Facts and debates on the future of the Amazon forest

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Abstract

The future of the Amazon rainforest is a matter of much concern worldwide. It has been predicted that increasing deforestation and the impact of climate change would rapidly and dramatically reduce the extent of the forest area and its density. Some authors have suggested the possibility of a catastrophic savannisation or die-back of the forest in a relatively short time due to global warming and deforestation combined. This die-back in turn would itself contribute to an acceleration of global warming. The Amazon is also involved in debates about energy, including concerns that deforestation adds to CO_2 emissions and that expanding biofuel crops and oil-gas exploration and extraction further threaten the forest. This paper, which essentially follows the climate projections of the latest (2007) report from the Intergovernmental Panel on Climate Change (IPCC) as well as other available data and scientific results on the prospects of global and regional climate, examines the evidence about deforestation trends and about the expected impact of climate change over the

Resumo

O futuro da floresta amazônica é uma grande preocupação mundial. Prevê-se que o desmatamento crescente e o impacto das alterações climáticas, de forma rápida, reduzirá drasticamente a extensão da área florestal e a sua densidade. Alguns autores têm sugerido a possibilidade de uma "savanização" catastrófica or "morte gradual" (die-back) da floresta, em um tempo relativamente curto, devido ao aquecimento global e desmatamento "combinado". Esta "morte gradual" (die-back), por sua vez, contribuiria para a aceleração do aquecimento global. A Amazônia também está envolvida em debates sobre energia, incluindo as preocupações de que o desmatamento contribui para as emissões de CO_2, e que a expansão da produção de biocombustíveis e exploração de gás de petróleo e extração, podem ameaçar ainda mais a floresta. Este trabalho, que decorre essencialmente das projeções climáticas do último relatório (2007) do Painel Intergovernamental sobre Mudanças Climáticas (IPCC), bem como outros dados e resultados científicos sobre as perspectivas do clima global e regional, examina as evidências sobre as tendências do desmatamento e so-

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Amazon. It concludes that deforestation rates are much lower than previously thought and rapidly decreasing; that deforestation is largely concentrated along the basin's borders outside the vast rainforest core; and that, even in the absence of the observed declining trends in deforestation, catastrophic forecasts of rapid Amazon 'die-back' also lack scientific basis, especially when predicted to occur in a few decades or within this century.

bre o impacto esperado da mudança climática sobre a Amazônia. Conclui-se que as taxas de desmatamento são muito menores do que se pensava com uma diminuição rápida, que o desmatamento está concentrado, principalmente ao longo das fronteiras da bacia fora do núcleo da vasta floresta tropical e que, mesmo na ausência das tendências observadas em declínio no desmatamento, previsões catastróficas da Amazônia, como uma rápida "morte gradual" (die-back), também não têm base científica, especialmente quando a previsão é para ocorrer em algumas décadas ou dentro deste século.

1. Introduction

There is widespread worry worldwide about the future of the Amazon rainforest, the largest forested area in the world. Alarming predictions of rapid shrinking of the forest through deforestation and climate change, as well as hypotheses that a "tipping point" may soon be reached causing the irreversible degradation of the entire forest into a savanna, have caused much concern. This paper examines the empirical evidence and theoretical approaches that may or may not justify those fears.

The Amazon basin requires special attention because of its relevance for greenhouse gases emissions and global carbon cycle that might be fundamental for global climate change. Certain forms of deforestation release carbon to the atmosphere, principally as CO_2, as the organic carbon stored in trees and soil is oxidized through burning and decay.[1] Other greenhouse gases, such as CH_4 and N_2O, are also emitted as a result of deforestation. Emissions of greenhouse gases from worldwide deforestation in the 1990s and early 2000s amounted to about 25% of the enhanced greenhouse effect estimated to result from all anthropogenic emissions of such gases. If the 1990s and early 2000s trends continue, it has been estimated that tropical deforestation may ultimately release about 50% as much carbon to the atmosphere as has been emitted from worldwide combustion of fossil fuels since the start of the industrial revolution (Houghton,

1 Logging does not release much carbon (except for leftover parts of the trees, like twigs, and possibly from the soil) as the wood is simply withdrawn from the forest and not allowed to decay there: the carbon stored in timber remains stored elsewhere in wood products. Logging with replanting actually sinks carbon in net terms. Slash and burn practices and the use of wood for fuel (in the form of firewood or charcoal) are the most common forms of carbon emission from deforestation. In a forest in equilibrium with a stable biomass, carbon emitted (and oxygen absorbed) by decaying vegetation (including natural forest fires) is balanced by carbon sunk (and oxygen emitted) by growing trees and plants, and thus a stable forest does not release (on average and in net terms) neither oxygen nor carbon.

2005). Besides, deforestation may contribute to more drastic changes in the climate of the Latin American region and elsewhere, affecting agricultural production and many vulnerable groups within the Amazon basin and without. Degradation and reduction of the Amazon forest is therefore of paramount importance, and the question of its extent and speed has produced studies since several decades ago (e.g. FEARNSIDE 1982)

There are also some studies that, based on hypotheses about increasing dryness of the Amazon climate, predict dramatic and abrupt changes in the Amazon rainforest, including its rapid "savannisation" or conversion to savanna, with probably large consequences for regional and world climate. This paper aims at examining the scientific basis of both sources of fear about the future of the Amazon: rapid deforestation and the expected impact of climate change.

2. Deforestation trends

According to FAO (2001), the highest amounts of (gross) deforestation (in million ha/yr during the 1990s) occurred in Brazil (2.3), India (1.9), Indonesia (1.7), Sudan (1.0), Zambia (0.85), Mexico (0.65), Myanmar (0.58) and the Democratic Republic of Congo (0.54). These **gross** rates are higher than the reported **net changes in forest area** (also FAO, 2001) because **net change** includes losses of natural forests but also increases in **plantations** and secondary forest **regrowth**. Absolute numbers, of course, are not very useful unless the absolute size of forests is taken into account. Percentage rates of change are more revealing. Relative annual net change rates estimated by FAO in the 1990s were lower in tropical Latin America (−0.46%) and higher in tropical Asia (−0.78%), despite large increases in Asian plantations.

However, these figures are quite disputed and rapidly improving in quality. FAO's historical series of forestry statistics have been questioned, especially as regards the 1960s and 1970s, but also for more recent periods. National statistics of dubious reliability and expert estimates (widely used by FAO for lack of better sources) are being replaced by hard data. Ground based intensive monitoring is much better nowadays, and is being rapidly complemented by satellite information. Image resolution is also improving. Forest cover estimates for 1990 and 1997 from the European-funded, satellite-based TREES project (ACHARD *et al* 2002a, 2002b) are (in global terms) quite close to the FAO **forest area** estimates, with a 1.9% relative difference at the global level, but with more significant regional differences: +3% for Latin America, −9% for Africa and −6% for Southeast Asia (Table 4 in ACHARD *et al* 2002a: 1002). The resulting **rates of deforestation** are also lower.

Reliance by FAO on secondary information, expert opinion and old country statistics may explain these differences. As "in many countries, primary information on forest area was not available or not reliable", FAO "had to rely on secondary information and/or expert estimates". Furthermore "a high proportion of developing countries had to rely on expert opinion for the latest area estimates" (FAO 2001). This may affect comparability. Local deforestation rates coming from field experts and surveys (FAO 1995, 2001) are often higher than estimates based on remote sensing.[2] Often field reports are lower than FAO estimates, which might be extrapolations of previous tendencies. For instance, field communications from Bolivia and Zimbabwe reported rates of deforestation six times lower than FAO's estimates (HOUGHTON & RAMAKRISHNA, 1999).

It is possible to reduce uncertainty about deforestation rates with the use of higher spatial resolution satellite data, and denser sampling. However, two estimates of deforested areas in the Brazilian Amazon, both based on Landsat data, differed by 25% (HOUGHTON *et al* 2001). The reasons for the difference have not been fully resolved, but seem to be related to differences in the sample of scenes used by each study. Estimates based on remotely sensed data are sensitive to their ability to capture the spatial variability of deforestation, calling for denser sampling and finer resolution (including better imagery, better groundtruthing, and improved ground monitoring). Samples generally consist of entire Landsat scenes, and the variability among scenes may be so high as to require >80% coverage of a region for an accurate estimate of deforestation (TUCKER & TOWNSHEND, 2000). In contrast, the sampling ratio used by Achard *et al* (2002a, 2002b, 2004) was only 6.5%, after stratification based on regional expert opinion; and that used by Hansen *et al* 2008 was just 0.21%. In both cases special techniques and sampling designs were used to compensate for the smaller size of the sampled area, but the overall effect may have been a large sampling error. It is also possible, especially in densely populated regions, that the size of clearings is often too small for a change in tree cover to be recognized in satellite images.

Furthermore, supra-national aggregation of national statistics has proved to be extremely difficult, due to incompatible definitions and inventory methods, often completely outdated (WATSON *et al* 2000). As more accurate data from remote sources are increasingly used, estimates and projections of deforestation have tended to decline. In the 1970s and 1980s there were projections of future deforestation rates above 2% per year, which were later shown to be wildly exaggerated.[3] When Brazil started satellite monitoring in 1988 the first estimates of Amazon forest change were in the range of 1.0-1.5% per year, but were later further corrected: FAO 1997 estimated the rate for the 1980s at 0.80% and at 0.70% for the 1990s (pp. 12 and 18); more careful and precise satellite observations (FAO 2001) decreased it to 0.46% for the 1990s (and the worldwide

2 This is not always the case: Hansen & DeFries 2004 used satellite data and reported rates higher than those reported by FAO 2001 in 5 out of 6 countries. However, this case is rather the exception: the general tendency is for field observations and estimates to be higher than those from satellites. Besides, reported rates have been declining as methods improve.

3 See for instance an "optimistic" estimate of 2.3% per year (at p.131) and a more pessimistic estimate of 4.8% percent per year (p.331) of deforestation in tropical forests, in Barney 1980, an official report to the President of the US. After thirty years, these estimates would have reduced tropical forests by 50.3% and 77.2% respectively.

rate for tropical forest was decreased to 0.55% per year for the same period).[4] Deforestation rates for the same decade, produced through the European Commission TREES project, were one quarter lower than FAO's rates worldwide, estimating an average rate of change in forest area of 0.43% at world level, and 0.33% for Latin American tropical forests. The balance of these various sources points to:

- A tendency to overstate deforestation in most estimates not based on satellite information, or using coarser image resolutions.
- A historical tendency towards decreasing estimates of deforestation rates for a given target period, as methods become more precise.
- A historical trend towards lower reported rates of net forest area change (even for the same period), due to increasing importance of (and attention lent to) plantations and regrowth.

The TREES study on deforestation, carbon emissions and identification of hotspot areas carried out by the European Commission Joint Research Centre (ACHARD *et al* 2002a, 2002b), uses tropical forests mapping at a resolution of 30x30m (or 20x20m at some sites) to estimate forest area in 1990 and 1997 and deforestation rates between those two years. The study sampled 6.5% of the total forest area, oversampling the areas in the hotspots estimated to undergo faster deforestation, and produced area-weighted estimates of forest area and its rate of change between 1990 and 1997. The area sampled was relatively small but the sampling model greatly reduced sampling error through stratification and varying sampling ratios depending on (reported) intensity of deforestation activity. However, as will be showed shortly, not all reported hotspots exhibited high deforestation rates.

In the case of Latin America the TREES study estimated that the annual decrease in primary forest cover area from 1991 to 1997 was 2.5±1.4 million Ha, falling from 669±57 to 653±56 million Ha (the error margins are 95% confidence intervals, and do not bias the estimate because they are similar at both ends of the period of analysis). This implies an annual **gross deforestation rate** of 0.38% relative to the 1990 forest area, or about 0.2% if calculated on the original size of the forest. Annual regrowth (reconversion to forest) was +0.04%. Tree plantation was not studied. Consequently, the resulting **net forest area change rate** for Latin America in the 1990s was estimated at –0.33%, or 2.2±1.2 million Ha per year, relative to 1990. This includes not only the Amazon basin but the whole of the study area in tropical Latin America, two thirds of which corresponds to the Amazon. For the Brazilian and Guyanas Amazon subregion the estimate net change is 1.32 million Ha per year in 1991-97, representing a net annual change rate of –0.31%, relative to a 1990 forest area estimated at 420 million Ha (ACHARD

4 The FAO's ***State of the World's Forests 2009*** (FAO 2009:113, Table 1) estimates an annual change of –0.51% for Latin America and the Caribbean in 2000-2005, probably reflecting the temporary rise in Brazilian figures that peaked in 2004. Rates have decreased after 2005 (as reported by the Brazilian Inpe reports), but are not yet reflected in FAO's published statistics.

et al 2002a:1001).[5] For the rest of the study area in tropical Latin America, including the non-Brazilian Amazon areas (Bolivia, Peru, Ecuador, Colombia) and Central America, the implied 1990 forest area was 249 million Ha and the annual decrease about 0.88 million Ha, at an annual net change rate of −0.35%. Besides changes in the extent of forests, the annually **degraded forest area** was estimated at 0.83±0.67 million Ha/yr, or 0.13% of the 1990 forest area (ACHARD *et al* 2002a: 999).[6]

The main qualitative conclusion of the Achard study is that deforestation in Latin America is confined to several 'hotspots' where remaining forests are increasingly fragmented or are already heavily logged and burnt. The 'hotspots', however, were found to be not uniformly 'hot'. Many, in fact, were remarkably 'cold'. The great majority of reported hotspots were areas **previously** deforested that **currently** exhibited relatively **low** rates of gross deforestation (especially considering their hotspot status) at the period analysed by the TREES study, i.e. during the 1990s (ACHARD *et al* 2002b:138). The high points in the sample of sites (hotspots or not) were one site at −4.77% in Colombia, one site −4.41% in Acre (Brazil), another at −3.2% in Rondônia; and three Brazilian sites between −3% and −2%, all at the edges of the basin. There were 9 sites between −2% and −1%, most located also at the basin's borders. Most sample sites (27 out of 46) were being slowly deforested at rates between −1% and 0%, and four sites exhibited 0% deforestation. Only 6 sites out of 46 showed annual rates faster than −2%, and only a third (15) faster than −1% (all relative to 1990). Therefore in the 1990s only a minority of the selected sites were actually being actively deforested at a rapid rate, although the sample was heavily concentrated on reported hotspots, allegedly undergoing rapid deforestation.

Table 1. Range of annual gross deforestation rates in hotspot areas (1990-97)

Location of hotspot areas	Mean annual gross deforestation rates
Central America	0.8–1.5%
Brazilian Amazon basin border belt	
Acre	4.4%
Rondônia	3.2%
Mato Grosso	1.4–2.7%
Pará	0.9–2.4%
Colombia-Ecuador border	~1.5%
Peruvian Andean piedmont	0.5–1.0%

Source: Achard et al 2002a:1001; 2002b:113.

5 Achard *et al* estimate also the amount of GHG emissions implied by their deforestation estimates; this aspect of their study elicited some debate (Fearnside 2003; Eva *et al* 2003; Fearnside & Laurance 2003), but the issue does not impinge on estimates of deforestation or forest area change rates, which are the matters discussed here.

6 Definitions used by the authors: "Deforestation is defined as the conversion from forest (closed, open, or fragmented forests; plantations; and forest regrowths) to nonforest lands (mosaics, natural nonforest such as shrubs or savannas, agriculture, and nonvegetated). Reforestation (or regrowth) is the conversion of nonforest lands to forests. Degradation is defined as a process within forests that leads to a significant reduction in either tree density or proportion of forest cover (from closed forests to open or fragmented forests)" (ACHARD et al 2002:1002, Note 10).

In the Brazilian Amazon, hotspots are mostly at the Eastern and Southern edges of the basin, and only exceptionally near or inside the wet rainforest core lowlands. As shown in Figure 1, most of the Amazon is still forest (the map is for 1999-2000, but little has changed since).

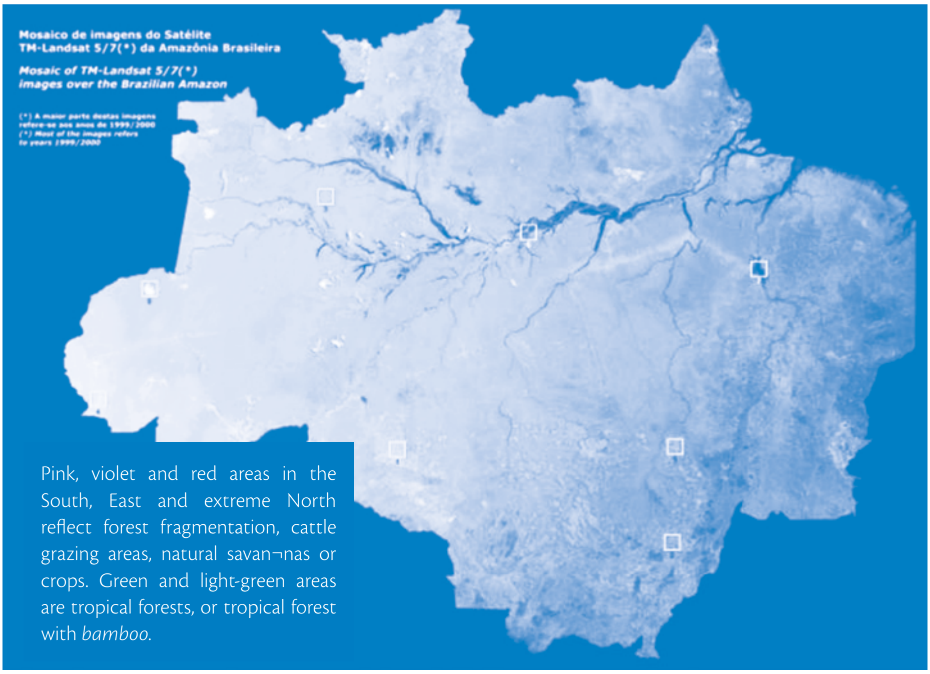


Figure 1. LANDSAT image of the Brazilian Amazon region (1999-2000).

Source: Inpe

The pinkish area at the top-left of the map is mostly a natural savanna area in Rorâima. The other non-forest areas are mostly at the East and South of the basin, plus small areas near the mouth of the Amazon River, or at specific points along the Amazon or along the Northern (Atlantic) coast. Few and small areas within the basin, mostly along the Amazon River, show signs of deforestation. It is worth remarking that the non-forest-coloured areas in the map are not all the result of deforestation, and even less equivalent to **recent** deforestation: they include natural savannas as well as areas originally covered by forest; these former forests, besides, were in part bush or other kinds of non-rainforest vegetation, although the inner borders of the non-forest belt and the small areas inside the core do include cleared rainforest.

In the TREES study, several hotspot areas in Rondônia, Acre, and the eastern side of the belt (especially in Pará), with rates around –2.3% on average during the 1990s, were those under higher (though not extreme) pressure. The hotspots in the South Eastern area of the belt (e.g. Mato Grosso and other neighbouring areas) were also relatively important, albeit with a more heterogeneous pattern (between –0.4% and –2.7%). Rates were also relatively high in the hotspot area between Colombia and Ecuador (about –1.5%, above the hotspot average) and to a lesser extent in the Peru piedmont hotspots along the Andes (–0.5% to –1.0%, well below the average). Most hotspot areas are in the borders of the Amazon basin, some at the source in the Andes and most in the plains of Southern and Eastern Brazil. Few important hotspot areas lie in the vast rainforest core (see map in ACHARD *et al* 2002a:1000, Figure 1, and Achard *et al* 2002b:35 and 66). Amazon deforestation in the 1990s was in fact "confined" (ACHARD *et al*'s word) to hotspot areas, most located at the basin's edges and many being deforested at rather slow rates (in view of their 'hotspot' status).

Hotspots represent (in terms of area) only a small fraction of the entire Amazon basin. All other areas in the Amazon region, outside hotspots, did not exhibit noticeable deforestation, including the vast core rainforest, mostly not suitable for crops or grazing. The total Amazon forest long term net change rate is (as of 2009) estimated at about –0.22%, implying a half life of about 315 years (the time required for the Amazon forest to be cut by half if that rate persists for more than three centuries). In fact, however, extrapolation of this sort is not valid: deforestation is taking place only at areas suitable for grazing or crops, at the edges of the basin, not much at the core, and land clearing is already decreasing its speed due to enhanced environmental protection and increasing unavailability of additional suitable land. It is therefore quite improbable that recent rates persist for long. At any rate, and unless some different process is at work (on which more later), there are no grounds to infer rapid disappearance or drastic shrinking of the forest in the current century, and less so in a few decades.

Droughts, fires and deforestation, increased population and paved roads are factors that are thought to endanger the Amazon basin, and likely to cause considerable short term changes in the hydrological cycle of the region. Nevertheless, the causal links are debatable. In some cases, it is prior deforestation that leads to increases in population and roads. The link from deforestation to changes in the hydrological cycle is also disputed. Studies of specific sub-basins (pristine versus recently deforested) show **no long term differences in precipitation and hydrology as a result of deforestation** (LINHARES *et al* 2007). New methods with improved resolution for specific areas or hotspots are being introduced and should be integrated in a wider continental study to obtain a better approach and estimation of the consequences of climate change in the region (rainfall and temperature shifts, droughts, floods, etc.).

The future is uncertain, even for hotspots. Models and predictions are constantly improving and diverse new scenarios are described. An important fact, however, is that as observation techniques improve the general change in the results for a given period has been towards **lower** estimated rates of deforestation, even for the same past period. Adaptation and mitigation policies are expected to increase in the coming years because of the international pressure and carbon related policies, and the governments involved, especially Brazil, are taking important steps in this regard. Updating studies on deforestation rates and climatic models should be carried on for this area, where the impact of global climate change on South American weather and vegetation is still not fully understood.

The gross deforestation speed in the Brazilian Amazon fell by 73% between 2004 and 2009, according to estimates of the Prodes system at Brazil's National Institute for Space Research (Inpe), based on mixed ground and satellite methods described in Câmara *et al* 2006. The loss of forest in 2007-2009 was the lowest since the Brazilian government started tracking deforestation on a yearly basis in 1988. As can be seen in Figure 2 deforestation rates in Brazil as reported by Prodes have fallen by more than two thirds since 2004 when 27,423 km^2 were cleared at the top of a seven-year escalation. Figures gradually decreased reaching a much lower deforested area of 11,532 km^2 in 2007, i.e. a decrease of 58% in three years, varying only slightly to 11,968 in 2008 (still 56.4% less than in 2004) in spite of strong market pressure for commercial agricultural frontier expansion arising from soaring agricultural prices worldwide. This unusual market pressure, which caused fears in various respects worldwide, was in large part a passing phenomenon. As prices fell substantially in the second half of 2008 and recession started to spread across the world, pressure to convert forest into farmland subsided, and at the same time the Government of Brazil vowed to increase efforts and resources to enforce environmental law. From 2008 to 2009 the deforested area decreased more sharply: the total for August-2008 to August-2009 was only 7464 km^2, a 38% decrease over the precedent year and 73% lower than the 2004 peak. These facts show an accelerating decrease in deforestation and give credence to hopes of further decreases in the rate of deforestation of the Brazilian Amazon. The 2009 results are equivalent to an annual gross deforestation rate of 0.13%, thus halving the historical average of about 0.25%.

Brazil, in fact, credits recent drops in gross deforestation rates to a step-up in law enforcement efforts, which by 2008 have netted hundreds of illegal loggers and corrupt officials, generating some $1.7 bn in fines according to Inpe, the Brazilian Space Research Institute (http://www.inpe.br) and the Brazilian Institute for the Environment, Ibama (http://www.ibama.gov.br/). The Brazilian government has also dramatically expanded the size and number of protected areas. Between 2002 and 2009, about 709,000 thousand km2 were designated as Protected Areas, especially at the deforestation frontier along the basin's Southern and Eastern borders (see SOARES-FILHO *et al* 2010 for a positive evaluation of the impact of this Protected Area expansion upon deforestation).

Inpe figures confirm that most deforestation takes place at the Southern and Eastern edges of the Amazonian Basin, and at some specific coastal spots in the North. Deforesting activity is concentrated in Pará with 57% of the total, with much lower shares of Maranhão, Mato Grosso and Rondônia, all at the Southern and Eastern edges of the basin (Table 2, Table 3 and Figure 2). These previously forested areas mostly belong to the margins of the Amazon basin; most of them were not covered by core rain forest but by other forms of tropical and subtropical vegetation, including a large share of bush and open forest, and a large proportion of secondary forest as discussed below.

Table 2. Amazon gross deforestation by state in Brazil, 1988-2008 (km2/year, 12 months to August

	1977-88	1989	1990	1991	1992	1993[a]	1994[a]	1995	1996	1997	1998
Acre	620	540	550	380	400	482	482	1208	433	358	536
Amazonas	1510	1180	520	980	799	370	370	2114	1023	589	670
Amapá	60	130	250	410	36	0	0	9	0	18	30
Maranhão	2450	1420	1100	670	1135	372	372	1745	1061	409	1012
Mato Grosso	5140	5960	4020	2840	4674	6220	6220	10391	6543	5271	6466
Pará	6990	5750	4890	3780	3787	4284	4284	7845	6135	4139	5829
Rondônia	2340	1430	1670	1110	2265	2595	2595	4730	2432	1986	2041
Roraima	290	630	150	420	281	240	240	220	214	184	223
Tocantins	1650	730	580	440	409	333	333	797	320	273	576
Amazônia Legal	21050	17770	13730	11030	13786	14896	14896	29059	18161	13227	17383

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Acre	441	547	419	883	1078	728	592	398	184	222	167
Amazonas	720	612	634	885	1558	1232	775	788	610	479	405
Amapá	0	0	7	0	25	46	33	30	39	0	70
Maranhão	1230	1065	958	1014	993	755	922	651	613	1085	828
Mato Grosso	6963	6369	7703	7892	10405	11814	7145	4333	2678	3259	1049
Pará	5111	6671	5237	7324	6996	8521	5731	5505	5425	5180	4281
Rondônia	2358	2465	2673	3099	3597	3858	3244	2049	1611	1061	482
Roraima	220	253	345	84	439	311	133	231	309	570	121
Tocantins	216	244	189	212	156	158	271	124	63	112	56
Amazônia Legal	17259	18226	18165	21394	25247	27423	18846	14109	11532	11968	7464

(a) Figures for 1993 and 1994 are actually the average of the two years.

Source: Inpe (2009) and http://www.obt.inpe.br/prodes/index.html. Results retrieved 16 June 2010.

Table 3. Share of states in Amazon gross deforestation, 1977-88 to 2009 (%)

	1977-88	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998
Acre	2.9%	3.0%	4.0%	3.4%	2.9%	3.2%	3.2%	4.2%	2.4%	2.7%	3.1%
Amazonas--	7.2%	6.6%	3.8%	8.9%	5.8%	2.5%	2.5%	7.3%	5.6%	4.5%	3.9%
Amapá	0.3%	0.7%	1.8%	3.7%	0.3%	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%
Maranhão	11.6%	8.0%	8.0%	6.1%	8.2%	2.5%	2.5%	6.0%	5.8%	3.1%	5.8%
Mato Grosso	24.4%	33.5%	29.3%	25.7%	33.9%	41.8%	41.8%	35.8%	36.0%	39.9%	37.2%
Pará	33.2%	32.4%	35.6%	34.3%	27.5%	28.8%	28.8%	27.0%	33.8%	31.3%	33.5%
Rondônia	11.1%	8.0%	12.2%	10.1%	16.4%	17.4%	17.4%	16.3%	13.4%	15.0%	11.7%
Roraima	1.4%	3.5%	1.1%	3.8%	2.0%	1.6%	1.6%	0.8%	1.2%	1.4%	1.3%
Tocantins	7.8%	4.1%	4.2%	4.0%	3.0%	2.2%	2.2%	2.7%	1.8%	2.1%	3.3%
Amazônia Legal	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Acre	2.6%	3.0%	2.3%	4.1%	4.3%	2.7%	3.1%	2.8%	1.6%	1.9%	2.2%
Amazonas	4.2%	3.4%	3.5%	4.1%	6.2%	4.5%	4.1%	5.6%	5.3%	4.0%	5.4%
Amapá	0.0%	0.0%	0.0%	0.0%	0.1%	0.2%	0.2%	0.2%	0.3%	0.0%	0.9%
Maranhão	7.1%	5.8%	5.3%	4.7%	3.9%	2.8%	4.9%	4.6%	5.3%	9.1%	11.1%
Mato Grosso	40.3%	34.9%	42.4%	36.9%	41.2%	43.1%	37.9%	30.7%	23.2%	27.2%	14.0%
Pará	29.6%	36.6%	28.8%	34.2%	27.7%	31.1%	30.4%	39.0%	47.0%	43.3%	57.3%
Rondônia	13.7%	13.5%	14.7%	14.5%	14.2%	14.1%	17.2%	14.5%	14.0%	8.9%	6.5%
Roraima	1.3%	1.4%	1.9%	0.4%	1.7%	1.1%	0.7%	1.6%	2.7%	4.8%	1.6%
Tocantins	1.3%	1.3%	1.0%	1.0%	0.6%	0.6%	1.4%	0.9%	0.5%	0.9%	0.7%
Amazônia Legal	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Source. Inpe, http://www.obt.inpe.br/prodes/index.html. Calculated from previous table.

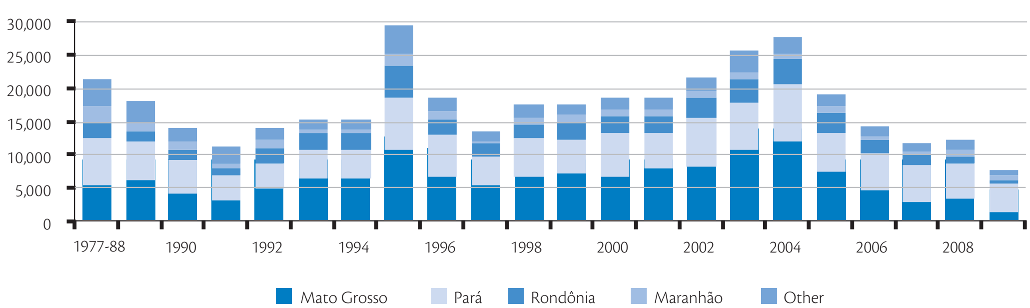


Figure 2. Gross deforestation in the Brazilian Amazon (km2/year, average 1977-88 and annual data 1988-2009, 12 months to August, Inpe, http://www.obt.inpe.br/prodes/index.html)

As these statistics show, gross deforestation has been reduced to insignificant figures in most states except Pará (in the Northeastern border of the Amazon region), where it has nonetheless been greatly diminished relative to previous years. Deforestation through land clearing by small subsistence farmers has been declining, but large-scale deforestation for cattle ranching or commercial crops is the most rapidly falling component. Smallholder land clearing is admittedly more difficult to control than large scale ranching and commercial logging. Total deforestation in the Brazilian Amazon is in 2009 by far the lowest since the satellite records started in 1988, and the rates of 2006-2009 had only been matched in a single past year (1991). High profile activity by the Federal Government in recent years (since 2004) indicates a real political will to address the problem of deforestation and more generally the Amazon forest conservation, as it had never before been shown by Brazilian authorities. This, and the strong deployment of law enforcement resources in the Amazon since 2004, further reinforces the hypothesis that the trend to curtail deforestation is likely to continue (SOARES-FILHO *et al* 2010).

Inpe estimates only **gross** deforestation (i.e. initial clearing of mature forest, as explained in INPE 2000. But clearing virgin forest is only part of the picture. Ramankutty *et al* 2007 developed a land-cover transition model to predict transitions between primary forest, cropland, pasture, and secondary forest. "Of the total (gross) deforested land over the 1961-2003 period, 6% remains in cropland, 62% remains in pastures, but almost 32% of the deforested land is in regrowing vegetation" (RAMANKUTTY *et al* 2007:59 and Fig.4 at the same page). Based on the initial (1961) size of forested areas, the Ramankutty study implies that the average rate of net forest area change from 1961 to 2003 in the Brazilian 'legal Amazon' region was 0.215% per year, about 0.04% lower than the 0.255% rate emerging from the Inpe gross deforestation series since 1988, and much lower than in the FAO 1961-2003 series. Ramankutty's model also suggests that clearing of new land is being replaced by re-clearing of fallow land: annual re-clearing has increased steadily, from nil in 1961 to about 0.5 million Ha/yr in the early 1980s, 1.7-2.0 million Ha/yr in the early 1990s and more than 3 million Ha/yr in the early 2000s, whilst new land cleared remained between 1.5 and 2 million Ha/yr since the late 1970s to 2003, and surely much less in 2005-2009, as gross deforestation has steadily dwindled, and available usable forest land becomes scarcer.

These reductions have great importance in terms of carbon emissions. Gullison *et al* (2007) estimate that " [r]educing deforestation rates [prevailing in the 1990s] 50% by 2050 and then maintaining them at this level until 2100 would avoid the direct release of up to 50 GtC [gigatons of carbon] this century" (GULLISON *et al* 2007:985). In fact, a deforestation rate reduction higher than that has been already achieved in the late 2000s, and the reduced rate would probably continue (or become yet lower) in the future, since the Government of Brazil has enacted a strong set of policies to that effect, on which there is wide consensus across the political spectrum, and moreover, forest land potentially usable for grazing or for growing crops is rapidly diminishing, especially in Eastern Amazonia.

3. Drivers of deforestation

Agriculture and proximity to paved roads are often mentioned among the main drivers of deforestation in the Amazon. However, causal direction is not always clear. Proximity to paved highways is a major correlate of deforestation rates and this relationship was determined empirically from data on deforestation and paved roads for 432 counties in the Brazilian Amazon (SOARES-FILHO *et al* 2006). These results are consistent with other authors that found human development and roads as main correlates of forest deterioration and deforestation rates through modelling and predictors analyses (VERA-DIAZ *et al* 2007; JHA & BAWA 2006; LAURANCE *et al* 2002; BAWA & DAYANANDAN 1997; ROJAS *et al* 2003). However, roads running deep into the core rainforest are surrounded only by a thin deforested strip at each side. Wider deforested areas can only be found at the edges of the basin, and their driver is the agricultural aptitude of soils (for crops or grazing). It is furthermore not clear whether (and where) deforestation (and associated economic activity on deforested areas) prompts road construction, or the reverse.

Forest is typically cleared in the Amazon to provide pasture for cattle grazing and in some areas by subsistence farmers to cultivate crops. Brazil has a booming beef export industry, as well as a growing domestic consumption of beef, and as a consequence cattle ranchers have been expanding their operations in the margins of the Amazon basin. Landless settlers, on their part, clear land for subsistence cultivation. In this context, we consider remarkable that large-scale commercial crops (maize, oilseeds, sugar cane, coffee, cotton, etc.) are **not** significant activities in deforested areas (Figure 3, based on data from INPE 2008). Sixty percent of the deforested land is destined to cattle grazing, 33% for subsistence farming, and just 1% for commercial crops. The rest is made of 3% logging and 3% residual factors (dams, roads, etc., **including fires**).

The effect of crops is indirect: expansion of commercial crops displaces cattle (only where grazing land is also cultivable), and livestock is then moved into newly deforested areas. But only a fraction of cattle was grazing originally on cultivable land. Moreover, it should be recalled that most expansion of agriculture in Latin America is driven mostly by increased productivity per hectare and only marginally by expansion of the agricultural frontier: from 1961 to 2007 Brazil's agricultural production grew by 468% at an annual rate of 3.34%, whilst total agricultural land increased only 75.1% at an annual rate of 1.28% (FAOSTAT data). This implies that 77% of all agricultural growth in the whole of Brazil is due to increased production per hectare, which grew at 2.03% per year, and only 23% to land expansion. Moreover, expansion of agricultural land in Brazil occurred mostly in the 1960s and 1970s: the annual rates were 2.94% in 1961-70, 1.39% in 1970-80, 0.75% in 1980-90, 0.79% in 1990-2000; in 2000-2007 the rate of land expansion dropped to just 0.11% per year. Agricultural output growth in 2000-07 was 4.25% per year, almost all due to better productivity and almost nil to new land being added (FAOSTAT data; output measured in value of production, net of re-use within the agricultural sector, e.g. as seed or fodder, at constant 1999-2001 international prices).

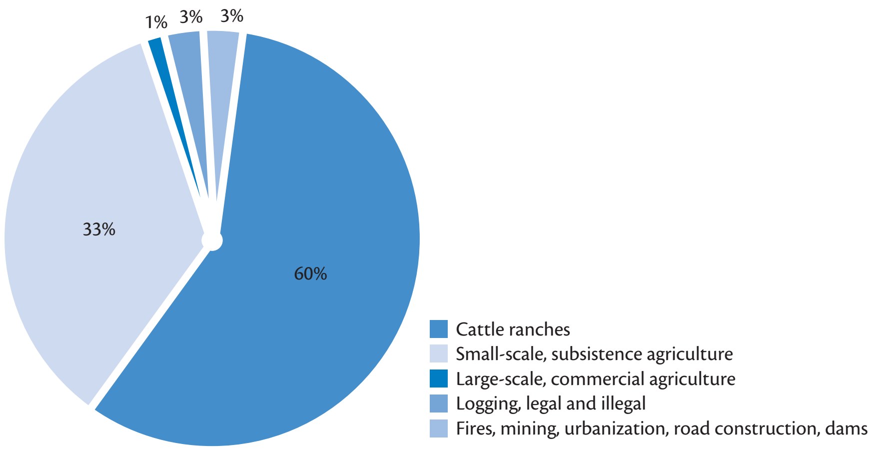


Figure 3. Drivers of deforestation in the Amazon, 2000-2005 (based on INPE 2008)

The expansion of agricultural land in Brazil (comprising annual and permanent crops as well as grassland, and including the whole country, not just Amazonia) steadily increased (albeit at a generally decreasing trend) until 1995, and then nearly stabilised. The annual change in 1995-2007 was very small, and was near to zero or with actual decrease in the more recent years of the series (Figure 4).

The short episode of relatively higher annual expansion of farm land in 1994-96, about 40,000 km^2 per year, probably reflects in part the record 21,000 km^2/year deforested in the Amazon in the 1994-96 period, but no such parallel expansion is noticeable in recent years: the new peak of 27,000 km^2 deforested in 2004 was not followed by any expansion in total agricultural land (some possible expansion in Amazonia may have been made up by reductions elsewhere, where new land is quite scarce; such reduction, moreover, is not likely to be a major factor in a period of excellent agricultural prices and rising exports and consumption; for the time being, anyway, no regional breakdown is available for these data). No matching expansion of logging was detected either (logging represents just about 3% of total deforestation).

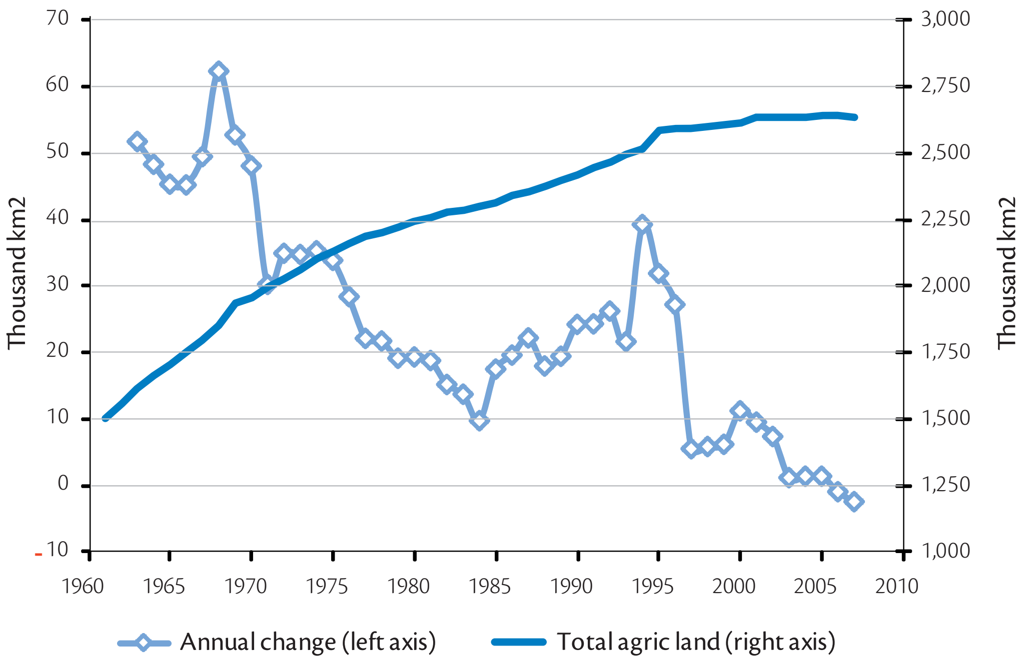


Figure 4. All Brazil. Total agricultural area (arable land, permanent crops and grassland, right axis) and annual change in agricultural area (left axis), moving 3-year averages, from 1961-63 to 2006-08, centred at the middle year, all in thousand km^2. Source: FAO (FAOSTAT) as per 20 October 2010.

For the whole of Brazil, the value of agricultural production (at constant prices) has greatly expanded in the latest half century, but such growth has been determined mostly (81%) by increases in average economic productivity of land (output value per hectare at constant prices) and only in a small proportion (19%) by the cumulative expansion of agricultural land, as shown in Figure 5 for 1961-2007. Moreover, the impact on output of expansion of farm land occurred mostly in the 1960s, 1970s and 1980s (at decreasing rates), coming almost to a halt in the two more recent decades, as shown in Figure 5, and as transpired also from Figure 4 before. These data refer to all Brazil, but most expansion of the agricultural frontier occurred indeed within the Amazon region, widely defined (albeit mostly not in the core rainforest).

Increased economic productivity is not to be confused with an equal increase in physical productivity: changes in land use and crop mix have also contributed to higher output per hectare. However, in that very period population increased greatly, per capita intake of dietary energy increased from about 2400 to about 3000 daily kilocalories per person, and agricultural exports soared.

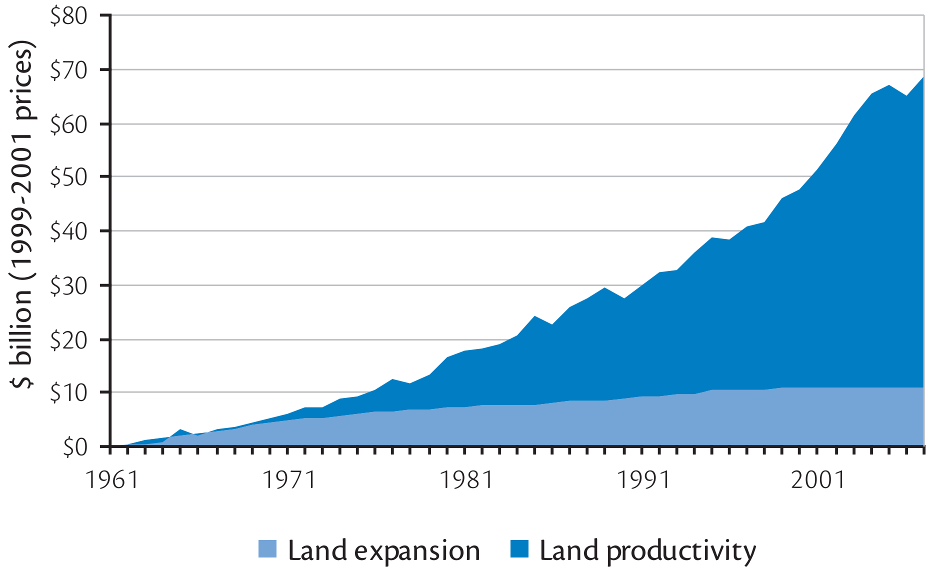


Figure 5. Figure 5. All Brazil - Contributions of land expansion and average land productivity to cumulative agricultural growth, 1961-2007 ($ bn at constant 1999-2001 international prices).

Based on FAOSTAT, www.faostat.fao.org.

There are indeed large areas with crops and cattle within the Amazon **hydrological basin**, but most of these areas are not cleared rainforest: they belong mostly to the large system of natural savannas or open bush systems surrounding the forest to the East and South. It is remarkable to note that a recent study on the economic and physical conditions for soybean cultivation within the Amazon hydrological basin (VERA-DIAZ *et al* 2008) finds that the most physically and economically suitable areas are located precisely where soybeans are already being cultivated, in the States of Mato Grosso, Rondônia and Acre, at the Southern edge of the basin, and at the savannas of Rorâima at the extreme Northwest, besides some other specific points. Most of the rest of the Amazon basin is not an adequate place for soybeans.[7] The authors remark that new roads may cause more deforestation, as most of it accompanies economic activity, but this kind of road-caused deforestation takes place only within a strip at most 20km wide, and often much narrower, along major roads.

7 EMBRAPA 1991 provides a thorough discussion of agro-ecological zoning in Brazil. For an analysis of expected sustainable agricultural growth in Brazil see Maletta 2000a.

Laurance *et al* (2002) performed a multivariate analysis of deforestation drivers and found that besides population density and the vicinity of roads, the other major correlate was the existence and severity of a dry season. On those grounds, they concluded: "Deforestation will be greatest in relatively seasonal, south-easterly areas of the basin, which are most accessible to major population centres and where large-scale cattle ranching and slash-and-burn farming are most easily implemented". This prediction coincides with observed trends. The same authors warn that policies encouraging migration to the Amazon would have a negative impact, increasing one of the main drivers (population density). Traditionally the Brazilian government (both Federal and State) pursued policies of settlement and land development (based on an old-fashioned geopolitical doctrine of "occupy it or risk losing it to foreign occupation"), and resisted foreign pressure to reduce migration in order to enhance environmental protection of the Amazon. Recent adoption of more proactive protection policies by the Government of Brazil, establishing protected areas close to the agricultural frontier, and limiting the scope of future road development to avoid environmental damage, may reduce the likelihood of these possible effects. This is also helped by increased outmigration from the Amazon, decreasing fertility and demographic growth, and little new migration into rural areas in a country that is already nearly 90% urban.

4. The Amazon forest and climate change

Besides the effect of human deforestation activity, the Amazon rainforest and its hydrological cycle would be also affected by climate change, which would in turn interact with deforestation, possibly accelerating changes in the forest. In addition, changes in the Amazon may have an impact on the climate of the rest of Latin America and the Caribbean as on other regions of the world. The future of the Amazon Basin is thus a topic of great concern worldwide; estimates of trends have been produced with many methodologies, some driving to extreme potential negative consequences for the region and the world. The trees of the Amazon contain 90–140 billion tonnes of carbon (SOARES-FILHO *et al* 2006), equivalent to approximately 9–14 decades of current global, human-induced carbon emissions (CANADELL *et al* 2007). This suggests to some authors that reducing global warming will be very difficult if emissions of carbon from tropical forests worldwide and the Amazon in particular are not curtailed sharply in the coming years (GULLISON *et al* 2007). These ecological services, some authors speculate, might be threatened by global warming interacting with deforestation, through a climate-driven substitution of forests by savanna and semi-arid vegetation, in what has been called the Amazon forest 'dieback' (NOBRE *et al* 1991; COX *et al* 2000, 2004; BOTTA & FOLEY 2002; OYAMA & NOBRE 2003; NEPSTAD *et al* 2007a, 2007b 2008; BETTS *et al* 2004; LENTON *et al* 2008). A discussion of dieback hypotheses is included later.

There is general agreement about the importance of tropical forests for the global carbon cycle and hence global climate, but published estimates differ significantly on the area affected by tropical deforestation, the resulting flux of carbon to the atmosphere and its feedbacks to the climate system (HOUGHTON 1999; FEARNSIDE 2000; MALHI & GRACE 2000; ACHARD *et al* 2002a, 2002b; DEFRIES *et al* 2002). For some future climate-change scenarios, it has been estimated that tropical forests could generate an unprecedented source of carbon, even in the absence of additional anthropogenic deforestation (COX *et al* 2000; CRAMER *et al* 2001, 2004). Many divergences between studies, especially those produced in the 1990s and early 2000s, are due to the use of uncertain data on deforestation that had been improving lately, and prospects of rapid deforestation have been to some extent moderated by recent decreases in clearing activity, increased re-clearing of secondary forest, and more energetic protection measures by the Brazilian Government, and also by a better understanding of deforestation drivers and the geographical distribution of forest clearing. Assessing the future conditions of the Earth system requires better quantification of the significance of both deforestation and climate-driven changes in biospheric carbon stocks, compared with background 'reference' conditions.

One question is whether climate-driven carbon loss could match or even exceed the impact of anthropogenic deforestation during the coming decades. If such an additional source appeared, then even with stable fossil fuel emissions there would be faster atmospheric CO_2 increase. Some estimates of a global anthropogenic deforestation flux of about 1.6 Gt C/yr had been considered realistic in the 1980s and 1990s (BOLIN *et al* 2000; PRENTICE *et al* 2001). Analyses of the spatial extent of tropical forest cover from long-term satellite time-series (such as Defries *et al* 2002, and more so the more recent data from TREES and other sources) challenge those estimates as unrealistically high. DeFries *et al* estimates 0.6 Gt C/yr as more probable for the 1980s and 0.9 Gt C/yr for the 1990s. More recent trends in the Amazon, showed before, suggest a further reduction for the 1990s, and that the rate in the late 2000s is still lower (and rapidly decreasing).

The magnitude of anthropogenic deforestation still determines the larger component of the role tropical forests may play in the global carbon cycle. The sources or sinks produced by climate change are significant components, however, and they strongly affect the spatial pattern of associated ecosystem changes (CRAMER *et al*, 2004). The uncertainty of flux estimates due to natural disturbances, however, is more problematic. Current knowledge on the relation between deforestation activities and the natural disturbance regime seems to be far too scarce, although several authors (e.g. UHL & KAUFFMAN 1990; COCHRANE & SCHULZE 1998) have pointed out that undisturbed forests also burn more frequently in more fragmented landscapes. Beyond fire, even less seems to be known about other natural disturbances in lowland forests, such as windstorms or insect outbreaks. There are too few observations and experimental evidence, despite the already dated efforts of Kauffman *et al* 1988 and Uhl *et al* 1988, to support statistical or process-based models of these disturbances.

Several studies advancing hypotheses of rapid savannisation of the Amazon require or assume a reduction in rainfall (as a consequence of climate change) to produce that effect. In a drier environment fires would spread faster and engulf the patched forest left behind by rapid deforestation. However, there is no clear evidence of a tendency towards a drier Amazon. As shown before, most climate models predict increased rainfall over the Amazon, but the main study projecting savannisation used only the one model predicting the largest reduction in rainfall. Droughts, of course, happen, and also fire, especially at the relatively drier basin's borders. In 2005, large sections of South-Western Amazon experienced one of the most intense droughts of the last hundred years. The drought severely affected human populations along the main course of the Amazon River and its Western and South-Western tributaries, the Solimões (also known as the Amazon River in the other Amazon countries) and the Madeira rivers, respectively. Water levels fell to historic lows and navigation of these rivers was suspended. The drought did not affect central or eastern Amazonia, a pattern that differs from El Niño–related droughts in 1926, 1983, and 1998. Marengo *et al* (2008, italics added) concludeThe causes of the drought were **not related to *El Niño*** but to (i) the anomalously warm tropical North Atlantic, (ii) the reduced intensity in northeast trade wind moisture transport into southern Amazonia during the peak summertime season, and (iii) the weakened upward motion over this section of Amazonia, resulting in reduced convective development and rainfall. The drought conditions were intensified during the dry season into September 2005 when humidity was lower than normal and air temperatures were 3°–5°C warmer than normal. Because of the extended dry season in the region, forest fires affected part of south-western Amazonia. Rains returned in October 2005 and generated flooding after February 2006.

Some authors had suggested that a severe drought may deplete the soil's water content to a degree that surpasses a threshold, triggering forest conversion to savanna in affected areas (e.g. Nepstad *et al* 2008). This argument will be discussed below in more detail, but it is worth noting here that even the extremely severe drought of 2005 failed to cause such an effect. Besides, the subsequent years (2006-2010) have seen above average precipitation over the Amazon.

In spite of such short term events, the long term impact of deforestation on hydrology and precipitation is unclear, and may be overstated. Linhares *et al* 2007 analysed two specific river basins in Rondônia from 1970 to 2001; one of them (Sucunduti) remained almost pristine, with its deforested area increasing from 0.02% to 0.4% (mainly from the opening of one road), whilst the other (Ji-Parana) was almost pristine in 1970 (3.6% deforested) but deforestation reached 55% in 2001, mainly for cattle ranching. The most interesting result of this comparative analysis was that **precipitation and river hydrology showed no trend in either basin, nor different trends between them**. There was a short-term hydrological response to **jumps** in deforestation (correlation in annual rates), but as land cover was restored by new growth the former trend in hydrological behaviour and precipitation was also restored. In conclusion, Linhares *et al* found "no long-term trends in precipitation, stream flow and hydrological response indicative of large temporal scale impacts of land-cover change."

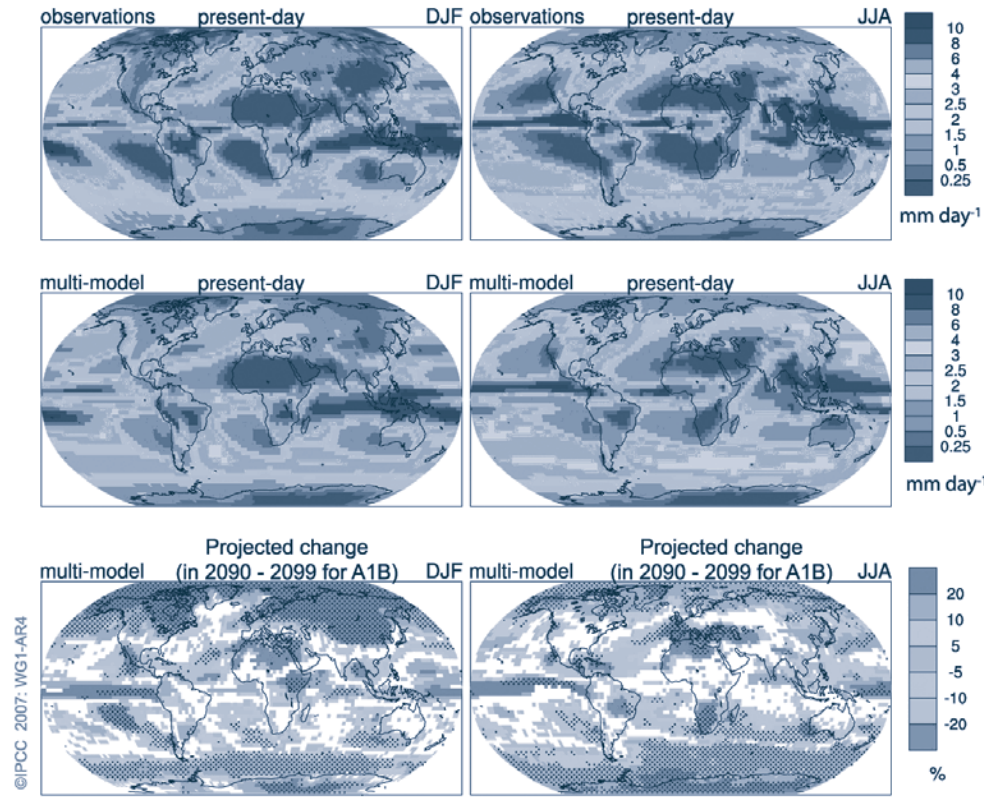
The IPCC projections for the Amazon do not foresee a transition to a drier environment. Quite the contrary: a majority of models concur in predicting **increased moisture**. There was variation across models, but the overall and preferred projection envisaged **increased** rainfall over the core rainforest of Western Amazonia, with also increasing rainfall in the rainy season over the less humid Eastern part of the basin (and marginal decreases in the dry season). Moreover, Malhi *et al* 2009 "examine climate simulations by 19 global climate models (GCMs) in this context and find that most tend to underestimate current rainfall", showing therefore a likely tendency to underestimate also the future level of precipitation.

The IPCC AR4 report (Solomon *et al* 2007b and Christensen *et al* 2007) produced estimates of precipitation under three scenarios: A2 (higher precipitation), A1B (intermediate) and B1 (lower). Only the intermediate projection of precipitation (under A1B) is shown in the IPCC report (reproduced here as Figure 6 at world level and Figure 7 for the American continent). The Technical Summary of the scientific report from the IPCC Working Group I (Solomon *et al* 2007b) shows with a combination of models at a rather coarse resolution and worldwide coverage, that precipitation over the Amazon basin will increase in the rainy season (centred on December-February), especially over the core rainforest and the Andean mountains where the main Amazon tributaries originate. At this world level of aggregation no sufficient agreement existed between models as regards the Eastern section of the basin.

Percent changes in precipitation at the "dry" season (also represented in the figures for the period June-August) are of much lesser actual importance since much less rain falls in that season (especially over areas with a dry season); however, projections show a slight increase of June-August precipitation over the Andes slopes and the Western part of the Amazon basin, little change or not enough agreement over the core rainforest (where there is no dry season), and decrease in the Eastern section of the basin. Notice that only projections corroborated by over 66% of the models are shown in the picture. It should also be noticed that in the core of the basin, where rainfall is over 3000 mm/year, there is actually **no dry season**, which occurs only in the external part of the basin with precipitation around 1600 mm/year.

Estimated and modelled baseline (1980/99) seasonal mean precipitation rates (mm/day) and projected percentage changes to 2090-99

Rainy season Dry season



Source: Figure TS30 in Solomon et al. 2007b:76. http://www.ipcc.ch/graphics/ar4-wg1/jpg/ts30.jpg.

Figure 6. Spatial patterns of observed (top row) and multi-model mean (middle row) seasonal mean precipitation rate (mm day–1) for the period 1979 to 1993 and the multi-model mean for changes by the period 2090-2099 relative to 1980-1999 (% change) based on the SRES A-1B scenario (bottom row). December-February means are in the left column, June-August means in the right column. In the bottom panel, changes are plotted only where more than 66% of the models agree on the sign of the change. The stippling indicates areas where more than 90% of the models agree on the sign of the change.

Figure 6 also compares actual measured precipitation (top row) to model predictions (middle row) for the "present day", actually 1979-93 average. It is noticeable that models used for this projection tend to underestimate actual levels of precipitation over the Amazon basin, and thus would also probably underestimate future rainfall. Comparing the first and second row of the chart, it is easily seen that for the rainy season (left) observed mean rainfall over the basin was mostly about 6-10 mm/day (top left) but only 2-4 mm/day were predicted (middle left). Likewise, during the dry season (right top and middle) observed precipitation over the Northern part of the basin is visibly heavier than predicted. Contrariwise, the very small level of precipitation in the Southern part of the basin during the dry season is observed to be around 0.25 mm/day in mot parts of that region, especially nearer to the Atlantic, whereas predicted values for the recent past in that area are mostly in the 0.25-0.50 mm/day range, thus **over**estimating the actual observations by up to 0.25mm/day; this error, however, has little consequence: a quarter of a mm/day (or less) is not a significant deviation, even for a dry season.

The tendency to underestimate rainfall in the rainy season, observed already for the baseline, probably affects also the predicted future levels of precipitation (2080-99), consequently understating rainfall over the Amazon basin during the 21st Century. Notice also that this particular projection is based on the A1B scenario, which predicts an intermediate increase in emissions and temperature among the SRES marker scenarios. Since precipitation depends on evaporation, and evaporation increases with temperature, projections based on other scenarios foreseeing more emissions and thus more warming, such as A1F1, B2 or A2, would predict **more** precipitation over the Amazon in the 1990s. Since predictions on temperature and impacts in IPCC reports show the implications of the various SRES scenarios, and some impact studies concentrate on the worst-case warming scenarios such as A2 or A1F1, it would have been more consistent to show all scenario results in the case of precipitation, instead of showing only A1B. In fact, combining predicted global warming (Table 10.5 in MEEHL *et al* 2007) and Table S10.2 in the Supplementary Material for MEEHL *et al* 2007), it is possible to calculate that **at the world level** the increase in precipitation would be 7.50 mm/day for A1B, 8.85 mm/day for A2 and 5.06 mm/day for B1 (no projection is published for A1F1, the scenario with strongest warming, and thus presumably highest increase in precipitation). Similar differences are expected in the Amazon rainfall simulations.

Since yearly precipitation is mostly determined by rainy-season rainfall, IPCC projections for precipitation over the whole year over the Amazon are also positive. The IPCC chart for Latin America in the chapter of AR4-WG1 devoted to regional projections (Figure 7) is clearer than the above world maps. Unfortunately, and potentially misleadingly, changes in precipitation in both figures are shown in percentage form only. It should be remarked that any percentage decreases in June-August actually refer to the very scant mean precipitation of the dry season (2-4 mm/day in Northern and Western Amazonia, and <1 mm/day in Southern and Eastern Amazonia).

An apparently "deep" reduction of about 50% in dry-season precipitation in Southeastern Amazonia (as shown in dark brown shade at the right side of Figure 7) means a predicted reduction of just about 0.5 millimeter per day, hardly capable of making any significant difference in an area and season where mean rainfall is about 1 mm/day, whereas a predicted 20% increase in the rainy season (Figure 7, central panel) may involve much more water, since seasonal precipitation in the rainforest is at 8-10 mm/day or above, i.e. 1500-1800 mm (or more) over six months. An increase of that amount by 20% during the rainy season implies an increase of some 300-360 mm, whilst a decrease of up to 0.5 mm/day in the drier season involves at most some 90 mm over the other six months. Total annual variation would be an increase of about 220-270 mm/year on average, decreasing eastwards. In fact that is what the annual figures show: yearly precipitation increases of up to 15% over the Amazon, decreasing eastwards (the white areas in the Eastern border are those where less than 66% of models agreed and therefore no conclusion was drawn by the IPCC).

Annual | December-February (Amazon rainy season) | June-August (Amazon dry/drier season)

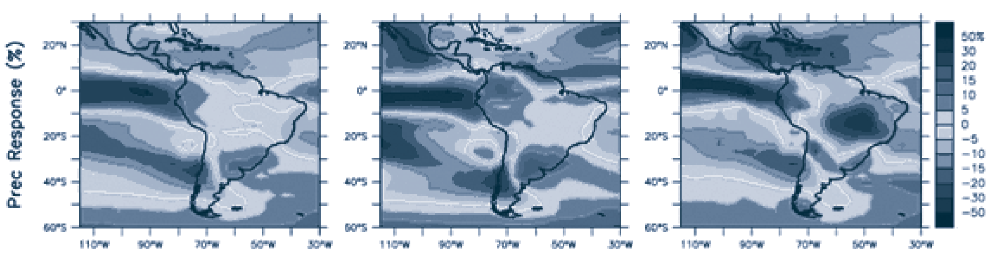


Figure 7. Predicted percent precipitation changes over Central and South America for the A1B scenario multi-model simulations (percent change in 2080-99 relative to 1980-99). Source: Christensen et al 2007: 869 (central panel of Fig.11.15). http://www.ipcc.ch/graphics/ar4-wg1/jpg/fig-11-15.jpg. The target period in this figure is 2080-99 whilst in Figure 6 it was 2090-99 (which is the usual in IPCC projections). Western Amazon region does not have a dry season. Percent changes in Eastern Amazon dry season refer to very small amounts of rainfall, whilst percent changes in the rainy season imply larger amounts.

In conclusion, IPCC projections for the Amazon do not envisage increased drought. Even in the relatively drier June-August season the Western portion of the basin (where no dry season exists) the forest in 2080-99 would receive **more** rainfall than in the reference period (1980-99), and the whole basin and even the arid Northeast of Brazil will receive significantly more precipitation during the rainy season, as shown in Figure 7. The core rainforest, besides, has no dry season at all.

The annual projection is consistently positive over the entire basin (left panel). Where an **annual** decrease is envisaged, e.g. in Eastern Amazonia and parts of the arid Brazilian Northeast (map at the left of Figure 7) it is predicted to be very small, in the range from 0% to -5%, not significant either on a yearly or seasonal basis.

5. The Amazon forest dieback hypothesis

Some experiments as well as model runs based on the Hadley Centre HadCM3 model (COX *et al* 2004; NEPSTAD *et al* 2007a, 2008; BETTS *et al* 2004; LENTON *et al* 2008) predict a possibly rapid large-scale substitution of Amazon forest by savanna-like vegetation by the end of the twenty-first century or even earlier (in some case as soon as 2030). According to these hypotheses, a combination of drought, expanding global demands for agro-fuels and grains, and positive feedbacks in the Amazon forest fire regime may drive a faster process of forest degradation which could lead in turn to a near-term forest dieback. Rising worldwide demands for bio-fuels and meat, Nepstad *et al* believe, are creating powerful incentives for agro-industrial expansion into Amazon forest regions. However, this economic hypothesis is rather simplistic. As seen before, no significant area of commercial crops (for bio-fuels or otherwise) is until now replacing Amazon forest, which is deforested mostly for subsistence farming (33%) and extensive cattle ranching (60%) plus 3% for logging. Soybean expansion occurs mostly in the cultivable lands of the Cerrado and other areas of West Central and South-Southeastern Brazil, which are mostly natural savannas or bush lands not covered by closed forest, though some of them belong to the Eastern and Southern margins of the Amazon hydrological system. As mentioned before, only a fraction of cattle-related deforestation may be attributed to conversion of land use from grazing to commercial crops. Most importantly, total Brazilian agricultural land (crops and grassland) has not expanded significantly in the latest 20 years. If market pressures (increased demand for beef, bio-fuels and other commercial crops) were as powerful a factor as Nepstad *et al* depict, the enormous price increases of the mid-2000s, especially in 2006-2008, would have caused a great surge in deforestation when in fact it **decreased** as prices went up (it had gone up instead in the 1990s and early 2000s, when agricultural prices were much lower). Deforestation exists, but at decreasing rates, and the regulation and protection framework is turning increasingly proactive.

Nepstad *et al* (2007a) attempted to test the hypothesis of severe droughts causing widespread tree mortality. The authors report: "A severe, four-year drought episode was simulated by excluding 60% of incoming throughfall during each wet season using plastic panels installed in the understory of a 1-Ha forest treatment plot, while a 1-Ha control plot received normal rainfall. After 3.2 years, the treatment resulted in a 38% increase in mortality rates". Notice that the effect found was **not** 38% mortality but 38% **increase in mortality rates**. Tree mortality rates, in fact, were between 2% and 3% in both the experimental and control plots (NEPSTAD *et al* 2007a:2064, central panel of Fig. 2). The **net** loss was much lower, due to new trees appearing during the experiment.

This resulted from a very severe artificial drought during four rainy seasons. Protracted droughts in the Amazon have been observed in the past, without savannisation effects: "Supra-annual drought events such as those associated with El Niño Southern Oscillation (ENSO) episodes are sometimes accompanied by higher adult tree mortality, […] higher or lower seedling mortality […], mast fruiting of some tree species […], reduced seed set in other tree species […], and increased forest flammability […]" (Nepstad *et al* 2007:2259, references omitted). The Nepstad experiment was based on the idea that future droughts may be more severe and last longer, with the ancillary hypothesis that climate change may cause ENSO to evolve towards a persistent El Niño state, or towards more severe and prolonged El Niño phases, and a theoretical framework based on the unsupported hypothesis of irreversible savannisation once a 'tipping point' (of unknown value) is reached in terms of reduction in tree cover.

Based mostly on that experiment, Nepstad *et al* (2007b, 2008) suggested that synergistic trends in (i) Amazon economies, (ii) forests and (iii) climate could lead to the replacement or severe degradation of more than half of the closed-canopy forests of the Amazon Basin **before the year 2030**:

> If sea surface temperature anomalies (such as El Niño episodes) and associated Amazon droughts of the last decade continue into the future, approximately 55% of the forests of the Amazon will be cleared, logged, damaged by drought or burned over the next 20 years, emitting 15–26 Pg of carbon to the atmosphere (NEPSTAD *et al* 2008:1737).

From the analysis in the paper it transpires that these effects are envisaged only for **Eastern** Amazonia, which is mostly not covered by forests: "Several lines of evidence suggest that the eastern Amazon may become drier in the future, and that this drying could be exacerbated by positive feedbacks with the vegetation" (NEPSTAD *et al* 2008:1740). As the authors (NEPSTAD et al 2008:1740, emphasis added) reckon:

> When GCMs are coupled to dynamic vegetation models, **some** predict a large-scale, **late-century** substitution of closed-canopy evergreen forest by savannah-like and semi-arid vegetation, **mostly in the eastern end of the basin** (COX et al. 2000, 2004; BOTTA & FOLEY 2002; OYAMA & NOBRE 2003). The lower evapotranspiration and higher albedo of this new vegetation reinforces the drying in a positive feedback. **Most coupled climate–vegetation models, however, do not predict this dieback** (FRIEDLINGSTEIN et al. 2003; GULLISON et al. 2007).

An important element in Nepstad *et al*'s theory is that drought reduced the amount of plant-available soil water (PAW). Nepstad and colleagues had run a model some years before (Nepstad *et al* 2004) applied to the period from 1996 to 2001, from which it emerged that "During the severe drought of 2001, PAW_{10m} fell to below 25% of PAW_{max} in 31% of the region's forests and fell below 50% PAW_{max} in half of the forests. Field measurements and experimental forest fires indicate that soil moisture depletion below 25% PAW_{max} corresponds to a reduction in leaf area index of approximately 25%, increasing forest flammability. Hence, approximately one-third of Amazon forests became susceptible to fire during the 2001 ENSO period." That implication of the model, however, was not matched with the actual amount of forest fires during and before the draught (it was in fact quite small, much smaller than the portion of forest affected by low PAW). "Field measurements also suggest that the ENSO drought of 2001 reduced carbon storage by approximately 0.2 Pg relative to years without severe soil moisture deficits", but it is also acknowledged that the model used "is sensitive to spin-up time, rooting depth, and errors in ET estimates. Improvements in our ability to accurately model soil moisture content of Amazon forests will depend upon better understanding of forest rooting depths, which can extend to beyond 15 m" (NEPSTAD *et al* 2004:704).

The Nepstad dire predictions of more rapid dieback, pursued relentlessly from paper to paper, and mostly inspired by the Amazon 2001 and 2005 droughts plus the hypothesis of El Niño episodes of increasing severity and frequency) emerge as a **possible** result of the **hypothetical** persistence of then-recent events (up to the mid 2000s) plus the **purely theoretical** hypothesis of a 'tipping point' to be **hypothetically** reached if deforestation advances past some **unknown** percentage of tree cover, thus **possibly** triggering an 'abrupt change' process of **unknown** duration but **supposed** to be very rapid. The critical percentage of tree cover that would trigger the dieback process, if it exists, is unknown, though hypothesized (for unclear reasons) to be 30%. This large reduction in three cover is assumed to happen in the near future, even if an artificial, very long and very severe 4-year drought only caused a much lower percentage of tree mortality (about 10% in four years), and no evidence of after-drought recovery was measured or analyzed. Evidence of forest recovery after human-caused deforestation (which is surely more dangerous than the death of specific trees within the forest) suggests regrowth and recovery to be quite fast (RAMANKUTTY *et al* 2007).

Several remarks are in order: (1) past Amazon droughts, even the rare supra-annual droughts, have never triggered this kind of process; (2) drying processes in Eastern Amazonia were simulated by some models, like in Cox *et al*, based on a **presumed** effect of global warming on ENSO, generating more frequent and more intense El Niño phases, or a persistent El Niño state, for which no evidence exists, as will be discussed below; (4) the Nepstad experiment was followed only through the artificial 4-year drought; continued observation of the experimental plot may show recovery along following normal years, after the loss of trees observed in the experimental plot;

the extent of recovery has not been observed in the Nepstad experiment, but past experience with deforested areas (as in RAMANKUTTI *et al* 2007) show rapid regrowth even in areas totally razed by human clearing activity.

The audacious predictions in Nepstad *et al* 2008 mostly rely, then, on hypothetical processes of abrupt change that are moreover supposed to be triggered and completed within a very short time. Abrupt change dynamics, whereby systems undergo rapid change after passing a critical value of certain variables, do not always mean, however, that the ensuing change is either immediate, rapid, or catastrophic. The timescales are longer. Other 'tipping point' theorists such as those revised by Lenton *et al* 2008 (and the IPCC report: see Meehl *et al* 2007: 775-776) reckon that **several centuries** and even *millennia* may elapse between the time a tipping point is reached and the time an effect is observable or completed. In most cases, however, the matter is purely hypothetical or definitional, since no actual tipping point (or the time needed to reach that point or for the effect to manifest itself) has ever been discovered or measured, for the Amazon dieback or for most other potential tipping elements.

While discussing tipping point hypotheses or 'abrupt climate changes', the 2007 IPCC report mentions several possible cases that have been suggested (not including the Amazon dieback). Actually some 'abrupt' changes seem to have occurred in the past, but not very rapidly at the human scale. The IPCC report comments about one of the most frequently cited paleo-examples:

> The cooling events during the last ice ages registered in the Greenland ice cores developed over **a couple of centuries to *millennia***. [...] Upon the crossing of a tipping point (bifurcation point), the evolution of the system is no longer controlled by the time scale of the forcing, but rather determined by its internal dynamics, **which can either be much faster than the forcing, or significantly slower**. Only the former case would be termed 'abrupt climate change', but the latter case is of equal importance. [...] **For the long-term evolution of a climate variable one must distinguish between reversible and irreversible changes** (MEEHL *et al* 2007, p.776, italics added).

The report insists that there is little (if any) evidence of the existence (or the irreversibility) of tipping points for various possible systems including the Atlantic Meridional Overturning Circulation, the melting of Greenland, and other natural systems. The Amazon is not mentioned in this context.

The Nepstad Amazon forest disappearance (or catastrophic shrinking) predictions, for the accomplishment of which only some 20 years are left, should be regarded with great caution, to say the least, in view of the overall scientific consensus on abrupt climate change, the lower rates of deforestation observed in recent years, improved protection of fragile areas and increasing establishment of protected areas in the frontier of deforestation, and lack of data on crucial issues such as the very existence of a tipping point, and parameters such as the critical value for the tipping point in case it exists, the time it would take for the subsequent process to complete, and the reversibility or irreversibility of the process. Indeed, Nepstad *et al* 2008 predicate the dieback upon condition of certain recent processes and events to continue unabated in the future, and acknowledge that (counteracting the trends on which the dieback projections are based) emerging changes are observed in landholder behaviour as well as recent successes in establishing large blocks of protected areas in active agricultural frontiers and practical techniques for concentrating livestock production on smaller areas of land. All these observed changes could reduce the likelihood of large-scale self-reinforcing replacement of forest by fire-prone bush.[8]

Models used by authors proposing the dieback hypothesis have large uncertainties and doubtful assumptions, and there is consequently a generalized lack of scientific consensus about the idea of an impending collapse or 'savannisation' of the Amazon forest. The hypothesis has been advanced by just a handful of authors, especially in its most extreme forms predicting the disappearance of the forest within a few decades. Even their proponents offer it just as a hypothesis and a mere possibility, and also state that **counter-tendencies are at work** and relatively **easy solutions are at hand**. In this vein Cox *et al* 2004 state in their conclusions: "The modelled Amazonian dieback phenomenon is therefore qualitatively understood, but we are still a long way from being able to estimate the probability of such an ecological catastrophe occurring in the real Earth system." The 2007 IPCC report on regional climate changes is also very cautious in this respect:

> In a version of the HadCM3 model with dynamic vegetation and an interactive global carbon cycle (BETTS *et al*, 2004), a [**forced**] tendency to a more El Niño-like state contributes to reduced rainfall and vegetation dieback in the Amazon (COX *et al*, 2004). But the version of HadCM3 participating in the MMD projects by far the largest reduction in annual rainfall over AMZ [**Amazon region**] (–21% for the A1B scenario). This stresses the necessity of being very cautious in interpreting carbon cycle impacts on the regional climate and ecosystem change

8 According to Nepstad *et al* 2008, another possible deterrent could be the establishment (in the UN Framework Convention on Climate Change) of compensations to tropical countries for reducing carbon emissions, which in turn may be turned into incentives for loggers, ranchers and farmers to avoid deforestation. However, this does not seem a sensible proposition for the problem at hand. No matter how effective it could be in the long term, it is a slow-moving incentive system that could hardly be put in place and have significant effect before the foretold catastrophe is completed by 2030. In fact, if the dieback timing postulated by Nepstad *et al* were correct, such a long-term policy would be useless: the forest would be long gone before such mechanism had any chance of yielding any significant effect. Inclusion of this proposal in the paper seems motivated more by the desire to advance an emission-mitigation policy than by any reasoned evidence of its efficaciousness or pertinence as a counter-measure for a supposedly imminent Amazon dieback. **Adaptation** measures should be more in order. However, on a more long-term view, REDD mechanisms might help finance a policy to halt deforestation by means of expanded protected areas (as discussed by Soares-Filho *et al* 2010).

> until there is more convergence among models on rainfall projections for the Amazon with fixed vegetation (CHRISTENSEN *et al* 2007, p.896; text in square brackets added).[9]

In other words, this passage of the IPCC report points out that Cox *et al* as well as Betts *et al* chose, among various available model implementations, one specific model predicting a **decrease** in Amazon precipitation (whilst most models predict an increase), and moreover, they used the one implementation of that model predicting **the most extreme** reduction of rainfall over the Amazon, to support their conclusions about a possible dieback. This model, besides, assumes as a determining causal factor the supposed tendency, for which no evidence exists, towards a more persistent El Niño state of ENSO in the immediate future.

Models are divided about future rainfall in the Amazon, some predicting more, some less, with **a majority predicting more** (the central IPCC prediction is an increase of rainfall). According to the authors of the regional 2007 IPCC WG1 report, only the use of various convergent models is the adequate way to predict such dramatic changes on such an important part of the world.

The irreversibility of the dieback process is also in question. Even if a considerable climate effect on the Amazon basin and the whole region has been envisaged by authors exploring the dieback hypothesis, they have also argued that **small efforts may change this scenario**. Forest dieback would be, in other words, reversible and, moreover, rather easily reversed. In a related article (NEPSTAD *et al* 2007) it is estimated that deforestation in the Brazilian Amazon could be brought to approximately **zero within 10 years** in the context of a 30-year programme costing $8 billion or $266 million per year, less than $2 per tonne of reduced carbon emission. This estimate is lower than previous ones (SATHAYE *et al* 2006, OBERSTEINER *et al* 2006, SOHNGEN AND SEDJO 2006, STERN 2006), largely because opportunity costs are not fully compensated, and spatially-explicit modelling of land use rents shows that most carbon emissions carry very low opportunity costs. The authors' programme includes the doubling of income and improved health, education and technical assistance services for 200,000 forest-dwelling families. The benefits also include a more secure rainfall system for central and southern Brazil, and the avoidance of $11 to $83 million per year in fire-related damages to the Amazon economy. Successful reduction of emissions to nearly zero in three decades is a daunting task, in spite of recent progresses, and will depend on the development of efficient, transparent institutions, suggesting its achievement is likely to take more time.

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9 Betts *et al* 2004, cited in this passage, underscore interactions whereby initial forest shrinkage due to lower precipitation causes further reductions in rainfall, which accelerate the dieback. This spiralling mechanism, however, is criticized by the same authors on grounds of inadequate model choice and for being based on an unlikely persistent El Niño. According to Gullison *et al* 2007, gradual reductions in deforestation rates to 50% of their value in the 1990s would produce significant reductions in carbon emissions over the 21st century, but those levels of reduction in deforestation rates have already been achieved through policy in the first decade of the century, without using any of the mechanisms (such as REDD or cap-and-trade) supposed to entail such reduction over a longer period.

Another study pointing towards the reversibility of any danger of savannisation is Malhi *et al* 2009. They emphasize that even if Western Amazonia is largely free of that danger, some parts of Eastern Amazonia may suffer water stress and thus more danger of fire. However, they add, "our analysis suggests that dry-season water stress is likely to increase in E. Amazonia over the 21st century, but the region tends toward a climate more appropriate to seasonal forest than to savanna" (MALHI *et al* 2009:20610). They reckon that deforestation has been greatly reduced since 2005, and suggest that "deliberate limitation of deforestation and fire may be an effective intervention to maintain Amazonian forest resilience in the face of imposed 21st-century climate change. Such intervention may be enough to navigate E. Amazonia away from a possible 'tipping point,' beyond which extensive rainforest would become unsustainable" (*ibidem*). They also remark on the positive effect of increased carbon dioxide (linked to climate change) on vegetation: "the 21st-century rise in CO_2 may to some extent mitigate the effects of enhanced seasonality in rainfall and lessen the likelihood of forest loss." (MALHI *et al* 2009:20613). The important role of atmospheric CO_2 had already been highlighted in Malhi & Grace 2000

Much of the alarm in previous prognosis rested on the severe 2005 drought **plus** the temporarily rising trend in deforestation observed in the few years leading to the 2004 peak. However, rainfall was particularly high after 2005, and deforestation is actually decreasing quite fast (75% fall from 2004 to 2009). The Brazilian government has committed large amounts of money for Amazon protection, in excess of the $8 billion estimated by Nepstad *et al*, and has even established an international fund calling for contributions of up to $21 billion to assist the Government to conserve the Amazon.

Soares-Filho *et al* 2010 find that the creation and enforcement of protected areas is highly effective: "The recent expansion of [protected areas] in the Brazilian Amazon was responsible for 37% of the region's total reduction in deforestation between 2004 and 2006 without provoking leakage [i.e. deflecting deforestation to other areas]".[10] The protected area network established by 2008 or already underway would have a total cost (net present value) of $147 billion, avoiding a total of 8 Pg of carbon emissions by 2050 at a cost of $5.6 per ton of carbon not emitted. These costs include protected area management plus opportunity costs of foregone agriculture and

10 The authors attribute a large part (more than 40%) of changes in deforestation (from the 1990s up to 2006) to changes in agricultural prices, especially the price rise from 2002 to 2006. However, deforestation kept decreasing after 2006, while world food prices soared in 2007 and 2008 and remained very high (albeit lower than the 2008 peak) in 2009-2010. As the same authors recognize, their period of analysis is too short for achieving far-reaching conclusions; and there is also evidence that most (or nearly all) growth in Brazilian agricultural output over latest decades is due to increased land productivity, with practically no increase in the amount of agricultural (arable or grazing) land. A repeat of the Soares-Filho analysis with more recent data would probably result in a higher share of decreased deforestation attributed to expansion and better enforcement of protected areas. Also, their analysis included many legally protected areas where no activity or legislation is in place to deter deforestation (e.g. military reserves or Indian land devolution); their exclusion would increase the share of protected areas where deforestation actually fell.

timber activity in protected areas. Thus the Brazilian policy of massive expansion of protected areas is already reducing deforestation and would drastically reduce it in the future.

Also, incomes and standards of living are improving in the Amazon as shown by positive trends in income, health, cooking fuel use and education statistics in the Brazilian household survey (PNAD), among other indicators. Assuming modest rates of growth in the standard of living (well below the historical rate of progress in the area) implies further improvement of these indicators, while subsistence farmers diversify their livelihoods, reduce land clearing, and reduce household use of firewood or charcoal as electricity and natural gas reach every home.

In fact, subsistence farmers are a decreasing share of the population in the region, as almost everywhere; their numbers are already dwindling in many places and not increasing in most, and bottled natural gas is rapidly replacing charcoal and wood as cooking fuel in the rural areas of the Amazon region, as indicated by recent PNAD Household Surveys in Brazil (now covering the rural Amazon areas, not included in previous PNAD waves up to 2003).

Authors hypothesizing a dieback of the forest in the near future also mention that several other concurrent trends (besides deliberate policy) could prevent a near-term forest collapse. As fire-sensitive investments accumulate in the landscape, landholders or settlers are likely to use less fire to clear land and invest more in fire control. Commodity markets are demanding higher environmental performance from farmers and cattle ranchers. Protected areas have been established in the pathway of expanding agricultural frontiers. All this implies that a dieback process, **if** its tipping point exists and **if** it is ever reached, would be also easily reversed, or may be already in the process of being deterred or reversed by ongoing processes. For the time being, as aptly summarised by some of its main proponents (Cox *et al*), it remains just a theoretical possibility or speculation, without any manner of empirical evidence.

6. Tipping points

The Cox *et al* and Nepstad *et al* Amazon dieback models use the idea that a "tipping point" would be reached once tree cover is reduced to a certain degree (e.g. –30%). Once that particular threshold is passed, it is argued, fires, heat and drought interaction may reduce the remaining forest to a savanna in a very short time. The actual existence or viability of such a mechanism is only hypothetical, and furthermore, the specific value selected for the tipping point (a 30% reduction in tree cover) is also not scientifically justified, and offered only as an example or, at best, a rough preliminary approximation. The Amazon dieback hypothesis has been thus proposed as one of several potential examples of "tipping elements", i.e. systems that may change abruptly after reaching a critical value, rather than evolving in a gradual or "linear" fashion (GLADWELL 2000; LENTON *et al* 2008).

Lenton *et al* formally **define** a "tipping element" as a system with the potentiality to pass a critical value of some parameter, beyond which large transformations occur:

Human activities may have the potential to push components of the Earth system past critical states into qualitatively different modes of operation, implying large-scale impacts on human and ecological systems. Examples that have received recent attention include the potential collapse of the Atlantic thermohaline circulation (THC) (1), dieback of the Amazon rainforest (2), and decay of the Greenland ice sheet (3). Such *phenomena* have been described as 'tipping points' following the popular notion that, at a particular moment in time, a small change can have large, long-term consequences for a system, i.e., 'little things can make a big difference' (4). (LENTON *et al* 2008:1786, italics added).[11]

After this informal introduction of the concept, Lenton *et al* give a more formal definition (supplemented by an axiomatic formulation in an Appendix) stating the conditions theoretically defining a tipping element. They include foremost a defining feature:

1. The system's parameters can be reduced to a single control element ϱ, and a critical value ϱ_{crit} exists from which a significant variation by $d\varrho > 0$ leads to a significant change in a crucial system feature F after some observation time T>0.

Furthermore, tipping elements are regarded as **policy-relevant** if these other conditions are met:

2. Human activities are interfering with the system such that decisions taken within certain "political time horizon" ($T_p > 0$) can determine whether the critical value ϱ_{crit} is reached. The time of the critical decision is denoted as T_{crit}, and should be shorter than T_p, i.e. $T_{crit} < T_p$.

3. The observation time required to observe a qualitative change in F, denoted by T, plus the time to trigger the process (T_{crit}) is within an "ethical time horizon" (TE). In symbols: $T_{crit}+T \leq TE$. Consequences in the very distant future (after TE) are of lesser concern.

4. A significant number of people care about the outcome. Consequently the change in F should be defined in terms of impacts.

All this is just an elaborate **definition**. It does not tell whether any actual tipping element does exist, has existed or will exist, or what its characteristics and values would be. Based on this definition, Lenton *et al* examine several potential candidates, including the melting of the Green-

11 Numbered citations in the cited Lenton's text correspond to (1) Rahmstorf S, Ganopolski A (1999) Clim Change 43:353–367; (2) Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Nature 408:184–187; (3) Huybrechts P, De Wolde J (1999) J Clim 12:2169–2188; (4) Gladwell M (2000). It is important to note that all "phenomena" cited in the paragraph are not actual "phenomena" (observable manifestations of Nature) but mere definitions and unobserved hypotheses derived from a "popular notion".

land Ice Sheet and the Amazon dieback. The two candidate tipping elements more directly concerned with this paper are the sea temperature rise after which El Niño becomes persistent or permanent, possibly determining drier conditions over the Amazon, and the possible tipping point causing the subsequent conversion of the Amazon forest into a savanna. Regarding the Amazon, Lenton *et al* start by stating that "simulations of Amazon deforestation **typically** generate 20–30% reductions in precipitation (78), lengthening of the dry season, and increases in summer temperatures (79) that would make it difficult for the forest to reestablish." (Lenton *et al*, 2008: 1790, italics added).[12] This phrasing is quite misleading. **Some** simulations do so, but not **typically,** and they do so mostly in Eastern Amazonia (outside the rainforest). In fact, as was already discussed, the likely change in Amazon precipitation is uncertain, but a clear majority of models (including the multi-model IPCC consensus prediction) forecast more moisture and precipitation as Lenton *et al* clearly state in other passages of their paper. In fact, among the small minority of models predicting drier conditions, the particular model on which the dieback hypothesis was predicated is also the particular model predicting the single largest rainfall reduction. Moreover, the alleged fall in rainfall is linked with changes in ENSO which are not likely ever to occur, and even less likely to occur in the near future.

Even admitting a (very dubious) decrease in precipitation over most of the Amazon forest during the 21st Century (contrary to the IPCC forecast), the actual prospect of a dieback has been emphatically doubted by Cox and his collaborators: the possible mechanism, they write, is understood, but whether it could or would happen is not known. The more dramatic dieback scenario envisaged by Nepstad *et al*, where the jungle is fragmented and destroyed by fires and deforestation, is even more unlikely with current rates of deforestation, and with deforestation taking place only in some specific hotspots, mostly located at the relatively less forested areas along the borders of the basin, and not at the large wet rainforest core, and occurring (even at hotspots) at not very high and generally decreasing rates. Moreover, as Nepstad *et al* 2007b emphatically remark, this process could be easily stopped, at relatively low cost, by policy measures. Effective policies are in fact already underway, and developments since 2007 have clearly shown a sharp decrease in deforestation rates, even in a period of soaring prices for agricultural commodities such as beef, cereals and soybeans.

7. El Niño connection

Lenton *et al*, like Cox *et al*, make the Amazon dieback dependent on the **prior** establishment of a persistent or permanent El Niño state of ENSO, because that is an essential factor of reduced

12 Citations are: (78) Zeng N, Dickinson RE, Zeng X (1996) J Clim 9:859–883; (79) Kleidon A, Heimann M (2000) Clim Dyn 16:183–199.

Amazon moisture in the few models predicting a reduced precipitation over the Eastern part of the region; but on the other hand the same Lenton *et al* paper cites work casting heavy doubts on this crucial condition ever happening, or (if it happens) to occur before several centuries ahead or even before the end of the current millennium, and this only if anthropogenic warming is not stopped or abated in the meantime. "Dieback of the Amazon rainforest has been predicted (2, 80) to occur under 3-4°C global warming **because of a more persistent *El Niño* state** that leads to drying over much of the Amazon basin (81)" (LENTON *et al* 2008: 1790, emphasis added).[13] However, the persistent El Niño precondition is not likely to occur in the foreseeable future, and Amazon temperature is not likely to increase by 3-4°C in the near future (IPCC projections envisage warming reaching 2-3°C at the end of the 21st Century; warming is predicted to be lower at the Tropics than at Arctic and other Northern locations). Diverging results are also acknowledged: "Different vegetation models driven with similar climate projections also show Amazon dieback (82), but other global climate models (83) project smaller reductions (or increases) of precipitation and, therefore, do not produce dieback (84)." (*ibidem*).[14] These potentially crucial opposite results, however, are mentioned just in passing and not pursued further. The fact that they are in the majority goes also unremarked. Only the very few model outcomes in favour of the dieback hypothesis are discussed at any length.

ENSO has indeed shown increased activity in recent decades, and this is often associated with climate change. However, there is little basis for this belief.

> Analysis of historical observations of SST [**sea surface temperatures**] indicates that El Niño had relatively high amplitude during the period 1885-1915, followed by a few decades of relatively low amplitude (1915–1950) followed by a return to higher amplitudes since about 1960. [...] Similarly, a four century time series of normalized NINO3 region SST from our coupled GCM (Fig. 1a) shows substantial fluctuations in amplitude on a multidecadal timescale (Knutson *et al* 1997:138; text in square brackets added).

Several other sources and methods confirmed these findings. The same authors analysed other research results and concluded that "much of the past amplitude modulation of the observed ENSO could be attributable to internal variability of the coupled ocean–atmosphere system", i.e. not to climate change in general, and much less to climate change in recent decades. Moreover:

13 Numbered citations are: (2) Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Nature 408: 184–187; (80) Cox PM, Betts RA, Collins M, Harris PP, Huntingford C, Jones CD (2004) Theor Applied Climatol 78:137–156.; and (81) Betts RA, Cox PN, Collins M, Harris PP, Huntingford C, Jones CD (2004) Theor Applied Climatol 78:157–175. Another related paper is Harris et al 2008.

14 Citations are: (82). White A, Cannell MGR, Friend AD (1999) Global Environ Change 9:S21–S30; (83) Li W, Fu R, Dickinson RE (2006) J Geophys Res 111:D02111; and (84) Schaphoff S, Lucht W, Gerten D, Sitch S, Cramer W, Prentice IC (2006) Clim Change 74:97–122.

> In two 1000-yr CO_2 sensitivity experiments, the **amplitude** of the model ENSO **decreases** slightly relative to the control run in response to either a doubling or quadrupling of CO_2. [...]The **frequency** of ENSO in the model **does not appear to be strongly influenced by increased CO_2**. Since the multidecadal fluctuations in the model ENSO's amplitude are comparable in magnitude to the reduction in variability due to a quadrupling of CO_2, the results suggest that the impact of increased CO_2 on ENSO is unlikely to be clearly distinguishable from the climate system 'noise' in the near future (Knutson *et al* 1997:138, italics added).

This is very important, because current predictions about world atmospheric carbon concentrations do not foresee more than $3\times CO_2$ in the 21st Century, reaching nearly $4xCO_2$ in some long-term extreme exercises (relative to pre-industrial times; $1.4\times CO_2$ is already reached), and the quoted results tell that even quadrupling the concentration ($4\times CO_2$) causes only a "slight decrease in amplitude" and no change in frequency. This means that the implied ENSO response is neither higher amplitude (with more frequent El Niño or La Niña extremes) nor a persistent El Niño state (with low amplitude at a warmer temperature). Models say ENSO would continue more or less unchanged, perhaps with slightly less amplitude at extremely high CO_2 concentration, not envisaged in the standard IPCC scenarios. Other more recent studies concur in concluding that the possible impact of climate change on ENSO is undecided or nil, as no consistent ENSO trend has been detected. As Lenton *et al* 2008 summarize:

> Under future forcing, the first OAGCM [Ocean Atmosphere Global Circulation Models] studies showed a shift from the current ENSO variability to more persistent or frequent El Niño-like conditions. Now that numerous OAGCMs have been intercompared, **there is no consistent trend in their transient response and only a small collective probability of a shift toward more persistent or frequent *El Niño* conditions** (61, 62). (LENTON *et al* 2008:1790; emphasis and text in square brackets added).[15]

Even this assessment stops short of the actual evidence: this 'small collective probability' of a more persistent or frequent El Niño refers to models not reproducing observed ENSO behaviour and actually not predicting on the whole a persistent El Niño: in fact Lenton *et al* go on writing: "the most realistic models simulate increased El Niño **amplitude** (with no clear change in frequency) (54)." (2008, italics added).[16] **More amplitude** means that El Niño and La Niña would be more intense, and thus may produce stronger effects when they come, but in fact it means **more variability**, not a more persistent or permanent El Niño condition which is rather associated with **less** variability and **lower** amplitude. If the more realistic models predict (however uncertainly)

15 Citations by Lenton et al in this paragraph are as follows: (61) Collins M, Groups TCM (2005) Clim Dyn 24:89-104; (62) van Oldenborgh GJ, Philip SY, Collins M (2005) Ocean Sci 1:81–95.

16 The citation is as follows: (54) Guilyardi E (2006) *Clim Dyn* 26:329–348.)

more amplitude, they are by implication **refuting** any trends towards a more permanent El Niño condition. On the other hand, models predicting increased amplitude are indeed more realistic than others as concerns current or past trends, but their predictive capacity is still very limited, and even their prediction of higher amplitude is quite uncertain. Eric Guilyardi, the very author cited by Lenton *et al* to support the above prediction of increased amplitude, writes:

> In many respects, these models are also among those that best simulate the tropical Pacific climatology (ECHAM5/MPI-OM, GFDL-CM2.0, GFDL-CM2.1, MRICGM2.3.2, UKMO-HadCM3). Results from this large subset of models **suggest the likelihood** of increased El Niño amplitude in a warmer climate, though **there is considerable spread of *El Niño* behaviour among the models**, and the changes in the subsurface thermocline properties that may be important for El Niño change **could not be assessed**. **There are no clear indications of an *El Niño* frequency change with increased GHG** (Guilyardi 2006:329; GHG=Greenhouse gases).

In more recent work, Guilyardi *et al* 2009a further write:

> The ability to simulate El Niño as an emergent property of these models has largely improved over the last few years. Nevertheless, the diversity of model simulations of present-day El Niño **indicates current limitations in our ability to model this climate phenomenon and anticipate changes in its characteristics** (italics added).[17]

Variance across models is very wide. Commenting on the AR4 report, Guilyardi *et al* (2009a:11) write: "While some models show an increase in ENSO variability in response to greenhouse gas increases, others do not exhibit any detectable change while others show a decrease in variability." In other words, there is no consistent signal of increased or decreased amplitude across models. Later, the same authors write:

> Discerning whether any future changes in ENSO amplitude are due to external forcing or are simply due to internal longer-term variation is complicated by significant decadal fluctuations both in observations and in long control integrations. Nevertheless, changes of ENSO variability, where they can be detected above these large natural variations, are highly model dependent, even if extreme scenarios are analysed (4xCO_2). Hence, even though all models show **continued** ENSO variability in the future **no matter** what the change of average background conditions, **there is no consistent indication at this time of discernible changes in amplitude or frequency for the 21st century** (GUILYARDI *et al* 2009a:11-12; italics added; references deleted).

In other words, all models see continued variability (no signs of a persistent El Niño condition) and there are no consistent indications of changes in amplitude or frequency even with the

17 See also Guilyardi et al 2009b and Collins *et al* 2010.

amount of climate change predicted for the 21st Century. Any alleged trends in ENSO due to climate change lack sufficient scientific basis and are still very much open to research.

Even the task of assessing agreement or disagreement of model results with past observations is also problematic in this case. "In many prediction problems [...] it is possible to verify predictions after the fact. This becomes practically very difficult in the case of the ENSO response to climate change, as the signal-to-noise ratio is very small due to strong interannual (and decadal) variability" (GUILYARDI *et al* 2009a:15). This is so for recent observations, but becomes especially true for paleo-evidence about the distant past based on corals and deep sea cores, fraught with large intrinsic uncertainties, as well as for relatively recent data showing overwhelming noise/signal ratios. In such conditions, telling good models from bad can only be done in a very coarse manner. Not only better models are needed but better data too.

> Hence, to improve decadal to centennial projections, process and feedback diagnostics are needed to limit the subset of models to those that are more consistent with the real world. Even if models do not predict significant changes in El Niño statistics in the future (e.g. amplitude or frequency), the relative balance of feedbacks (and the associated impacts) during ENSO could evolve, perhaps altering ENSO predictability (GUILYARDI *et al* 2008:12, references deleted).

More research is thus needed, with unknown prospects. From another point of view Guilyardi *et al* examine paleo-evidence from the early Pliocene (3-5 million years ago). Interpretation of that evidence may suggest the hypothesis that Pliocene climate included a permanent El Niño condition:

> During this time interval, and possibly before, the proxy data **may be interpreted** as showing a significantly reduced or virtually non-existent zonal SST [sea surface temperature] gradient along the equator with therefore no possibility for ENSO development (*ibidem*, italics and text in brackets added).

Thus far, then, the evidence for the early Pliocene would suggest to Guilyardi and collaborators (and also to Fedorov *et al* 2006) the possible absence of oscillation and therefore no likelihood of a persistent El Niño-like state in that early period. However promising this analogy may appear, simulations of Pliocene climate in our future does not produce a persistent El Niño (a "Pliocene paradox" in the words of Fedorov *et al*). The high-carbon Pliocene climate can be considered , in Guilyardi *et al* (2009a) words, as "a partial analogue" of our present climate, but the finding of those authors was that **current climate models do not predict a persistent El Niño even after forcing CO_2 concentrations one order of magnitude above current values**, i.e. above 10xCO_2, which is not only above Pliocene levels, but also far above the levels of concentration forced by all available climate scenarios and models: no foreseeable amount of anthropogenic greenhouse gases emissions would produce such extreme CO_2 concentrations, which are not foreseen even in the most extreme scenarios of anthropogenic climate change for the next few centuries (IPCC scenarios project 2-4 times pre-industrial concentrations for 2100 or beyond).

Perhaps the search of "mechanisms for a permanent El Niño" (the Fedorov paper's subtitle) should not be abandoned. Perhaps models should be further "improved" until they deliver the desired result (a persistent El Niño in the near future). Or perhaps there are real differences between the Early Pliocene climate and today's global warming. Or maybe current interpretations of paleo data for the Pliocene are wrong and there was no permanent El Niño in that distant past either. For now these possibilities are still open, but the weight of evidence tends to dismiss the analogy, pointing instead towards **no discernible ENSO trend**. Corroboration of speculative hypotheses that climate change would bring a persistent or more variable or more frequent El Niño remains as elusive as ever.

A sample of perspectives on ENSO can be found in Díaz & Markgraf 2000. Though the whole book is relevant, see especially Sun 2000, who proposes a theoretical model of the coupled ocean-atmosphere system over the equatorial Pacific, which has two equilibrium states: one oscillatory in a cooler environment, and one steady in a warmer climate where surface sea temperature is much higher than the colder deep ocean. This framework, the author suggests, would imply a steady El Niño condition at some point in the past (possibly as recently as the early Holocene, 6000 years ago, as suggested in Markgraf & Díaz 2000), a hypothesis not sustained by the more detailed work of Guilyardi *et al* 2008 even under extreme CO_2 concentrations (and thus much warmer conditions), which are not only much higher than those prevailing in the early Holocene but even higher than those of the Early Pliocene.

The 2007 IPCC report is understandably quite sceptical about a persistent El Niño. It finds no clear trend toward a more persistent El Niño condition (a consequence of greater frequency **cum** higher temperature and **lower** amplitude) or even toward wider amplitude of oscillation (MEEHL *et al* 2007). They approvingly cite Guilyardi 2006 and also van Oldenborgh *et al* 2005, who ranked 19 models based on their skill in present-day ENSO simulations.[18] Using the most realistic six of these models, no statistically significant change was found in the amplitude of ENSO in the future (MEEHL *et al* 2007: 779). The 2007 IPCC report concludes: "Therefore, there are **no clear indications at this time regarding future changes in El Niño amplitude in a warmer climate**" and moreover "there is **no consistent indication at this time of discernible future changes in ENSO amplitude or frequency**" (MEEHL *et al* 2007: 780, italics added).

These sobering IPCC conclusions are important because some previous models had yielded alarming predictions of wider ENSO amplitude, or (contrariwise) a more persistent El Niño state,

18 Van Oldenborgh & Burgers (2005) have also explored the relationship between ENSO and precipitation.

both with large potential impacts on continental climate and agriculture. Those changes were expected to materialize in the near term. These previous models were widely echoed in the press, in the countries concerned and in policy discussions.

In spite of their own analysis on ENSO, Lenton *et al* (after acknowledging the IPCC consensus that current evidence does not support any trend towards a more persistent El Niño, or towards more amplitude in the oscillation) choose to disagree:

> Given also that past climate changes have been accompanied by changes in ENSO, we differ from IPCC (12) and consider there to be a significant probability of a future increase in ENSO amplitude. The required warming can be accessed this century (54) with **the transition happening within a millennium**, but **the existence and location of any threshold is particularly uncertain** (Lenton *et al* 2008: 1790, emphasis added).[19]

Notice first that even accepting the dissenting position of Lenton *et al*, the transition (to a persistent El Niño or to a higher amplitude of oscillation, which is not quite the same) is supposed to happen only "within a millennium", with a tipping point in warming, triggering the start of that long process, to be "accessed this century". A persistent El Niño or more widely oscillating ENSO would thus occur far later than the very short term envisaged for its alleged **consequence**, the Amazon dieback. The existence, timing and value of the alleged warming threshold which would trigger the long transition to a persistent El Niño are also uncertain (to say the least). Moreover, little actual evidence is offered to support the dissent of Lenton *et al* from the collective IPCC consensus on this crucial point concerning ENSO: The phrase "**Given that past climate changes have been accompanied by changes in ENSO"** cites as support the work of Guilyardi *et al* reviewed above, about the **possible** interpretation of deep-sea cores paleo-evidence of Early Pliocene temperatures as indicative of a dampened ENSO in that period, but not mentioning that those authors failed to corroborate this interpretation, nor the curious fact encountered by Guilyardi *et al* that available models fail to produce a dampened ENSO or persistent El Niño under Pliocene-like or even more severe conditions, e.g. forcing more than 10xCO_2 concentrations, which would be above the estimated Pliocene carbon level, and far above the highest predictions about climate change and carbon concentrations in the coming centuries, thus suggesting that the supposedly persistent El Niño in the Pliocene may be a wrong interpretation of paleo evidence, and that (even if that interpretation were correct) its replication in the future is highly unlikely.

The table of tipping elements in Lenton *et al* 2008 includes a transition towards more amplitude of ENSO (to occur within 1000 years and triggered within 100 years, both periods longer than predicted for the Amazon dieback). Moreover, that ENSO transition is towards more **am-**

19 Citations in this passage are: (12) Meehl et al 2007; (54) Guilyardi E (2006) Clim Dyn 26:329–348; (61) Collins M, Groups TCM (2005) Clim Dyn 24:89–104; (62) van Oldenborgh GJ, Philip SY, Collins M (2005) Ocean Sci 1:81–95;

plitude, not towards a persistent El Niño. More amplitude for ENSO is by no means equivalent to a more persistent or permanent El Niño (or La Niña): it is rather the opposite, and –as Lenton *et al* acknowledge– models do not foresee changes in frequency. The IPCC reckons that trends towards increased amplitude or towards more frequency are not recognizable. A persistent El Niño condition may result from dampened amplitude and/or increased frequency under warmer sea surface temperatures, but hardly from increased amplitude and no change in frequency. On the other hand, enhanced amplitude for ENSO is said to be predicted to happen within a millennium and the required triggering warming to be reached within 100 years (Lenton *et al* 2008:1790), with no indication of a near-term persistent El Niño, but a hypothetical **result** of a persistent El Niño (the Amazon drought-related dieback) is presumed to happen in less than 50 years, much before its cause.[20]

To sum up: even for the most outspoken proponents of "tipping point" hypotheses about the Amazon, such as Cox, Nepstad, Lenton and their collaborators, the possibility of an Amazon abrupt dieback is a highly speculative and uncertain event, a mere possibility dependent on the prior establishment of a persistent or nearly permanent El Niño, and based on one totally atypical Global Circulation Model (one of the small minority of models predicting decreasing precipitation over Eastern Amazonia, and in fact in the one version predicting the largest such reduction, contrary to the majority of models and model runs). Even in the artificial and extremely long drought induced by Nepstad *et al* (2007a) signs of widespread forest decay were not observed, and the experiment did not looked into the following period of recovery. Other studies of secondary re-growth show it to be quite strong and speedy, even in areas where forests were razed to the ground by humans. It is also reckoned that a persistent El Niño has itself, if any, a very small probability, with evidence not showing any consistent trend; and that even if it happens it would develop over a very long time. In the most favourable case, for which no evidence is presented, a transition to more amplitude in ENSO (not a permanent El Niño) would happen "within this millennium" but definitively well after this century, and without any sign of a threshold to be passed or having been passed. More ENSO amplitude would not mean a permanent El Niño, and no consistent signal exists for marked decrease of precipitation over the Amazon, and less so for the near future. No proof is offered that this hypothetical millennial increase in ENSO amplitude would imply a permanent El Niño (if anything, it is rather the opposite) or

20 One possible argument to explain the apparent inconsistency might possibly be that the *T* column in Lenton's table (LENTON *et al* 2008:1788) is actually a mistaken notation for t_{crit}, the time required to reach each tipping point, instead of *T*, the additional time required to observe a qualitative change (LENTON *et al* 2008: 1786-7). In fact, the table does not explicitly mention t_{crit} and does not differentiate between t_{crit} and *T*. In this interpretation, the triggering point for the Amazon would be reached within 50 years, and the unstoppable shrinkage of the forest would ensue afterwards for an unstated, and perhaps long, period. But this possibility is denied by other examples in the table and by the article's text, which confirm that the *T* column is meant to signify the *T* period in Lenton's notation and not t_{crit}. Moreover, even in this hypothetical case the inconsistency between the ENSO and Amazon periods would persist. Besides, Lenton *et al* would have to deal with the proposition by Nepstad *et al* about the relatively inexpensive measures that would reverse the "unstoppable" dieback process.

would be the effect of a tipping point reached by critical human decisions taken this century, which are the durations required by the rather arbitrary political and ethical time horizons proposed by Lenton *et al*.[21] Even if an ENSO tipping point (assuming it exists) is reached this century, its supposed effects (a persistent El Niño) would not materialize for many centuries, and likewise would happen with one of its alleged consequences, i.e. decreased Amazon precipitation, allegedly triggering forest dieback.

Many of these problems are not discussed in Lenton *et al* 2008. Moreover, even the contentions, uncertainties and qualifications actually discussed in the text by Lenton *et al* (or in their cited references) are not mentioned in the main table presented in the paper (p. 1788). Several tipping point elements are included with their expected time-to-event, *T* (e.g. less than 50 years for the Amazon forest disappearance), with no mention of the critical triggering time t_{crit} which in the case of the Amazon should be practically now or already in the past. These *T* estimates are included in the table without comment, other than a generic footnote (p.1788, note †) stating: "Numbers given are preliminary and derive from assessments by the experts at the workshop, aggregation of their opinions at the workshop, and review of the literature." It should be remarked, indeed, that there is *not* a consensus or anything approaching a consensus in the scientific community and the existing literature on the near-extinction of the Amazon forest within a few decades, nor indeed for many of the other tipping elements in the table. Such hypothesis for the Amazon, with varying periods to the event, has been raised by a few authors like Cox, Nepstad and their collaborators, offering some simulations based only on a very peculiar model, but all these authors explicitly state that it is just a theoretical possibility still lacking sufficient empirical evidence to make it feasible or probable at **any** future date, let alone scheduling it to happen just a few decades ahead. The scientific community at large has not embraced anything resembling this kind of theory. This tends to suggest that the group of experts attending Lenton's workshop, and his review of the literature, were somewhat less than balanced, and perhaps less than statistically representative.

Tipping elements exist, of course. The next straw may break the camel's back. An unnoticed HIV infection today, **if untreated**, may kill a person within a few years. Climate tipping points may also exist. There is some evidence of "abrupt" climate change in ancient times, but "abrupt" in this context, as said before, may mean "from several centuries to millennia" (in the words of the IPCC report, MEEHL *et al* 2007:774). When the AR4 report considers "abrupt change" hypotheses and discusses several examples, **not including the Amazon**, the general impression is of scepticism. The less negative opinion is about the Greenland Ice Sheet (GIS), but the speed envisaged is somewhat less than abrupt: "The few simulations of long-term ice sheet [behaviour] suggest

21 Arbitrary indeed: Why one century and one millennium? Why not two centuries and five millennia, or any other combination? The conclusions may vary accordingly.

that the GIS will significantly decrease in volume and area over the coming centuries **if a warmer climate is maintained** […], a process which would take **many centuries** to complete" (MEEHL *et al* 2007:776, italics added). The report does not explicitly endorse those "few simulations" (which in fact foresee complete ablation after 3000 years of gradual deglaciation, conditional on the unwarranted assumption that anthropogenic global warming persists that long). For other abrupt changes the evaluation is still less positive. For example on the eventual collapse of the Western Antarctic Ice Sheet (WAIS): "Present understanding is insufficient for prediction of the possible speed or extent of such a collapse" (*ibidem*).

Evidence for the potential existence of tipping points for major environmental processes such as the rapid disappearance of the Amazon forest and, moreover, evidence that such tipping points exist at some definite value of certain policy-sensitive variables and/or at certain definite period in the near future, are scant to say the least. That the change may occur in a few decades is still less likely. Indications about the irreversibility of tipping points are even less evident, especially in cases of delayed effect. Moreover, the very proponents of the tipping point hypothesis advance the idea that modest policy initiatives may reverse the process. The hypothesis of abrupt Amazon dieback within the foreseeable future remains, on the whole, exponentially speculative: a speculation based on several layers of other speculations, each of which has a small or vanishing chance of coming true anytime soon.

8. Summing up

Extensive agricultural activity in the Brazilian Amazon hydrological basin has increased in the last three decades, albeit mostly in the borders of the basin, not in the core rainforest. Since this increased land use is recent, the region is still susceptible to an array of economic and social pressures. Pasture is the main land use in the Amazon region, because it represents one of the most inexpensive agricultural alternatives after deforestation and requires a relatively small and largely unskilled labour force. Only specific areas (always at the outer borders of the basin) are devoted to crops. Skole *et al* (1994) and Fearnside and Barbosa (1998) estimated that 75% of the deforested land had been managed as pasture at one stage or another; some 45% was converted directly to pasture (FEARNSIDE, 1996). Most of the rest is cleared for subsistence agriculture. However, deforestation for conversion to grassland is relatively rare nowadays: most deforestation is done by subsistence settlers. Development activities, including new roads, electric power distribution, financial incentives and improvement of river transportation and ports, have added value to cleared land in the Amazon basin and promoted the trend of converting forest and bush to pastures and croplands, but the impact extends mostly to narrow strips along the roads and small areas around ports. Nowadays, soybean cultivation, originally concentrated in the south-east and central parts of Brazil, has been extended in the borders of the Amazon region, especially in the states of Rondônia and Mato Grosso, but not usually over recently deforested areas. New roads (e.g. Cuiabá-Santarém BR-163) and improvements in waterways and port infrastructure (e.g. Santarém and Porto Velho) will probably reduce soybean export costs and would accelerate the cultivation of soybean on former pasture lands, and even promote the clearing of native vegetation, mainly from the Cerrado bush vegetation, for pasture cultivation, but are unlikely to have much effect on virgin rainforest clearing. Fragile and easily swamped soils under the rainforest are not suitable for commercial mechanized cultivation, or even for grazing or subsistence farming. Rates of deforestation at the basin's borders are not therefore extrapolable to the vast wet rainforest core. Besides, re-deforestation of secondary regrowth is rapidly increasing.

Livestock grazing will continue to be the largest land use in the Amazon region in the coming decades. Therefore, it is essential to continue promoting scientific research on pasture management, as part of a sustainable-development strategy for the Amazon, allowing for continuing beef production without further intrusion into the forest. Development of more intensive forms of livestock raising and fattening, based on cultivated fodder and grain instead of natural pasture, is already substituting for natural grassland; intensively produced beef (specifically demanded by several export markets) would probably expand in the coming years. Proactive protection measures by the Government are checking the expansion of the agricultural frontier and greatly reducing the rate of deforestation.

The total size of the deforested area in the Amazon basin, sometimes estimated on the basis of the high rates measured at some of the hotspots, is indeed much lower than those estimates. The Brazilian government's estimated figure for the extent of gross historically accumulated deforestation, based on satellite imagery and extensive fieldwork, is 587,727 km^2, or approximately 12% of the total Brazilian Amazon basin area (INPE 2000). This is gross deforestation of primary forest clearing. According to the regrowth percentages estimated by Ramankutty *et al* 2007, about one third of the gross deforested area is covered by secondary regrowth forest, not counting areas with planted trees (which are also growing). Net deforestation is likely to be lower than two thirds of the gross figure due to regrowth and plantations. The historical span for this accumulated effect is not clear, but in the very conservative hypothesis that it took place entirely within the latest 50 years and not taking secondary growth or plantations into account, deforestation would amount to an exponential rate of 0.25% per year. As a matter of fact, assuming 50 years is arbitrary: clearing began much before, actually centuries ago. Some of the "deforested" areas may have been in that condition from preindustrial or prehistoric times. As said before, part of the cleared primary forest is already regrown into secondary forest, and some has been replaced by planted trees.

For the latest two decades (1988-2009) for which satellite imagery is available, the Brazilian government estimate of an average yearly deforestation of 17,098 sq.km implies an annual rate of 0.36%, lower than the 21,000 sq.km (0.44%) estimated for 1977-88 which reflected the acceleration of forest destruction that started with the encouragement for deforestation given by the military government installed in 1964 and reigning until the 1980s, and not stopped immediately by the first democratic administrations after dictatorship ended (see Table 2). However, recent and energetic action by the Brazilian government has reduced the annual deforested area to about 12,000 km^2 per year in 2006-2008 and to 7,400 km^2 in 2009. This implies an annual rate in 2006-09 of about 0.22%, and 0.15% in 2009, relative to the Brazilian Amazon region, below the long-term historical record of 0.25%, and with a strong declining tendency.[22]

At an annual **gross** rate of 0.25%, and assuming no corrective measures are taken to slow gross deforestation even more, and that progress in deforestation would proceed at the same rate even over non suitable land at the core of the basin, the half life of the Amazonian rainforest (i.e. the time required for it to be reduced exponentially to 50% of the **total basin size**, including parts not having forest cover in recent centuries and areas not useful for grazing or crops) would be 327 years. It would take 1247 years at that exponential rate for the current forest to lose 90% of its present area, in the unlikely case that anybody wants to deforest the wet core where little (if any) agricultural activity can take place. This includes all causes of gross deforestation, anthropogenic or otherwise (including, for instance, forest fires not started by humans and non-anthropogenic climate change). The historical annual gross rate mentioned (0.25%) is already higher than the current rate (0.22% in 2006-08 and 0.15% in 2009). It is also noteworthy that, as noted before, more than a third of the gross deforestation reflected in those rates is now taking place in regrown areas, not on pristine forest. The net rate of primary deforestation (gross deforestation minus clearing of secondary regrowth), even not counting plantation of new trees, is significantly lower (0.09% in 2009 and about 0.15% in 2006-08). In the future, deforestation of primary forest is very likely to fall further as decreasing returns from deforestation are encountered, regulatory barriers expand and are enforced, and more regrown seconddary forest becomes available.

In fact, as already mentioned, Brazil and other countries are stepping up environmental protection policies to protect the Amazon, and it is therefore expected that the historical (and current) deforestation rate would be forced to keep subsiding, helped also by a declining population growth rate, a more rapidly declining **rural** population, the gradual but accelerating replacement of fuel wood by natural gas, and the exhaustion of the more accessible and drier parts at the basin's margins, more suitable for crops and grazing than rainforest lowlands at the basin's core.

22 These rates are relative to the size of the Brazilian part of the Amazonian hydrological basin covering 4,776,980 km^2, which makes nearly 70% of the entire Amazon basin. Only part of it has ever been covered by rainforest.

Most agricultural production growth in Brazil (more than 80% in 1961-2007 and nearly 100% since the 1990s) comes from increasing production per hectare, whilst only a small fraction (19% since 1961 to 2009, and nearly 0% in the 1990s and 2000s) comes from increased farmland area. Encroaching on forests for agricultural purposes (either crops or livestock) has become rather marginal and is rapidly dwindling.

Hypotheses envisaging 'abrupt' savannisation or 'die-back' of the Amazon forest in the near future, as well as the idea that climate change would make the rainforest drier and more prone to ravaging fires, have so far no satisfactory scientific basis and remain just as farfetched speculations.

Implications are vast in various respects. Climate change and its effects would not be significantly accelerated by a positive feedback from a vanishing Amazon forest; carbon emissions from Amazon deforestation are already on the wane and expected to keep diminishing. Decreasing numbers of Amazon households use forest wood as fuel in their homes, increasingly substituting natural gas. Agricultural expansion in Brazil (with its significant and growing contribution to the world's food output) would probably continue, mostly based on increasing productivity, and without much encroachment onto Amazon forest land.

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