agricultural production and exports

For our estimates of carbon fluxes related to deforestation we have assumed implicitly that all carbon related to agricultural use of originally forested land remains in the country. However, increasingly agricultural products are being exported (Fig. 4). Specifically for Brazil there is a strong trend over the last decade of soybean products and meat from cattle. In terms of carbon the amounts remain small (Table 1) and so even with large uncertainties, at present the contribution to the overall carbon budget is negligible. It is worth noting that according to DeFries et al. (2010), trends in deforestation are strongly related to increasing exports (see also Nepstad et al., 2006a).

3.7 Role of additional components: rivers, Volatile Organic Carbon compounds (VOCs), fire

For the carbon balance of South America riverine carbon discharge to the oceans is a net sink. We consider here just the loss of carbon via this route by the Amazon River. Inorganic carbon from weathering is $\sim 0.02\,\mathrm{Pg\,C\,yr^{-1}}$ (Probst and Mortatti, 1994) and of organic carbon $\sim 0.05\,\mathrm{Pg\,C\,yr^{-1}}$ (Richey et al., 1990). Outgassing of organic carbon from rivers is part of a closed within-basin loop and thus cancels in a hydrological basin-wide carbon balance.

We do not explicitely consider emissions due to fire for two reasons. For some systems fire is part of the natural cycle and thus similar to the river outgassing loop is neutral on longer times-scales, although fire activity may contribute to interannual variability which we will miss with the analysis presented here. Secondly components due to biomass burning associated with deforestation are included in the deforestation flux estimates (leading potentially to a bias in the "debris" decay constant in our book-keeping model).

Finally the VOC loop is in essence closed over large spatial scales as well.

4 Synthesis

As policymakers try to determine the best route to mitigation of carbon dioxide release as a consequence of fossil fuel burning, and climate research strives to assess the extent to which the land surface can "draw-down" atmospheric CO_2 in to the future, then it is becoming ever more important to understand all components of the global carbon cycle. In particular, detailed regional studies are needed to close the carbon balance. Here we attempt this for the South American continent.

Although our study is not entirely complete, by relying on those data and estimates for which sources are clearly traceable and for which we have only limited methodological concerns, fossil fuel emissions, estimates of intact forest growth, deforestation and exports of agricultural products, we find that South America had been a net source to the atmosphere during the 1980s (~ 0.3–0.4 Pg C yr^{-1}) and close to neutral (~ 0.1 Pg C yr^{-1}) in the 1990s with carbon uptake in old-growth forests nearly compensating carbon losses due to fossil fuel burning and deforestation (Fig. 11). The one study employing an atmospheric approach which we have confidence in methodologically is broadly consistent with these results.

The situation seems to be changing over the last decade. Although annual mean precipitation over tropical South America (as diagnosed by river discharge) has generally a long-term upward trend, particularly over the last decade, dry seasons have tended to become drier/longer (and thus wet seasons wetter). It is currently unclear what the effect of these climate changes on the old-growth forest carbon sink will be but first measurements seem to indicate that it may be weakened at least in drought years. Accordingly the carbon balance of South America may be turning towards a weak source to the atmosphere (in the 2000's). The development of the tropical forest regions of the continent is advancing steadily with exports of agricultural products being an important driver with exports witnessing a strong upturn over the last decade indicating that such drivers may become a main control on deforestation unless some sort of trade barriers are implemented.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/9/627/2012/bgd-9-627-2012-supplement.pdf.

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Table 1. Summary of carbon flux estimates for South America.

Process	Period (fluxes in Pg C yr^{-1})*						
	1975–1979	1980–1984	1984–1989	1990–1994	1995–1999	2000–2004	2005–2009
Fossil fuel (2005–2007)	0.12	0.14	0.15	0.17	0.21	0.23	0.25
Deforestation							
(a) immediate release	0.37	0.63	0.62	0.47	0.51	0.70	0.31
(b) release with time lags	0.20	0.36	0.48	0.47	0.50	0.57	0.48
Old-growth forests		−0.21 ± 0.23	−0.21 ± 0.23	−0.57 ± 0.17	−0.53 ± 0.14	−0.45 ± 0.25	0.66 ± 0.23 in 2005
River carbon export	−0.07	−0.07	−0.07	−0.07	−0.07	−0.07	
Export of agricultural products (Brazil)	0.006	0.007	0.008	0.01	0.015	0.027	0.034
Total		0.22	0.35	0.0	0.08	0.28	~ 0.86**

* the sign convention is that a positive flux is directed to the atmosphere

** assuming a release of 1 Pg C from dead trees due to the 2005 drought over 5 yr.

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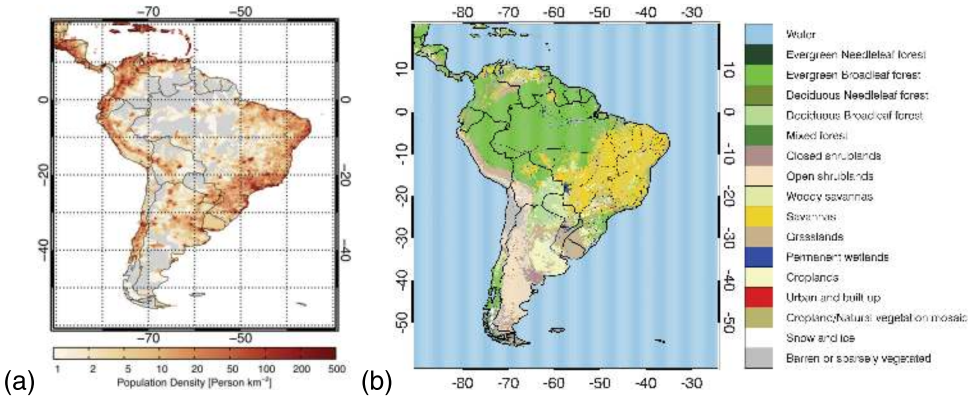

Fig. 1. **(a)** Population density in South America in the year 2005 (CIESIN, 2011) and **(b)** Land cover map of South America from MODIS, 0.05° spatial resolution obtained from http://modis-land.gsfc.nasa.gov/landcover.html (Friedl et al., 2010).

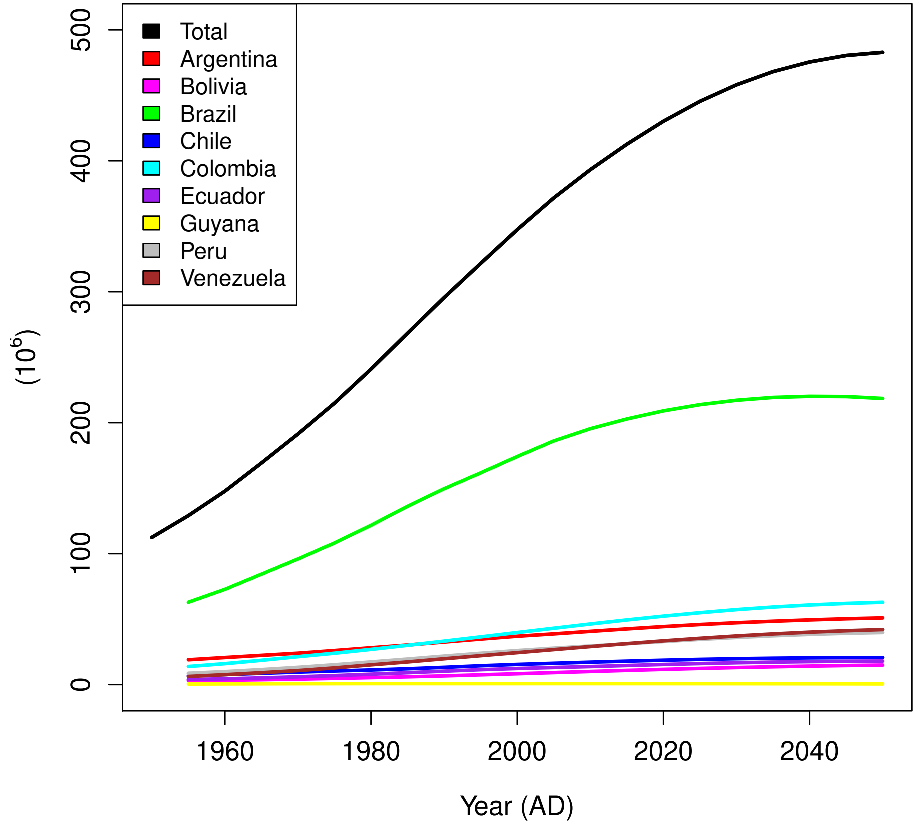

Fig. 2. Observed (until 2007) and predicted population growth for South America by the United Nations (http://esa.un.org/unpd/wpp/index.htm).

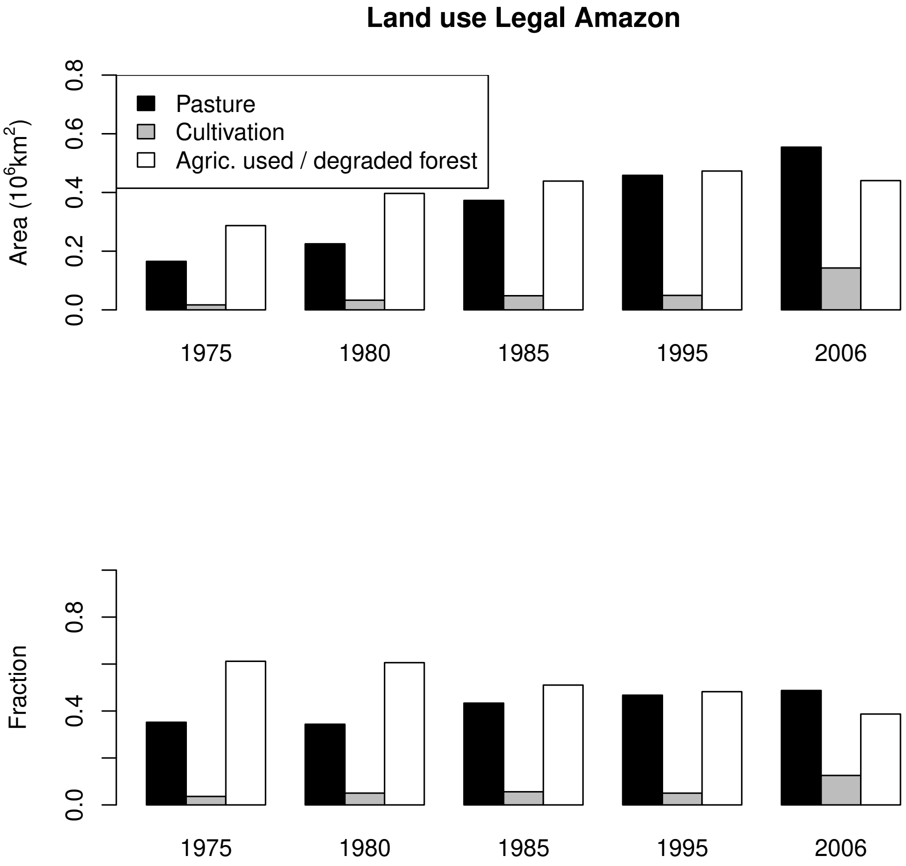

Fig. 3. (a) Agriculturally used land by area in the legal Amazon and **(b)** fraction of agriculturally used area by each of the three land use practices (from IBGE, AGROPECUARIA 2006; http://www.ibge.gov.br/home/estatistica/economia/agropecuaria).

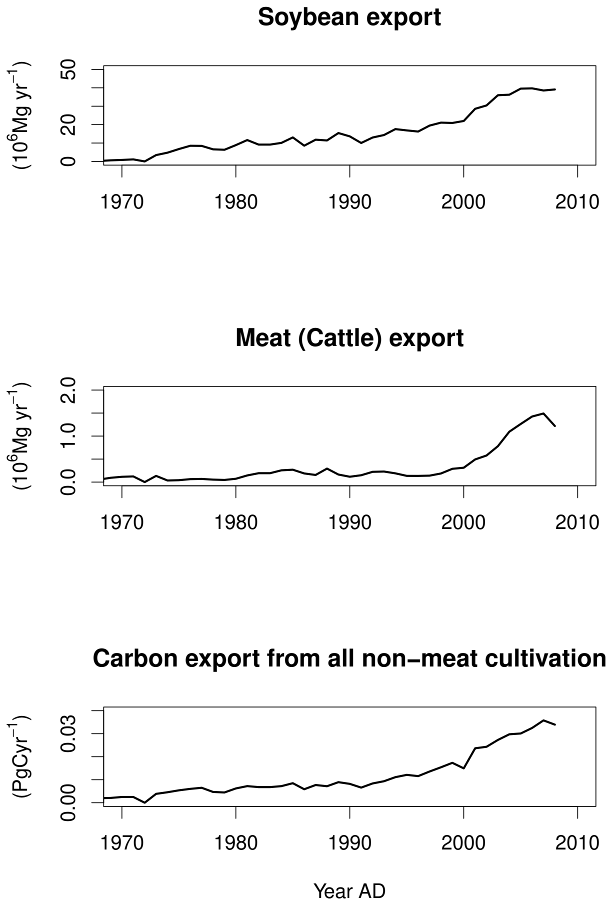

Fig. 4. Exports of agricultural products from Brazil according to FAO statistics (http://faostat.fao.org).

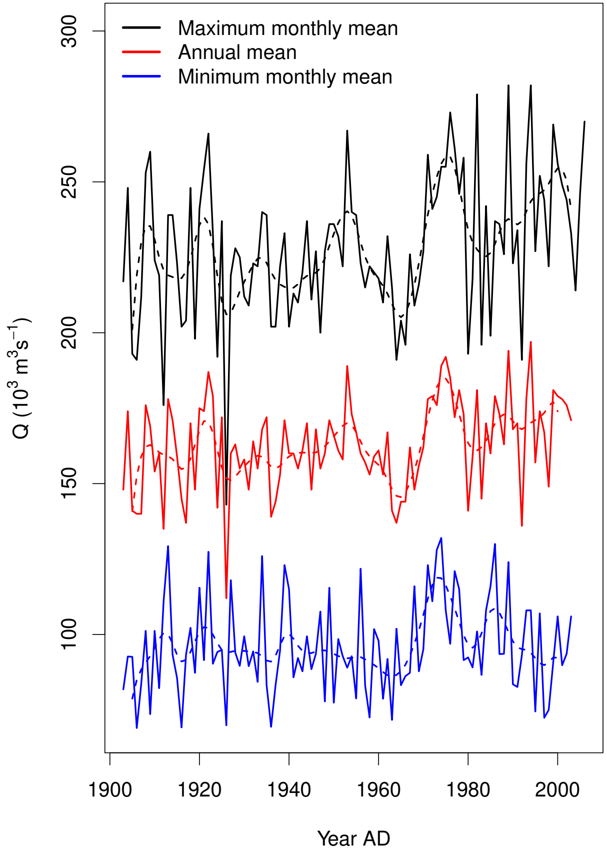

Fig. 5. Maximum monthly (black), minimum monthly (blue), and annual mean (red) river discharge at Obidos measured by Hydrological Service ANA, Brazil, http://www2.ana.gov.br/ and, where measurements are missing, estimated from upstream river gauge stations by Callède et al. (2004), based on data from the same data-source.

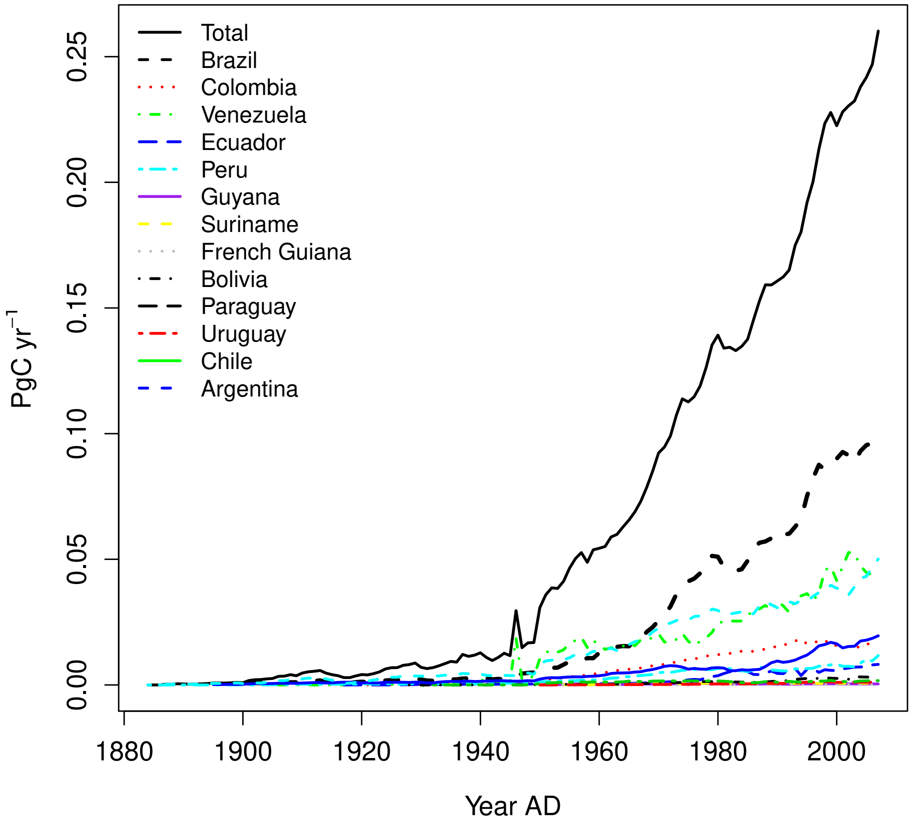

Fig. 6. Fossil fuel emissions estimated based on national energy statistics (Marland et al., 2008).

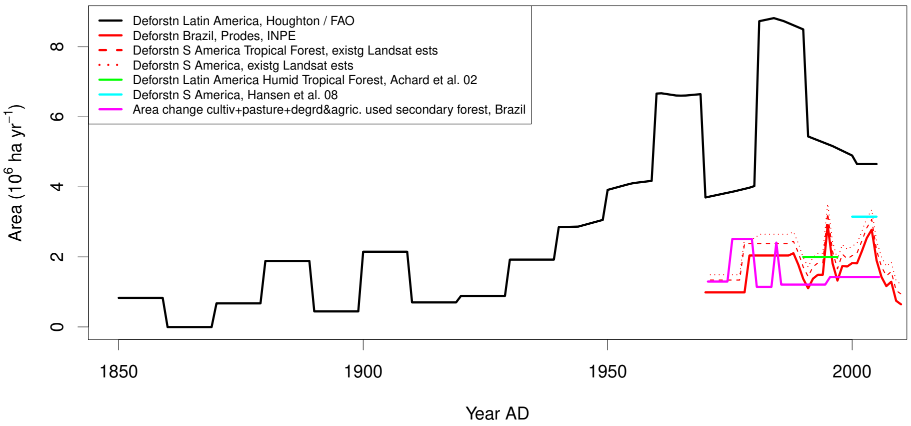

Fig. 7. Comparison of various estimates of annually deforested area in South America, tropical South America and Brazil, respectively, and annual change in agriculturally used land in Brazil based on government statistics (AGROPECUARIA, same as in Fig. 3). The displayed estimates from top down are the following: (i) deforestation rate by area in South America according to FAO statistics (provided by R. Houghton in 2011), (ii) same but just for Brazil and estimated by INPE, Brazil based on Landsat images (PRODES, http://www.obt.inpe.br/prodes/prodes_1988_2011.htm), (iii) same based on PRODES and published studies of deforestation based on remote sensing (mainly Landsat) as listed in Appendix A4, (iv) same as (iii) but including in addition published remote sensing based estimates for the rest of South America as listed in Appendix A4, (v) deforestation rate by area for Latin American humid tropical forests of Achard et al., 2002 based on remote sensing, (vi) same but for South America as estimated by Hansen et al., 2008, (vii) total change in cultivated area per year due to agriculture in Brazil based on Brazilian government statistics (UNICA, http://www.unica.com.br/dadosCotacao/estatistica).

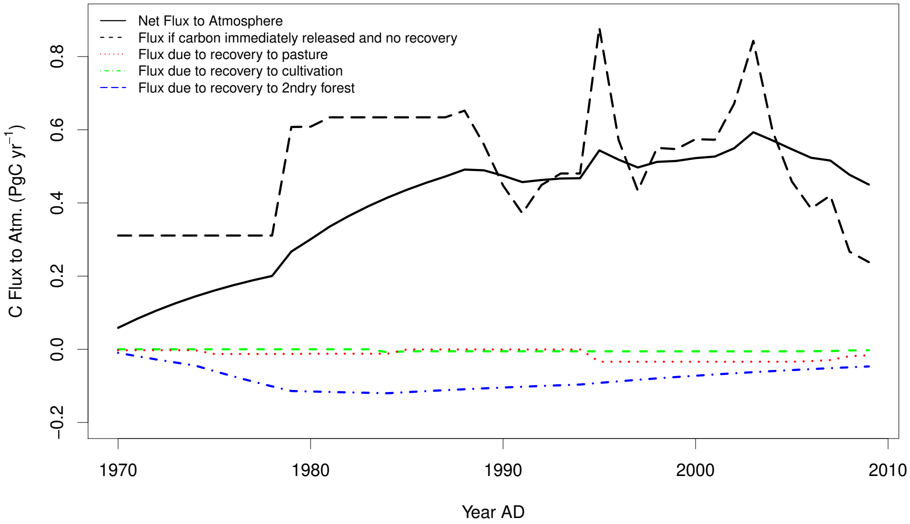

Fig. 8. Estimates of carbon released to the atmosphere from South America due to deforestation for two scenarios: **(a)** carbon is released gradually and regrowth is taken into account using a simplified bookkeeping model following Houghton 1983 as described in Sect. 3.2 and Appendix A4, **(b)** all forest carbon after deforestation is released immediately to the atmosphere and there is no regrowth.

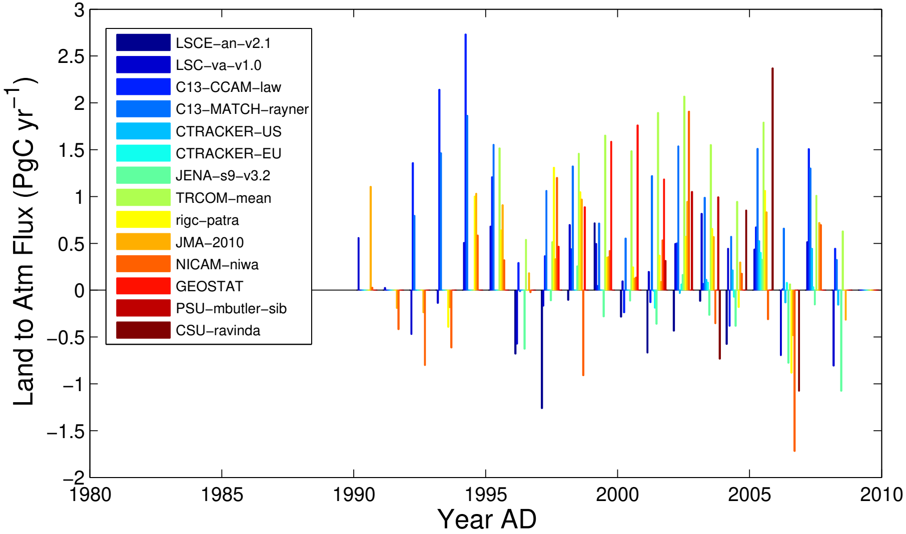

Fig. 9. Net carbon flux estimates from South American land to the Atmosphere (i.e. a positive value is a flux to the atmosphere) estimated based on atmospheric CO_2 concentration data and inverse modeling of atmospheric transport using a range of specific mathematical inversion techniques. For details view summary article on atmospheric inversions in this volume.

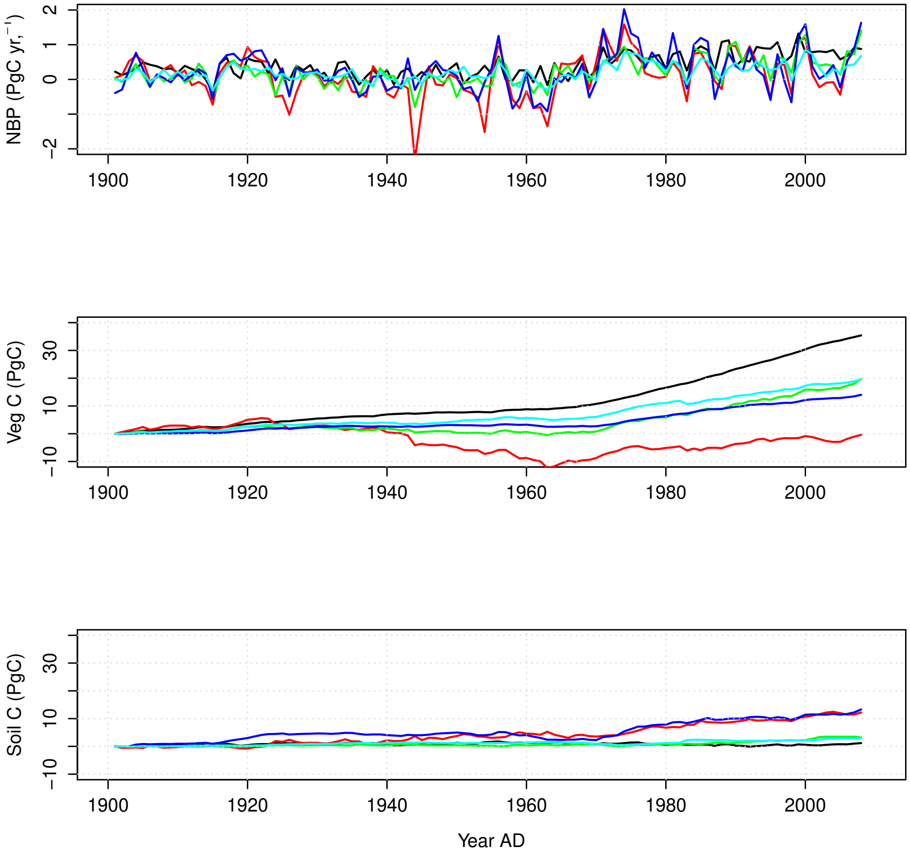

Fig. 10. Dynamic Land Vegetation Model predictions of net carbon flux from the atmosphere to land vegetation ("Net Biome Production NBP") for all of South America **(a)**, and cumulative carbon uptake/release by living vegetation **(b)** and soils **(c)**.

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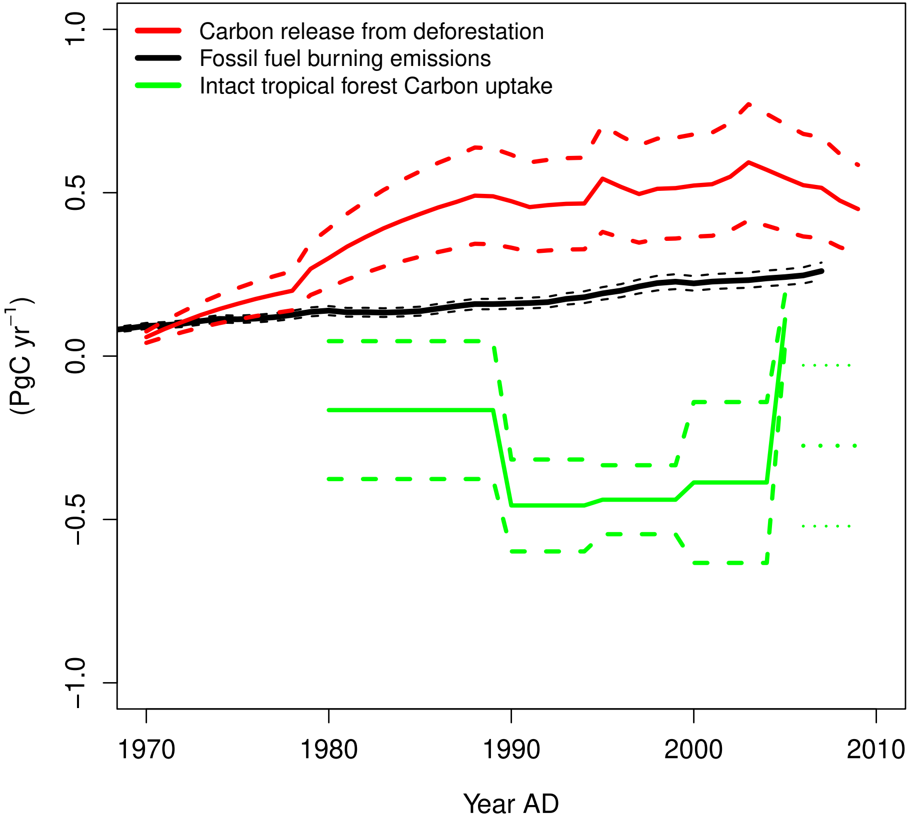

Fig. 11. Flux estimates from South America to the atmosphere (a positive value indicates a flux to the atmosphere) due to deforestation and a simplified bookkeeping model, fossil fuel burning and carbon uptake by intact tropical forests.

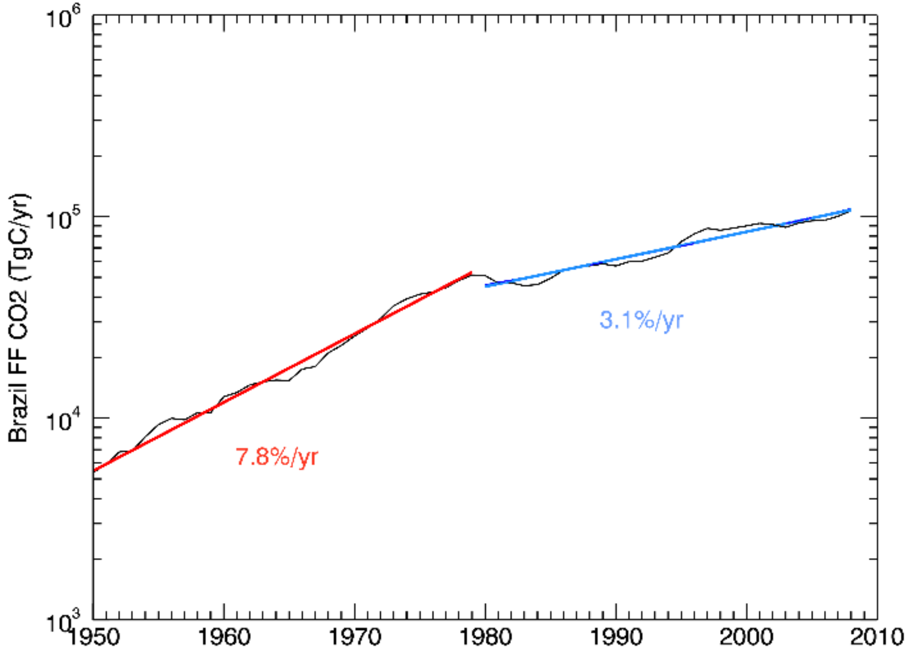

Fig. 12. Fossil fuel emissions from Brazil (Boden et al., 2011) and exponential functions fitted to the emissions for the period from 1950 to 1980 and 1980 to 2010 respectively