FORESTS AND EMISSIONS: A CONTRIBUTION TO THE ELIASCH REVIEW

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Contents

Units and conversion factors used in this report and the related literature

1 Gigatonne (Gt) ≡ 1 × 10_9 tonnes ≡ 1 Petagramme (Pg)

100 Gt CO_2 contains 27 Gt carbon

100 Gt CO_2 ≡ 13 parts per million (ppm) concentration in the atmosphere

Key Messages

HISTORICAL IMPACTS OF FOREST ACTIVITIES ON CARBON EMISSIONS AND SQUESTRATION

- Deforestation and forest degradation emits carbon to the atmosphere.
- Afforestation and reforestation removes carbon from the atmosphere.
- Net deforestation has contributed 22% to 43% of the historical CO_2 rise.
- Since 1980 global forest cover has decreased by an estimated 2.2 million km^2 due to human action.
- Most deforestation is now occurring in the tropics. Tropical forest cover declined by between 1.1 and 2.5 million km^2 between 1980 and 2000.
- Tropical deforestation resulted in emissions of between 70 and 147 Gt CO_2 between 1980 and 2000.
- Accurate estimation of emissions from deforestation and degradation is difficult.
- The forestry sector is currently the third largest contributor of global greenhouse gas emissions, and is a larger emitter than the transport sector.

FOREST CARBON SINKS

- The current rate of CO_2 rise is only approximately 57% of fossil fuel emissions due to uptake by land ecosystems and oceans.
- One hectare of tropical forests is estimated to take up approximately 3 tonnes of CO_2 per year.
- The effects of a lost forest carbon sink could be long-lasting.
- The historical CO_2 rise could have been 10% faster without the tropical forest carbon sink.

FUTURE PROJECTIONS – DEFORESTATION

- If deforestation continues until all tropical forest is removed, total anthropogenic greenhouse gas concentrations could exceed 550 ppm CO_2 equivalent, even if future fossil fuel CO_2 emissions were zero.
- The IPCC SRES emissions scenarios project 15% - 29% deforestation of tropical forests by 2050, leading to estimated emissions of 79 to 332 Gt CO_2.
- The SRES scenarios also project some tropical areas to undergo afforestation / reforestation, with these areas representing of 8% - 17% of current forest extents by 2050. This would provide the potential for uptake of 40 to 199 Gt CO_2, but with a lag of many decades before full uptake is realised.
- Future drivers of land-use change vary between regions.
- The SRES scenarios project lower rates of deforestation and emissions from Amazonia than more recent, bottom-up scenarios. A “business-as-usual” bottom-up scenario projects 40% deforestation by 2050 in the absence of intervention policies, emitting approximately 117 Gt of CO_2. A “governance” scenario projects 15% deforestation, which is still twice as much as the SRES A2 scenario.

FUTURE PROJECTIONS – IMPACTS OF CLIMATE CHANGE ON FORESTS

- Impacts of climate change on forests could be significant but are highly uncertain.
- Climate change may reduce or remove the forest carbon sink in some tropical areas in the latter part of the 21st Century.
- Even under climate change, tropical forests as a whole are expected to remain an overall net carbon sink in the absence of direct human-induced deforestation.
- Severe impacts of climate change on tropical forests may be more likely if the forest is already affected by forestry activities. Forest degradation may therefore increase the likelihood of climate-carbon cycle feedbacks accelerating CO_2 rise.

FUTURE PROJECTIONS – LOSS OF THE FOREST CARBON SINK

- The projected atmospheric CO_2 rise due to the IPCC SRES scenarios is greater when the lost carbon sink is taken into account – this is termed the "land use amplifier" .
- If the forest carbon sink is strong, total tropical deforestation could increase the 21st Century CO_2 rise significantly. As well as directly emitting CO_2, deforestation could reduce the land carbon sink exerting an additional impact on the CO_2 rise.
- Loss of the tropical forest carbon sink would also limit our ability to reduce CO_2 concentrations following the overshoot of a stabilisation target.

FURTHER EFFECTS OF FOREST COVER ON CLIMATE CHANGE

- The type of vegetation covering the landscape affects climate through the water cycle and the exchange of energy between the land and atmosphere.
- Past deforestation in the mid-latitudes regions has acted to cool these regions by increasing the surface albedo. Nevertheless, this cooling may be smaller than the warming effect of the contribution of deforestation to the past CO_2 rise.
- Afforestation / reforestation in temperate regions would still act to mitigate global warming overall, but the effect of sequestering CO_2 would be partly offset by the warming effect of decreased surface albedo. In some parts of the boreal forests, the warming effect of decreased surface albedo would outweigh the cooling effect of CO_2 sequestration.
- As well as emitting CO_2, tropical deforestation exerts an additional warming effect by reducing evaporation and cloud cover.
- Large-scale tropical deforestation is expected to reduce regional precipitation
- Large-scale tropical deforestation may modify climates around the world by altering the atmospheric circulation.
- At the global scale, most historical deforestation has taken place in mid-latitudes so the overall biophysical effect has been a cooling through increased surface albedo. However, since most future deforestation is

projected to take place in the tropics, biophysical effects would add a further warming to that expected from CO_2 emissions alone.

- Tropical deforestation could also affect climate through aerosol emissions.

PART 1: HISTORICAL CHANGES IN FOREST COVER AND RESULTING EMISSIONS

1.1. IMPACTS OF FOREST ACTIVITIES ON CARBON DIOXIDE EMISSIONS AND SEQUESTRATION

Forest clearance emits carbon to the atmosphere

There are several methods implemented to clear forested land each causing the emission of CO_2 to the atmosphere. Slash and burn is used to clear forest for farming. After trees are cut down the under-story is burnt, leaving clear land for either cultivation or pasture. Often these areas enter a fallow-cropping cycle where land is cultivated for a few years and then abandoned once soil fertility declines. Abandonment allows the re-growth of vegetation, the primary forest being replaced by either rough pasture or secondary forest. These areas are often re-cleared at rates that rival primary forest deforestation[1]. Logging involves the removal of trees for land management or commercial activities. Clear-cut logging denudes large areas of trees, leaving behind stumps and litter material. Selective logging removes individual, valuable trees. In tropical forests, logging is generally selective because most trees are not valuable (with the exception of some Asian forests). Damage is associated with tree-felling and extraction and with increased vulnerability to fire. In principal, selectively logged forests allowed to recover can still have high biodiversity value and provide many ecosystem services such as carbon storage[2]. However, in practice, selective logging can be a precursor to complete clearance.

Deforestation causes the release of carbon dioxide from the terrestrial biosphere. Carbon is lost immediately from plant material burnt during clearing. There is also a slower release of carbon associated with the decay of dead plant material left on site. Carbon stored in forest soils is often an equal or greater pool than that stored in aboveground biomass[3]. This pool is dependent on litter inputs from vegetation and is thus sensitive to deforestation. There is large potential for carbon loses from South-east Asian tropical peat swamp forests. Forestry activities on peatlands lead to rapid soil carbon losses through drainage, decomposition and fires[4]. Carbon is also lost in the longer term through break-down of the harvested wood, the rate of this depending on the end product.

[1] Hirsch *et al.* (2004)
[2] Putz & Pinard (1993)
[3] Table 2 in House *et al.* (2002)
[4] Joosten & Couwenberg (2007)

Forest degradation also releases carbon

Degradation of the forests after deforestation also has associated emissions. Post-logging forests have increased sensitivity to burning[5]. Reduced canopy cover allows increased light penetration which dries the organic debris in the under-story increasing its flammability. Forest fires can kill between 10-80% of the living plant biomass[6]. Removing the forest canopy also reduces the amount of precipitation that is intercepted and evaporated. This can increase run-off (floods) causing soil erosion and damaging remaining vegetation[7]. Clear-cutting, selective logging and the associated access roads fragment the forest. Trees on forest edges are more likely to suffer water-stress leading to dieback and enhanced fragmentation[8].

Carbon dioxide can be sequestered by afforestation and reforestation

Afforestation is the planting of new forests on lands which, historically, have not contained trees whereas reforestation describes the establishment of trees on land that has been cleared of forest within the recent past[9]. In recent times mid-latitude forest area has expanded. This is due, in part, to an increase in afforestation projects. China, for example, has been implementing an afforestation scheme aimed to reduce land deterioration[10]. However, forest plantations still account for less than 5% of the total forest area[11]. Agricultural intensification in the mid to high latitudes has decreased the amount of land used for agriculture and consequently forest cover has expanded in these regions. Both afforestation and reforestation have the potential to create and maintain CO_2 sinks. However, increasing agricultural intensity has associated carbon costs that must be considered to determine the magnitude of such sequestration. Current estimates suggest that as yet afforestation and reforestation have not had a significant impact on the global terrestrial carbon sink[12].

Carbon is also accumulated in re-growing vegetation following tropical deforestation. The amount of carbon sequestered depends upon land-cover dynamics post-deforestation. If recovery is allowed, and the land develops secondary forest, a small fraction of emissions can be mitigated; estimated at between 3 and 12 % of tropical forest emissions in the 1990s[13]. However, rates of clearing secondary forest have been shown to equal initial deforestation[14] leading to further significant carbon emissions[15].

[5] Nepstad *et al.* (1999)
[6] Cochrane & Schulze (1999); Holdsworth & Uhl (1997)
[7] Nepstad *et al.* (1994)
[8] Giambelluca *et al.* (2003)
[9] As defined by the IPCC AR4
[10] Li (2004)
[11] FAO (2005)
[12] IPCC AR4 WG1 Chp 7 Denman *et al.* (2007)
[13] Achard *et al.* (2004); DeFries *et al.* (2002b)
[14] Hirsch *et al.* (2004)
[15] Steininger (2004)

Net deforestation may have contributed 22% to 43% of the historical CO_2 rise

The contribution of land use emissions to the historical CO_2 rise has been estimated using climate carbon-cycle models[16], by performing simulations with fossil fuel emissions alone and fossil fuel plus land use changes. Since historical land use change and the associated emissions processes are poorly known, these studies have included a number of reconstructions of land use change, emissions and models. With this approach, historical land use emissions are estimated to have contributed between 22% and 43% of the total CO_2 rise from 1750 to 2005[17]. This suggests that if no deforestation had taken place, the present-day CO_2 concentration would be between about 335 ppm and 360ppm, as opposed to 383[18].

[16] Brovkin *et al.* (2004); Matthews *et al.* (2004)
[17] IPCC AR4 WG1 Chp 2 Forster *et al.* (2007)
[18] Mauna Loa observatory CO_2 annual mean 2007 http://www.esrl.noaa.gov/gmd/ccgg/trends/

1.2. RECENT CHANGES IN FOREST COVER AND CARBON DIOXIDE EMISSIONS

Since 1980 global forest cover has decreased by an estimated 2.2 million km^2 due to human action.

Most deforestation until the mid-20th Century occurred in temperate regions. However, in more recent decades, land abandonment in Western Europe and North America has lead to natural reforestation. Conversely, deforestation is now progressing rapidly in the tropics. Globally forest cover has been decreasing over the last 30 years (Table 1). The total net change for 2000-2005 is the equivalent of 200 km^2 of forest cleared daily. Globally rates of forest loss are slowing; current rates are 18% lower than in the 1990s and 26% lower than in the 1980s. The slowing of global deforestation rates most probably reflect increased forest cover in the mid-latitudes rather than a decrease in deforestation in the tropics. For example, net increase in forest area in Asia between 2000 and 2005 is due to afforestation projects in China which mask the large scale deforestation in tropical areas such as Indonesia (Figure 1). In fact the Asia region houses the country with the largest gain and the country with the second largest loss in forest area.

Table 1. Estimated annual change in forest area since the 1980s by continent and globally. It must be noted that deforestation rates carry large amounts of uncertainty (See Box 1)

Region	Annual change in forest area (10^3 km^2)		
	1980s[19]	1990s[20]	2000-2005 [20]
Africa	- 28	- 44	- 40
Asia	- 9	- 8	10
Europe	2	9	7
North and Central America	- 12	- 3	- 3
Oceania	- 0.4	- 4	- 4
South America	- 52	- 38	- 43
Global	**- 99**	**- 89**	**- 73**

[19] FAO (1990)
[20] IPCC AR4 WG3 Chp 9 Nabuurs *et al.* (2007), after FAO (2005)

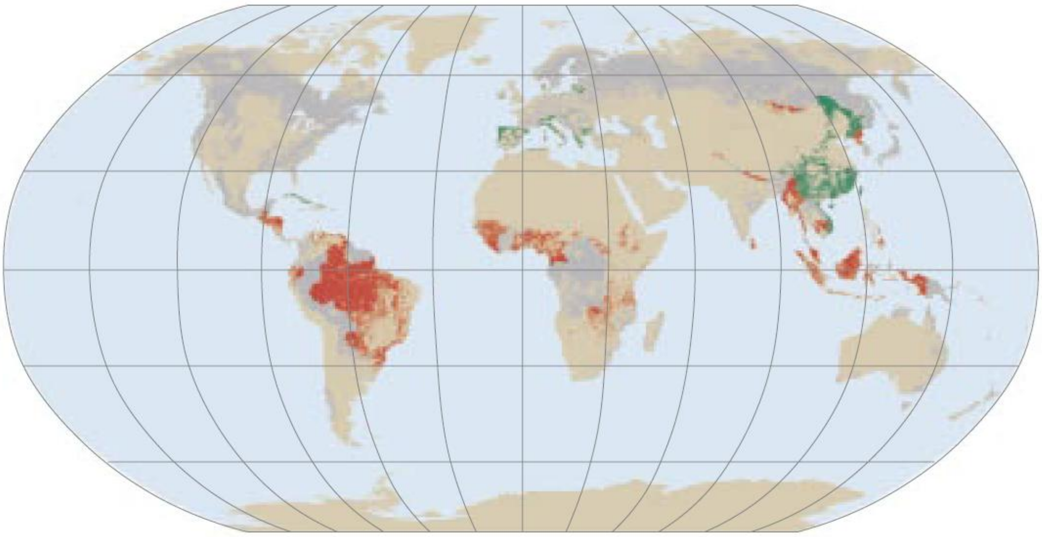

Figure 1. A global map showing countries with large net change in forest area between 2000-2005.[21]

Most deforestation is now occurring in the tropics. Tropical forest cover declined by between 1.1 and 2.5 million km^2 between 1980 and 2000

Tropical forests represent 37% of the total world's forest area[22] but contain as much carbon as temperate and boreal forests combined[23]. As tropical trees sequester more carbon than non-tropical trees, deforestation in these regions will emit more CO_2 per unit area.

Estimates of deforestation rates vary greatly (Table 2). For example rates estimated using the United Nations Food and Agriculture (FAO) country survey data for the 1990s were 31% higher than rates estimated by FAO remote sensing methods. The FAO remote sensing estimates were in turn, 33% higher than deforestation estimates derived from AVHRR (Advanced Very High Resolution Radiometer) measurements. Even excluding dry tropics, where the data are most uncertain and the divergence greatest[24], rates from the FAO country survey are still 23% higher than estimates derived from remote sensing[25]. These estimates do not only vary in magnitude but also in direction. The FAO country survey shows a slowing of deforestation rates between the 1980s and 1990s whereas the AVHRR show rates increasing. Despite these discrepancies, some regional trends are consistent. For example both FAO country survey and AVHRR methods show an increase in deforestation rates in Africa and a decrease in rates in Latin America. It is clear that in order to properly asses the extent of global and tropical forest loss a unified and consistent approach must be taken (See Box 1).

[21] FAO (2005)
[22] FAO (2005)
[23] Houghton (2005)
[24] Houghton & Goodale (2004)
[25] Achard *et al.* (2002)

Table 2. Estimates of net deforestation of tropical forests in the 1980s and 1990s.

	All tropics (10^3 km^2)			Humid tropics (10^3 km^2)	
	FAO Country Survey [26]	AVHRR [27]	FAO Remote Sensing [26]Error! Bookmark not defined.	FAO Country Survey [28]	TREES[28]
Net forest change - 1990s					
Tropical Asia	-24	-20	-20	-25	-20
Tropical Africa	-52	-4	-22	-12	-7
Tropical Latin America	-44	-32	-41	-27	-22
Pan tropics	**-120**	**-56**	**-83**	**-64**	**-49**
Net forest change - 1980s					
Tropical Asia	-24	-12			
Tropical Africa	-39	-3			
Tropical Latin America	-71	-36			
Pan tropics	**-134**	**-51**			

Figure 2 shows a map of tropical deforestation hotspots in the 1980s and 1990s[29]. The Amazon forest is being cleared across a large belt extending from eastern to southern Amazonia. Drivers of deforestation include expansion of cattle and soy bean production. Pockets of cleared forest also arise surrounding settlements and roads. In Africa, deforestation in the Congo basin is limited, largely because of civil conflict limiting investment and infrastructure expansion. Shifting agriculture (slash and burn) tends to be restricted to the secondary forest mosaics, and only partially affects the primary forest. Illegal logging, urban expansion and fuel requirements are also drivers of deforestation. Most tropical forests in Asia are under intensive exploitation for timber and conversion to agricultural lands, in particular oil palm plantations for the production of vegetable oils[29]. Shifting cultivation is also thought to be on the increase.

[26] FRA (2000)
[27] DeFries *et al.* (2002)
[28] Achard *et al.* (2002)
[29] Mayaux *et al.* (2005)

Figure 2. Main tropical deforestation front in the 1980s and 1990s[30]. The map shows the number of times each 0.1 ° grid was identified as being affected by rapid deforestation (pink = 1, red = 2, dark red = 3).

Tropical deforestation resulted in emissions of between 70 and 147 Gt CO_2 between 1980 and 2000

Estimates of global emissions due to changes in land-use increased slightly, but not significantly, over the 1980s and 1990s (Table 3). The majority of these emissions originated from deforestation in the tropics. In total, between 3.7 and 8.1 Gt CO_2 were emitted annually from tropical forests as a result of deforestation in the 1990s (Table 3). The land use carbon source has the largest uncertainties in the global carbon budget. This is due to combined uncertainties associated with estimating deforestation rates and forest carbon density. Uncertainty ranges should decrease as science and technology develops more robust analytical techniques (See Box 1).

Table 3. Land to atmosphere emissions resulting from land-use change in the 1980s, 1990s and 2000-2006 ($GtCO_2$ yr^{-1}). Positive values indicate carbon losses from the land ecosystems. Numbers in parentheses are ranges of uncertainty. Estimates for the 1980s and 1990s are reproduced from IPCC 4th assessment[31]

	Tropical Americas	Tropical Africa	Tropical Asia	Pan-Tropical	Non-tropics	Total Globe
2000-2006						
Canadell et al (2007)	2.2	0.7	2.2	5.1		
1990s						
IPCC AR4	2.6 (1.5-2.9)	1.1 (0.7-1.5)	2.9 (1.5-4.0)	5.9 (3.7-8.1)	-0.1 (-1.8-+1.8)	5.9 (1.8-9.9)
1980s						
IPCC AR4	2.2 (1.1-2.9)	0.7 (0.4-1.1)	2.2 (1.1-1.8)	4.8 (3.3-6.6)	0.2 (-1.5-+2.2)	5.1 (1.5-8.4)

30 Mayaux *et al.* (2005)
31 IPCC AR4 WG1 Chp 7 Denman *et al.* (2007) Best estimate calculated from the mean of Houghton (2003) and Defries *et al*. (2002), the only two studies covering both the 1980s and the 1990s. For non-tropical regions where Defries *et al*. have no estimate, Houghton has been used.

The forestry sector is currently the third largest contributor of global greenhouse gas emissions, and is a larger emitter than the transport sector.

In 2004 the estimated emissions of 8 Gt CO_2 from forestry contributed approximately 17.3 % to the total CO_2 emissions, with 56% of CO_2 being emitted by fuel use and cement production[32]. When emissions of other greenhouse gases (GHGs) are taken into consideration, and compared with CO_2 in terms of a 100-year global warming potential (GWP), emissions from forestry comprise 17.4% of total global GHG emissions which is the third largest contribution after energy supply and industry[32] (Figure 3). At the global scale, forestry is a larger emitter than the transport sector.

It is important to note that many of the world's forests are historically and currently managed. Assessment of the CO_2 balance of boreal, temperate and tropical forests showed that net ecosystem exchange (the balance between sequestration of carbon through photosynthesis and loss of carbon through plant and soil respiration) is controlled by non-climatic conditions such as management and site history[33]. Therefore, through management of forest resources, the forestry industry exerts some control over trace gas exchange.

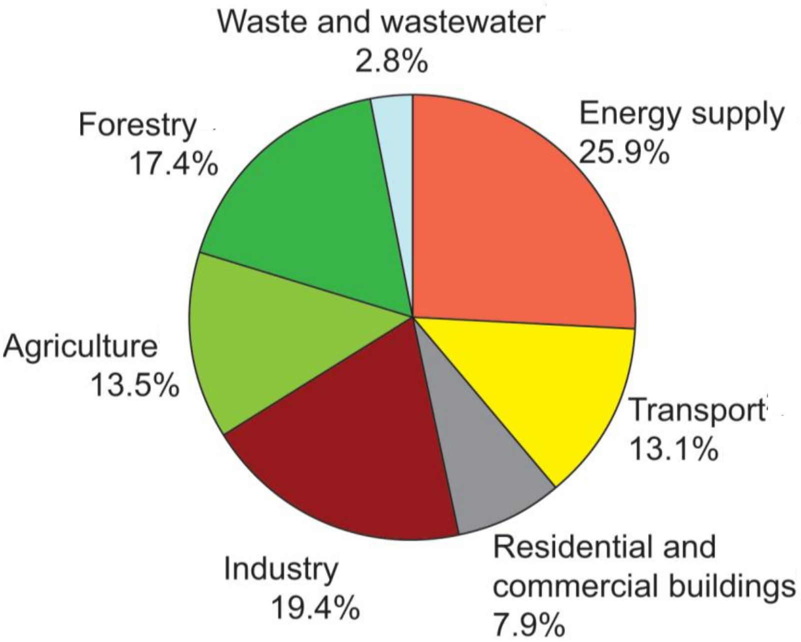

Figure 3. Relative contribution of sectors to total anthropogenic greenhouse gas emissions by in 2004[32], including non-CO_2 greenhouse gases expressed as CO_2 equivalent.

[32] IPCC AR4 WG3 Chp 9 Barker *et al.* (2007)
[33] Luyssaert *et al.* (2007)

Box 1: Our ability to accurately estimate carbon emissions resulting from deforestation

Accurately quantifying carbon emissions resulting from deforestation is difficult due to several key uncertainties. Uncertainties lie in estimations of deforestation rates and forest carbon stocks. The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) reported apparent inconsistencies between inventory-based emissions estimates[34] and emissions estimates obtained by applying historical land use change reconstructions to terrestrial biosphere models[35], with these models giving a decrease in land use emissions since the 1950s in contrast with the ongoing rise until 1990 suggested by the inventory method[36]. House et al[37] attribute this inconsistency to the use of different estimates of deforestation, especially in the tropics. The rising emissions estimate of Houghton[36] used tropical deforestation rates from the United Nations Food and Agriculture Organisation (FAO) Forest Resources Analysis[38] whereas the falling estimate of McGuire et al[39] used the cropland areas of the FAO-STAT database as used by Ramankutty and Foley[40]. In climate-carbon cycle model simulations[41], the historical CO_2 rise was overestimated by the models when the Houghton[34] land use emissions were used as inputs.

The wide estimate range of forest area and rates of forest loss is due in part to the varying analytical methods, definitions of forests and deforestation implemented. The FAO country survey, using a compilation of reports from member countries, has been criticized for limited, inconsistent and infrequent monitoring[42]. Estimates of deforestation rates using remote sensing techniques are lower than those generated by the FAO[43] and generally thought of as more accurate. Assessment of the technical capabilities for monitoring deforestation from a pan-tropical perspective has been implemented[44] in response to the United Nations Framework Convention on Climate Change (UNFCCC) process. Achard et al[44] suggest that remote sensing capabilities have increased since the 1990s and operational forest monitoring systems at the national level are now feasible for most developing countries. Initiatives to take these mid-resolution assessments pan-tropical are in place. For example future FAO surveys will use a remote sensing survey of a 10 x 10 km^2 sample at each intersection of the 1 degree lines of latitude and longitude. A test of such a survey in central Africa was shown to estimate deforestation to within ± 25 %[45].

34 Houghton (1999)
35 McGuire *et al.* (2001)
36 Houghton (1999) and (2003)
37 House *et al.* (2003)
38 FRA (2000)
39 McGuire *et al.* (2001)
40 Ramankutty & Foley (1999)
41 Brovkin *et al.* (2004); Jones *et al.* (2003)
42 Grainger (2008)
43 Ramankutty *et al.* (2007)
44 Achard *et al*. (2007)
45 Duveiler *et al*. (2007)

Box 1. continued.

There are also errors associated with determining current carbon stocks in both plant and soil pools. Uncertainty in biomass estimates were found to be a key source of disagreement regarding estimates of carbon emissions from tropical deforestation[43]. At the plot scale is it possible to estimate carbon stocks to a high level of accuracy[46]. As no methodology can as yet directly measure regional and national carbon stocks, a lot of work has focused on the scaling up from these plot level harvests. Most current estimates of emissions from tropical deforestation come from a biome-average approach which links compilations of point-based biomass harvest data with forest inventory data. This approach introduces positive and negative bias for example over-estimating young and dry tropical forest and under estimating humid and dense forests[47]. More accurate estimates of above-ground carbon stocks can be made from ground-based forest inventory data which uses destructive sampling to develop generalised allometric equations. One such study[48] derived allometric relationships from a pan-tropical dataset of over 2400 trees from 27 different sites and can be used to accurately (±12.5 %) estimate forest carbon stocks across a wide range of forest types. This method is thought to be more accurate than biome-averaging but is time-consuming and costly. There is little available data for key areas in Africa. There is also large potential for use of remote sensing in conjunction with ground based measurements to evaluate forest carbon stocks. Ideally sampling in this way would be linked to deforestation estimates to maintain experimental consistency and improve accuracy.

Other factors also introduce error when estimating carbon emissions from deforestation. For example the response of soil carbon to deforestation is unclear but in areas of tropical peat forest the potential for CO_2 emissions due to forest activities is great (30 tC ha^{-1}) [49]. Also, the mode of forest clearing and land-cover dynamics post clearing will also affect the magnitude of emissions. The IPCC[50] suggested that the methodology of Houghton[51] overestimated land use emissions by neglecting forest re-growth. Use of 70% of these emissions in a climate-carbon cycle model, as suggested by IPCC[50], produced a good fit to the observed CO_2 rise.

[46] Brown *et al*. (2000)
[47] Gibbs *et al*. (2007)
[48] Chave *et al*. (2005)
[49] Achard *et al.* (2004)
[50] IPCC 2nd assessment (1995)
[51] Houghton (1999)

PART 2: FOREST CARBON SINKS AND THE AIRBORNE FRACTION OF CO_2 EMISSIONS

The current rate of CO_2 rise is only approximately 57% of fossil fuel emissions due to uptake by land ecosystems and oceans

As well as being a store of carbon which can be exchanged with the atmosphere through human-induced deforestation, afforestation and reforestation, global land ecosystems also appear to be acting as a carbon sink through other processes. The current uptake of carbon on land is estimated as 9.5 Gt of CO_2[52] (Figure 4) which is larger than the estimated emissions 5.9 Gt of CO_2 from net deforestation. In combination with a similar or larger sink of carbon in the ocean waters, this is offsetting some of the total anthropogenic emissions of CO_2 (Figure 4). Consistent with this is the observation that the current rise in CO_2 concentration in the atmosphere is only approximately 57 % of the fossil fuel emissions (Figure 5), and approximately 40% of total emissions including land use. This suggests that without the carbon uptake by land ecosystems and ocean waters, the past rise in CO_2 caused by anthropogenic emissions would have been considerably greater. The CO_2 concentration in 2005 was measured as 378[53], a rise of 100ppm since the pre-industrial level of 278 ppm. The total historical fossil fuel and land use emissions are estimated as 1760 Gt CO_2[54]. If all these emissions had remained in the atmosphere, the CO_2 concentration could be approximately 600 ppm, i.e. the CO_2 concentration could already have doubled.

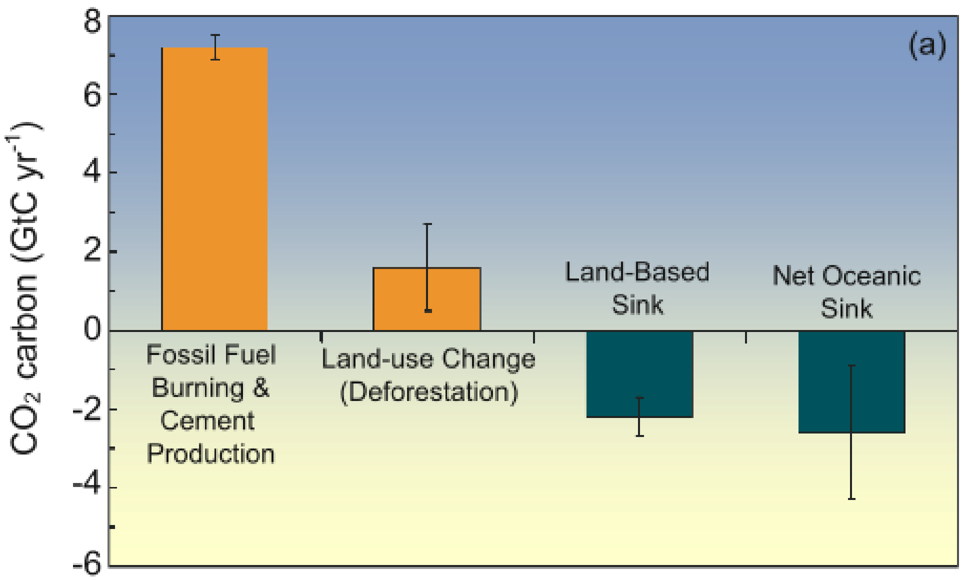

Figure 4. Present-day global sources and sinks of CO_2 carbon as assessed in the IPCC 4th Assessment Report (copyright IPCC 2007)

[52] As assessed by the IPCC AR4 WG1 Chp 7 Denman *et al.* (2007)
[53] IPCC AR4
[54] House *et al.* (2002)

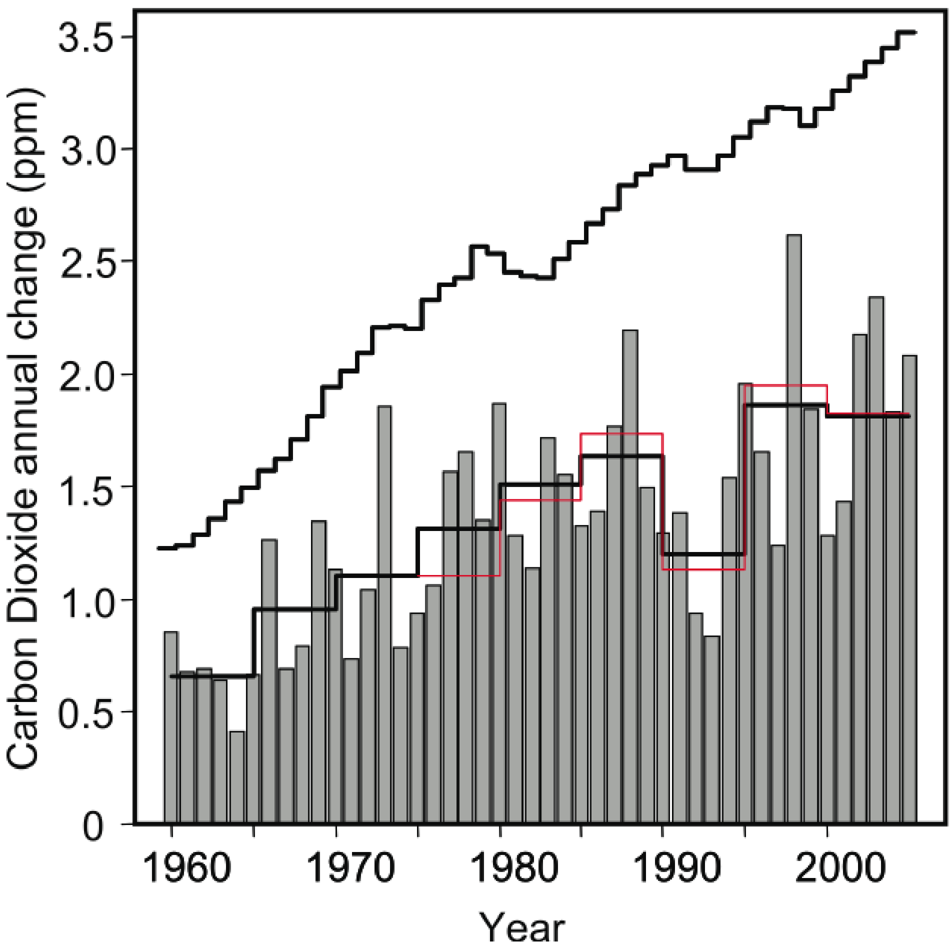

Figure 5. Comparison of annual fossil fuel CO_2 emissions (upper stepped line) with annual rise in atmospheric CO_2 concentration (bars, with lower stepped line showing the 5-year mean). (copyright IPCC 2007)

A number of mechanisms have been proposed to explain the land carbon sink. Some of this may be due to re-growth of forests on abandoned land, or nitrogen fertilization, but there is also strong evidence that much of the sink arises from enhanced rates of photosynthesis in response to the CO_2 rise itself. This is often termed "CO_2 fertilization". The evidence for CO_2 fertilization comes from a variety of sources including laboratory experiments, studies with plants grown in open-top chambers containing enriched CO_2 concentrations, and field experiments in the open air using the "Free Air CO_2 Enrichment" (FACE) technique which involves releasing CO_2 into the near-surface air over a plot of vegetation of a few m^2 in area, and studying the response of the vegetation[55]. The magnitude of the impact of CO_2 enrichment varies considerably between plant types, with the net primary productivity of woody vegetation increasing by 23 % to 25 % under a 50 % increase in CO_2 concentration[56], and has been the subject of some debate[57].

[55] Hendrey *et al.* (1993)
[56] Norby *et al*. (2002)
[57] Long *et al.* (2006); Denman *et al*. (2007)

While vegetation takes up carbon from the atmosphere, it also transfers significant quantities of carbon into the soil. Vegetation drops litter in the form of leaves, twigs and branches, which become part of the soil and build up the carbon content of the soil. Carbon in the soil is released back to the atmosphere through soil respiration; the rate of soil respiration can depend on environmental factors particularly temperature and soil moisture.

One hectare of tropical forests is estimated to take up approximately 3 tonnes of CO_2 per year

Field studies in forest areas involving measuring the basal diameter of trees[58] indicate that old-growth tropical forests provide a carbon sink of 2.6 ± 1.2 tonnes of CO_2 per hectare per year (Figure 6). The total live biomass sink could be 4.4 ± 1.5 Gt CO_2 yr^{-1} [59]. Further evidence for the tropical carbon sink is provided by atmospheric inversion modelling studies, which combine atmospheric models with observations of CO_2 concentrations in order to infer the exchanges of CO_2 between the surface and the atmosphere across the world[60]. Such studies suggest that the tropics are either neutral or a net sink, despite emissions from deforestation, which implies that undisturbed forests are a net sink of CO_2. Coupled climate-carbon cycle models also suggest a net sink at the present time (Figure 7). The carbon sink may be the result of enhanced productivity associated with CO_2 fertilization or nitrogen deposition[61], or a consequence of climate change.

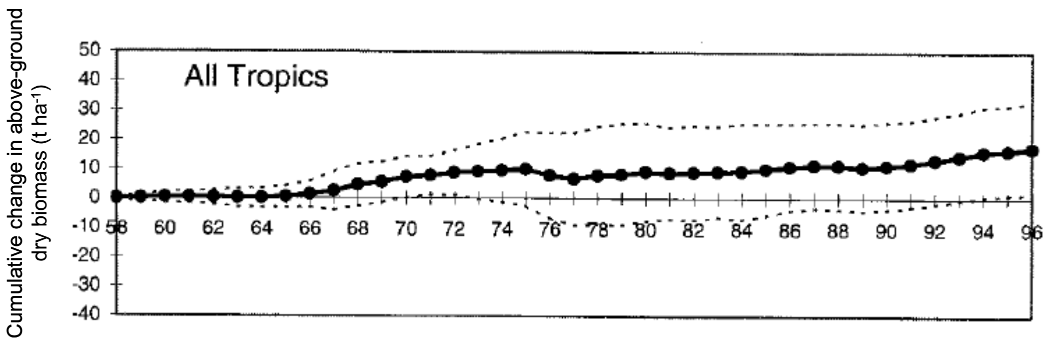

Figure 6. Cumulative change in above-ground biomass (tC ha^{-1} yr^{-1}) of old-growth tropical forests estimated from measurements of tree basal areas[62]

[58] Phillips *et al.* (1998); Malhi & Grace (2000); Phillips *et al.* (2008)
[59] IPCC AR4 WG1 Chp 7 Denman *et al.* (2007)
[60] Stephens *et al*. (2007)
[61] Friend *et al*. (2006)
[62] Reproduced from Phillips *et al*. (1998)

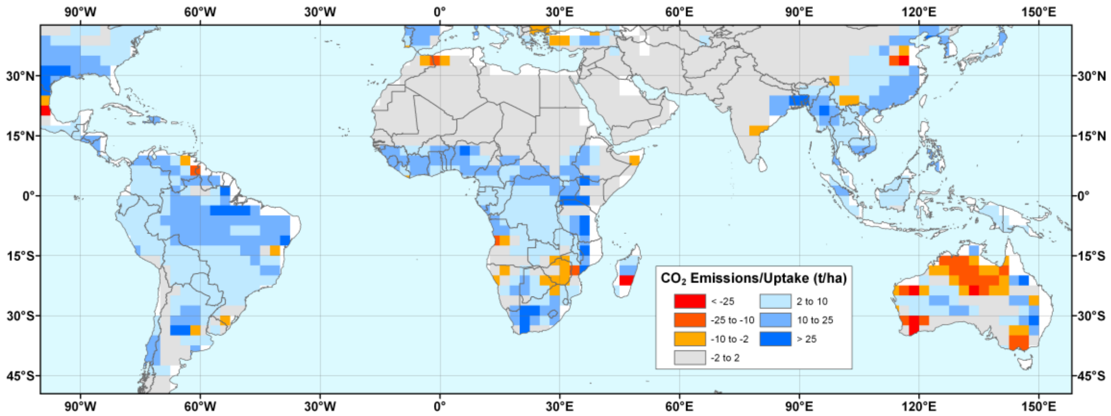

Figure 7. Simulated vegetation carbon change in broadleaf forests over the 1990s in the Hadley Centre coupled climate-carbon cycle model, expressed as sources/sinks of CO_2.

As well as leading directly to the emission of CO_2 to the atmosphere, deforestation results in the loss of this sink. This could therefore have an additional effect on the rate of CO_2 rise. This has been termed the "land use amplifier"[63] as it amplifies the effect of emissions from other sources. Such amplification is not accounted for if deforestation is compared with fossil fuel use in terms of emissions alone, so comparison in terms of cumulative emissions could underestimate the true effects of deforestation.

The effects of a lost forest carbon sink could be long-lasting

A key issue is that removal of a carbon sink has long-term implications for CO_2 rise. While the emissions due to the removal of an area of forest occur over a short period, the absence of the sink will persist indefinitely unless the forest is replaced. As a simple illustrative example, if a hectare of forest were sequestering 3 tonnes of CO_2 per year[64], the presence of this forest over 40 years has resulted in the sequestration of 120 tonnes of CO_2. If that hectare of forest initially stored carbon equivalent to 600 tonnes of CO_2[65], deforestation of that hectare would have resulted in the emission of most of that 600 tonnes of CO_2 in the short term, but would also mean that the forest would not have been able to sequester 120 tonnes over the last 40 years. The long-term impact on cumulative net emissions over those 40 years is therefore 20% greater than would have been expected if only the initial emissions were taken into account.

Since the forest carbon sink strength is expected to evolve over time in response to the CO_2 concentration and climate change, the long-term effects of sink loss need to take such changes into account. The sink may weaken in future due to ecological effects[64], with slow-growing species with high carbon density being out-competed by faster-growing species with lower carbon density. Climate change may also impact on the sink (See Part 4), but the effects of both are extremely uncertain.

[63] Gitz & Ciais (2003)
[64] Phillips *et al.* (1998)
[65] Using an average estimate of plant carbon density from House *et al.* (2002)

The historical CO_2 rise could have been 10% faster without the tropical forest carbon sink

If tropical forests are a carbon sink, this implies that their presence has helped to remove a fraction of historical CO_2 emissions from the atmosphere. The absence of tropical forests would have led to a reduction in the overall terrestrial carbon uptake and hence an acceleration of the historical CO_2 rise. A simple climate-carbon cycle model[66] has been used to simulate the CO_2 rise resulting from historical emissions in two cases, one with tropical forests present and another with tropical forests removed. In the latter case, the emissions from the removal of the tropical forests were not considered; this study focussed purely on the impact of removing the carbon sink. The model suggested that if the tropical forest carbon sink had not been present, the present-day CO_2 concentration would have been approximately 10ppm higher than currently observed (Figure 8). The past CO_2 rise of just over 100ppm would therefore have been accelerated by 10%.

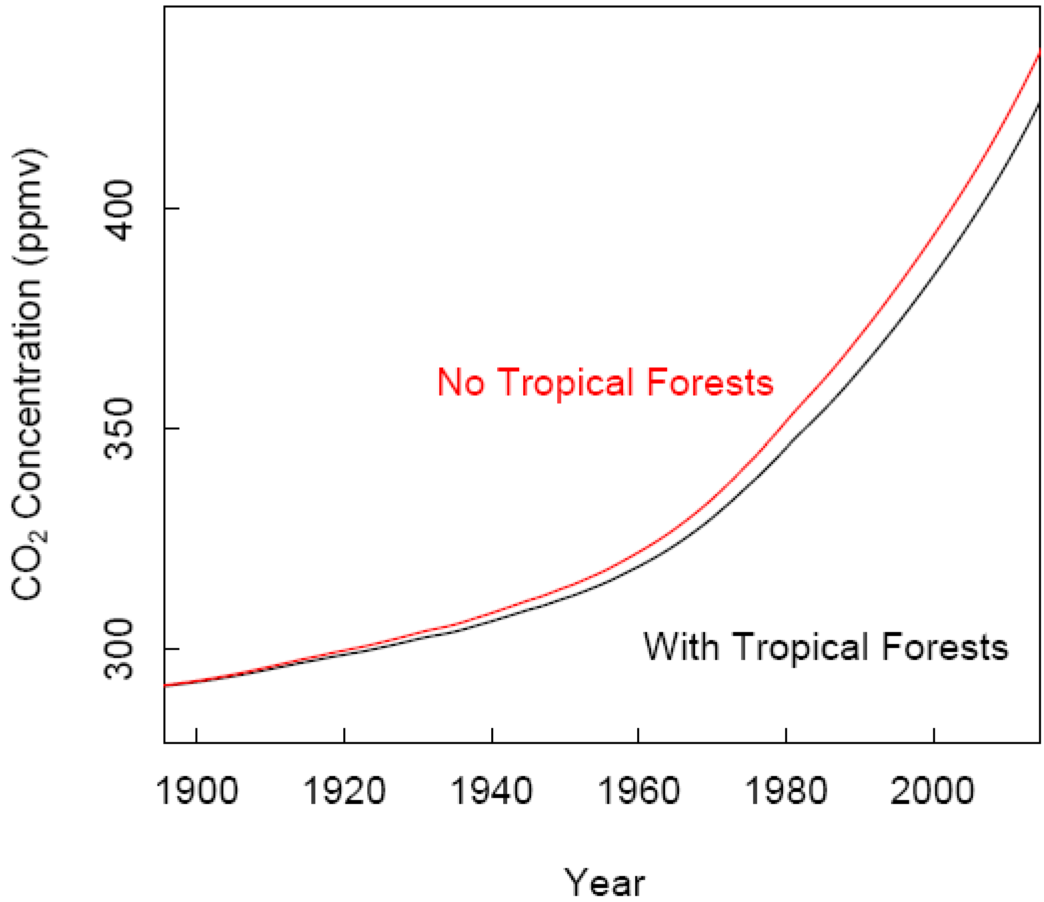

Figure 8. Simulated historical CO_2 rise with and without the tropical forest carbon sink. The emissions that would have resulted from removing the tropical forests are not included, in order to identify purely the role of the lost carbon sink.

[66] Huntingford *et al.* (2008)

PART 3: SCENARIOS OF FUTURE FOREST COVER CHANGE AND EMISSIONS

If deforestation continues until all tropical forest is removed, total greenhouse gas concentrations could exceed 550 ppm CO_2 equivalent, even if future fossil fuel CO_2 emissions were zero.

Many scenarios of future deforestation or reforestation are of course possible, so it is useful to bound these by considering extreme scenarios of total deforestation or reforestation[67]. Including the loss of vegetation and soil carbon, complete tropical deforestation would result in estimated emissions of between 748 and 1450 Gt of CO_2. This would increase atmospheric CO_2 by 41 to 134 ppm, above the current concentration of 383ppm[68]. The concentrations of other Kyoto gases (methane, nitrous oxide, PFCs, HFCs and SF6) are currently at approximately 50ppm CO_2 equivalent (CO_2e) [69], so if these levels remain and deforestation continues until all tropical forests are removed, the total CO_2 equivalent concentration of Kyoto gases could reach 474 to 567ppm. Therefore even without further fossil fuel CO_2 emissions, the often-suggested GHG stabilisation target of 550ppm CO_2e could be exceeded if tropical deforestation were to continue indefinitely.

Complete global deforestation would emit 1650 to 3007 Gt of CO_2, contributing 130-290 ppm to the increase in CO_2 concentration[67]. Total reforestation of previously deforested land would sequester an estimated 733 to 807 Gt of CO_2, reducing CO_2 concentrations by 40-70ppm[67]. These estimates ignore any effect of an increasing carbon sink strength over time.

The IPCC SRES scenarios project 15% - 29% deforestation of tropical forests by 2050, leading to estimated emissions of 79 to 332 Gt CO_2.

The IPCC "SRES" emissions scenarios include a land use change component[70]. Some of the models used to generate these scenarios were also used to generate spatially-disaggregated scenarios of land cover change including deforestation and afforestation. One such model, IMAGE[70] related land cover change to demand based on population changes, income, technological advances and land/productivity potential, and was used to project future forest cover changes under different SRES scenarios at a half degree spatial scale.

Under four commonly-used SRES scenarios, IMAGE projected some areas of deforestation in all tropical regions, but also some areas of reforestation or afforestation in all regions. Overall, tropical forest cover in Africa and Asia is projected to decrease continually to 2050 in all scenarios (Table 4a). In Latin

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67 House *et al.* (2002)
68 IPCC AR4 WG1 Chp 2 Forster *et al.* (2007); Stern (2006) Depending on the airborne fraction which could range between 0.41 and 0.71 by 2100 according to the strength of climate-carbon cycle feedbacks (Friedlingstein *et al*, 2006)
69 Forster et al (2007); Stern (2006)
70 Special Report on Emissions Scenarios (SRES), Nakićenović *et al* (2000). SRES includes a large number of scenarions, here we focus on four scenarios known as A1B, A2, B1 and B2. A number of Integrated Assessment Models were used in SRES, but here we focus on land use from IMAGE (Strengers *et al*, 2004)

America, total tropical forest cover decreased by 2050 in only the A2 scenario (Table 6, Figure 9). In the other three scenarios, deforestation in Latin America was more than offset by reforestation / afforestation at the continental scale, leading to overall gain by 2020 and 2050 (Table 6, Figure 10)). However, the carbon uptake per unit area of reforestation does not cancel the carbon emissions from deforestation, at least in the short to medium term, because the timescales of emissions and uptake are different. Deforestation leads to a rapid release of much of the forest carbon to the atmosphere through the initial clearance process, followed by a more gradual release of the remaining carbon through subsequent decay or burning of leftover material or the eventual disposal of any forestry products. Reforestation and afforestation lead to uptake of carbon over long periods determined by the growth rate of trees and other vegetation. Uptake by afforestation / reforestation is therefore generally slower than the emissions from deforestation.

Here we separately examine the deforestation and afforestation/reforestation components of the IMAGE SRES land use scenarios, and estimate the eventual total emissions and uptake of carbon from these forest changes (Tables 4,5 & 6). The emissions estimates should be regarded as the long-term commitment to emissions, reflecting the change in the carbon stored in the ecosystem on replacing forest with crops or grassland[67]. It is assumed that all carbon lost from the ecosystem is eventually emitted to the atmosphere; in practice, some of these emissions could be delayed by years or decades. Similarly, the estimates of uptake by afforestation/reforestation should be regarded as the potential total uptake once the forest has achieved a mature state including the store of carbon in the soil. This process would require many decades. A reliable quantification of the relative contributions to deforestation and afforestation/reforestation to the net carbon balance at any given time would require global scale simulations with realistic terrestrial ecosystem models; such studies have not yet been carried out.

The tropical deforestation projected to occur by 2020 under the A1B, A2, B1 and B2 SRES emissions scenarios is estimated to lead to a commitment to CO_2 emissions of between 50 and 157 Gt CO_2. Some of these emissions would not occur until after 2020 due to lags in the emissions following deforestation as discussed above. Deforestation projected by 2050 is estimated to lead to committed emissions of between 79 to 332 Gt CO_2 (Table 4b), with the range depending on both the variation between the forest cover change scenario and uncertainty in the emission from a given scenario. Total emissions are highest under the A2 scenario (between 152 and 332 Gt CO_2 following deforestation by 2050) and lowest under the B1 scenario (between 79 and 172 Gt CO_2 following deforestation by 2050).

Table 4. a) Deforestation component of forest area change relative to 2000 (10^3 km^2) in the four main SRES scenarios. b) Committed CO_2 emissions relative to 2000 from vegetation and soil only due to the deforestation component (Gt CO_2). Red text denotes forest loss and emissions. The dates are those by which the areas given in (a) have changed from forest to non-forest classification in the IMAGE model projection; some of the emissions would take place after these dates.

a) Contribution of deforestation to projected net forest cover change (10^3 km^2)

	Latin America		Africa		Asia	
	2020	2050	2020	2050	2020	2050
A1B	220	743	650	998	374	838
A2	542	1,447	791	1,305	489	917
B1	213	388	623	844	344	631
B2	170	339	782	1,428	479	968

b) Commitment to CO_2 emissions (Gt CO_2) due to deforestation component of forest cover.

	Latin America		Africa		Asia	
	2020	2050	2020	2050	2020	2050
A1B	9-20	31-68	28-60	42-92	21-45	39-85
A2	23-50	61-134	34-73	55-121	16-34	36-77
B1	9-19	16-36	26-58	36-78	15-32	27-58
B2	7-16	14-31	33-72	61-132	20-44	41-89

The SRES scenarios also project some tropical areas to undergo afforestation / reforestation, with these areas representing of 8% - 17% of current forest extents by 2050. This would provide the potential for uptake of 40 to 199 Gt CO_2, but with a lag of many decades before full uptake is realised.

The afforestation/reforestation component of the scenarios projected for 2050 is estimated to lead to potential uptake of between 40 and 199 Gt CO_2 (Table 5b). This uptake would partly offset some of the emissions from deforestation, but would take place over many decades with a significant lag between the land first becoming forest and the maximum carbon storage being achieved.

Table 5. Afforestation / reforestation component of the projected forest area change relative to 2000 (10^3 km^2) in the four SRES scenarios, b) CO_2 sequestration in vegetation and soil relative to 2000 due to the afforestation / reforestation component of forest cover change (Gt CO_2). Green text denotes forest gain and carbon uptake. The dates are those by which the areas given in (a) have changed from non-forest to forest classification in the IMAGE model projection; much of the uptake would take place after these dates.

a) Contribution of afforestation / reforestation to net forest cover change (10^3 km^2)

	Latin America		Africa		Asia	
	2020	2050	2020	2050	2020	2050
A1B	311	1,140	230	350	112	121
A2	271	621	175	215	147	126
B1	312	1,537	236	399	149	220
B2	324	926	193	196	130	142

b) Potential CO_2 uptake (Gt CO_2) due to afforestation / reforestation component of forest cover change

	Latin America		Africa		Asia	
	2020	2050	2020	2050	2020	2050
A1B	13-29	48-105	10-21	15-32	5-10	5-11
A2	11-25	26-57	7-16	9-20	6-14	5-12
B1	13-29	65-142	10-21	17-37	6-14	9-20
B2	13-30	42-92	8-18	8-18	5-12	6-13

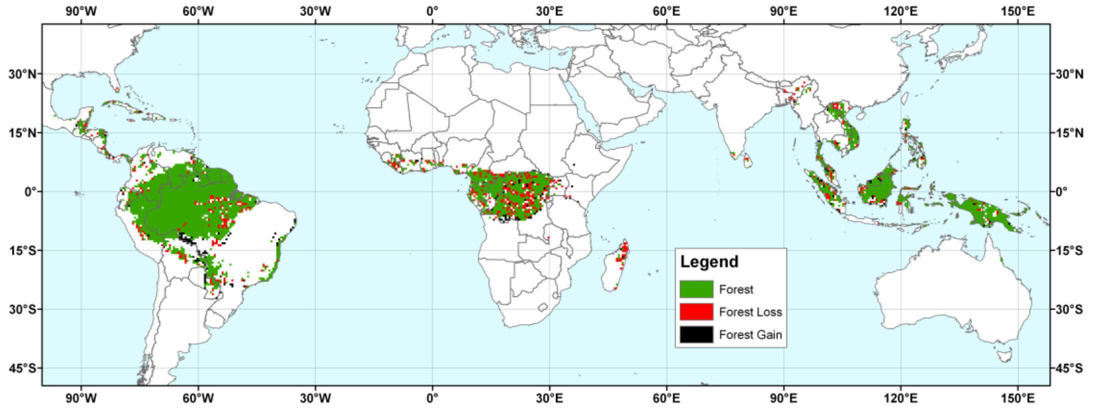
Table 6. Projected net change in forest area relative to 2000 (10^3 km^2) in the four main SRES scenarios. Net forest loss is shown in red, net forest gain is shown in green .

	Latin America		Africa		Asia	
	2020	2050	2020	2050	2020	2050
A1B	92	398	420	648	277	796
A2	271	826	616	1,090	227	712
B1	98	1,149	387	445	196	411
B2	158	658	589	1,232	348	826

The net global land cover changes (Table 6) in these four SRES emissions scenarios are projected to increase atmospheric CO_2 concentrations by between 20 and 127 ppm by the end of the 21st Century[71].

[71] Sitch *et al*. (2005)

a)



b)

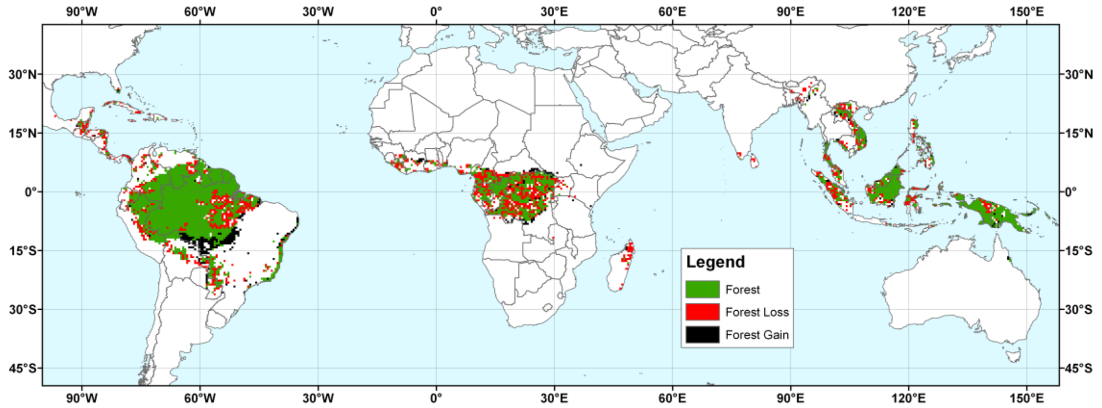


Figure 9. Tropical Forest Difference relative to 2000 in SRES A2 scenario (a) 2020 (b) 2050

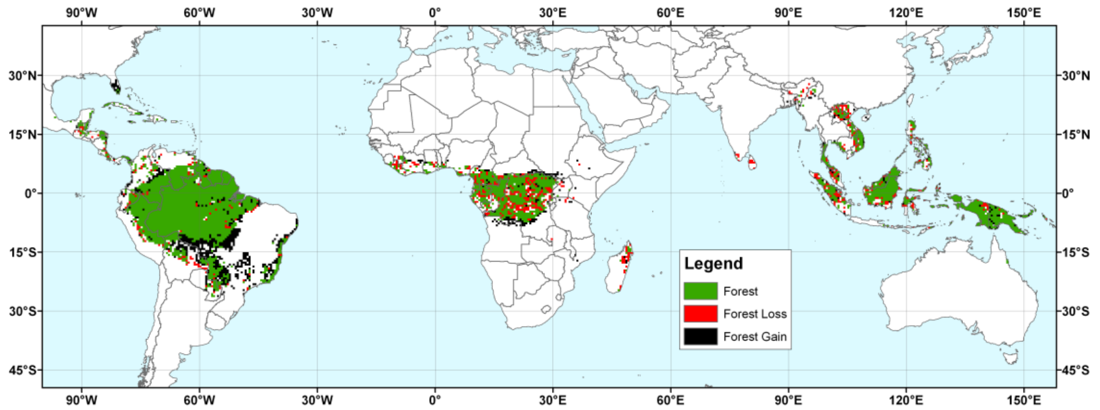


Figure 10. Tropical Forest Difference in 2050 relative to 2000, SRES B1 scenario

Future drivers of land-use change vary between regions.

Differences in deforestation rates and thus emissions between SRES scenarios can be explained by differing demographic, economical and technological drivers. In South America the projections show net emissions due to deforestation only from the A2 scenario. Net gain in forest area in the A1B scenario is likely due to improved economy whereas gain in B scenarios is due to increased environmental awareness (government intervention). In A1 and B1 scenarios technological transfer increases agricultural efficiency and thus decreases land-use change. In Africa it appears that limiting technological advance through maintained regionalisation is a key driver of forest loss (largest loss in A2 and B2 scenarios). This is likely caused by increase pressures on forest resources from shifting agriculture. In Asia, by 2050, emissions are comparable between A1B, A2 and B2 and lower under scenario B1. This suggests that in these models demographic and economical drivers are less important than environmental awareness and global transfer of technology.

The SRES scenarios may significantly underestimate deforestation and emissions from Amazonia. A "business-as-usual" bottom-up scenario projects 40% deforestation by 2050 in the absence of intervention policies, emitting approximately 117 Gt of CO_2. A "governance" scenario projects 15% deforestation, which is still twice as much as the SRES A2 scenario.

Alternative scenarios have been generated for Amazonia using a bottom-up methodology[72] considering recent deforestation trends, plans for highway paving, level of compliance with legislation on forest reserves, and the existence and establishment of protected areas. A "business-as-usual" scenario assumes that current deforestation trends continue, highway paving proceeds as scheduled, the level of compliance with legislation remains low and that no new protected areas are created. Under this scenario, 2.1 million km^2 of closed-canopy forest are removed by 2050, a reduction of 40% from the present day (Table 7a, Figure 11a). This would emit 117 Gt of CO_2 from the loss of above- and below-ground forest biomass[72], or up to 191 Gt of CO_2 if generalised data suggesting large soil carbon loss applies this region[73].

A "governance" scenario with the same methodology assumes the implementation and enforcement of new legislation, the establishment of more protected areas and pre-emptive management of the impact of road paving. This scenario is regarded by its authors as "extreme" but "plausible", and implies a loss of 0.9 million km^2 of closed-canopy forest by 2050, more than halving the emissions from biomass loss to 55 Gt of CO_2[72] (Figure 11). Despite being considered "extreme", this scenario nevertheless has a rate of deforestation which is twice that implied by the SRES scenario with the greatest for loss by 2050 (the A2 scenario) (Table 7). Since these bottom-up scenario have been published more recently and take account of specific processes and understanding of local drivers of deforestation, rather than globally-generalised relationships between population, GDP and deforestation as in the SRES approach, the bottom-up scenarios would appear to be more plausible. Emissions from deforestation in Amazonia may therefore be twice or four-times greater than the scenarios used in most climate model projections of future climate change.

[72] Soares *et al.* (2006)
[73] Calculated using values for vegetation and soil carbon from House *et al.* (2002)

Table 7. a) Forest area change in Amazonia since 2000 (or 2003 in the case of Soares et al, 2006) (10^3 km^2) and b) emissions of CO_2 (Gt) associated with the deforestation. The tables compare figures derived from the “bottom-up” methodology of Soares et al (2006) with those derived from generalised global SRES scenarios[74]. Carbon emissions are shown in red and carbon sinks are shown in green.

a) Forest area change in Amazonia

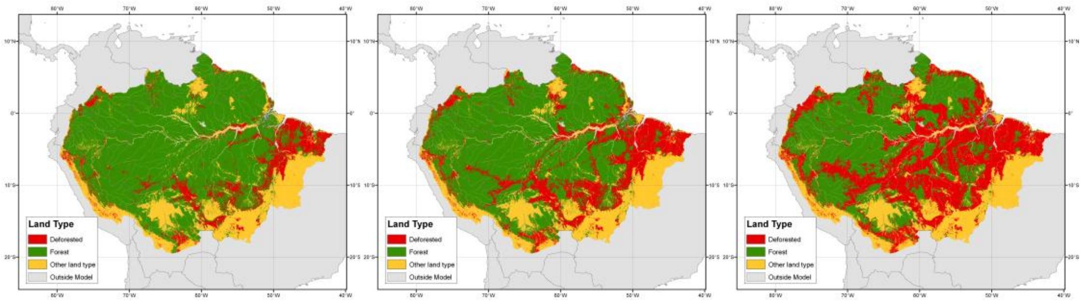
	Soares-Filho BAU	Soares-Filho Governance	SRES Scenario A2	SRES Scenario B1
2020	682	449	197	56
2050	2067	913	435	627

b) Emissions of CO_2 associated with deforestation

	Soares-Filho BAU	Soares-Filho Governance	SRES Scenario A2	SRES Scenario B1
2020	22.8 - 47.8	15.0 - 31.4	6.6 - 13.8	1.9 - 3.9
2050	69.0 - 144.8	30.5 - 63.9	14.5 - 30.5	20.9 - 43.9

a)

2000 **2020** **2050**



b)

2000 **2020** **2050**

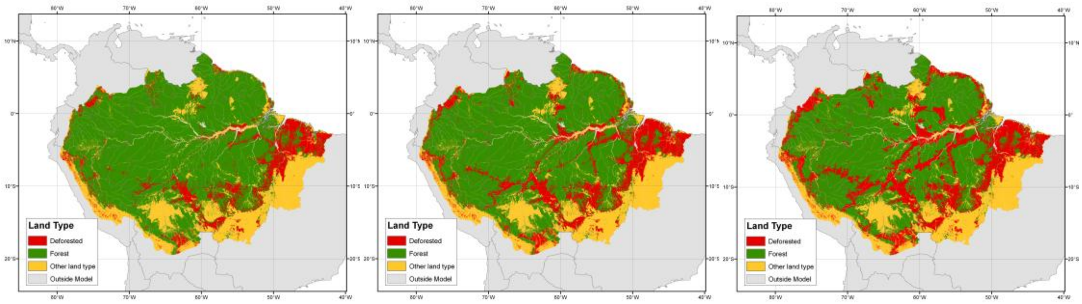


Figure 11. Projection of deforestation in Amazonia under a) “business as usual” and b) “increased governance”[74]

[74] Soares et al (2006); Figures in Table 7b were calculated using projections of deforestation from Soares et al (2006) and from the IMAGE model in conjunction with values of vegetation carbon from House et al (2002).

PART 4: IMPACTS OF FUTURE CLIMATE CHANGE ON FORESTS

Impacts of climate change on forests could be significant but are highly uncertain

Since the local climate is a strong determinant of the type of vegetation that can exist in a location, climate change may itself lead to changes in the coverage, species composition and carbon content of forests. The extent and character of temperate and boreal forests is strongly influenced by temperature, while tropical forests rely on high rainfall. Annual average temperatures around the world are expected to increase by between approximately 0.5°C and 2°C by the 2050s[75], and while this is expected to lead to an increase in global average precipitation, some areas may receive less precipitation or significant changes in the seasonality of precipitation as a result of changes in atmospheric circulation.

However, the timing, magnitude and spatial pattern of such impacts are difficult to predict. The future rate of global warming is uncertain, as a result of uncertainties in the future rates of emissions of greenhouse gases and their build-up in the atmosphere, and in the response of global temperature to a given rise in greenhouse gas concentrations. Moreover, the regional patterns of climate change that would be associated with a particular level of global warming are highly uncertain, especially the patterns of precipitation change. Climate models are used to simulate the future climate change that would result from a given emissions scenario, but the various models show varying levels of agreement in their simulations of regional climate[76]. Similarly, the responses of ecosystems to changes in their local climate are also uncertain; ecosystem models and ecological understanding are used to assess the potential impacts of projected climate changes, but again the various ecosystem models and analysis techniques can produce widely different results[77]. Some forest areas may become more productive as a result of climate change; others may become less productive or even become unable to support forest cover if the climate change is sufficiently severe (Figure 12).

[75] See IPCC AR4
[76] See IPCC AR4 Summary for policy makers SPM 7 and WG1 Chp 11 Christensen *et al.* (2007)
[77] Cramer *et al.* (2001); See IPCC AR4 WG2 Chp 4 Fischlin et al (2007); Sitch et al (2008)

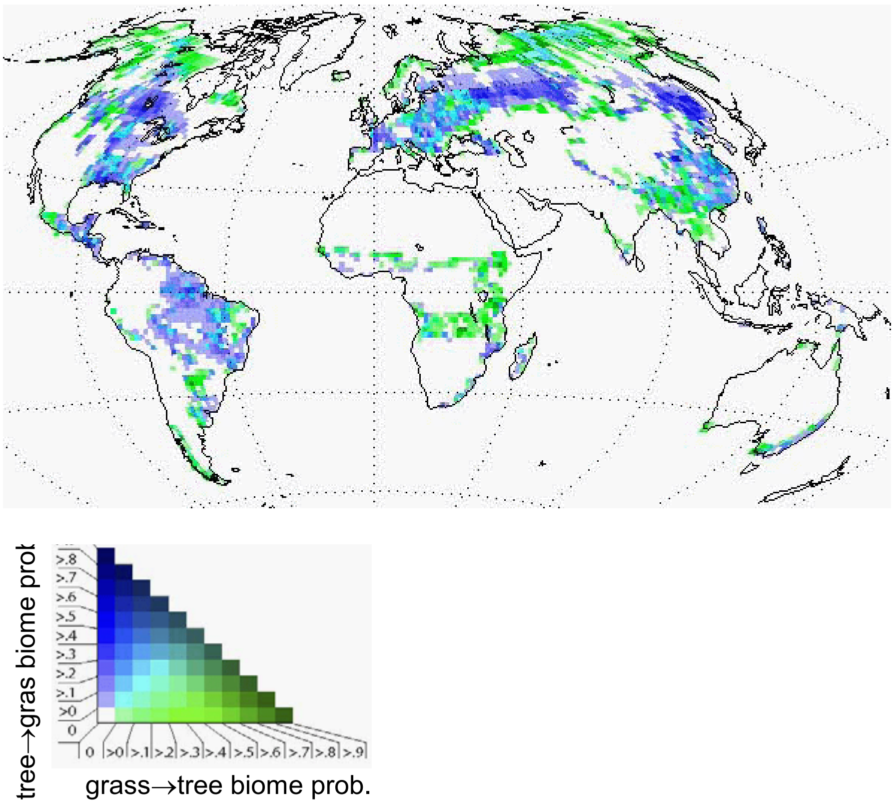


Figure 12. Level of agreement between climate models on implied ecosystem transitions from tree to grass or grass to tree biomes in the LPJ dynamic global vegetation model[78] driven with the IPCC AR4 climate model simulations and the maps shows the proportion of climate simulations that produce vegetation change from either grass to tree or tree to grass.[79] Copyright National Academy of Science (2006)

Climate change may reduce or remove the forest carbon sink in some tropical areas in the latter part of the 21st Century

One area at risk appears to be Amazonia; some climate models simulate a future climate of Amazonia that could no longer support rainforest according to a number of vegetation models (Box 2). Not all models simulate such a severe change in this region, but there does appear to be a consensus amongst models on some degree of drying in eastern Amazonia. Rainfall in parts of Amazonia appears to be linked to anomalous warming in the tropical north Atlantic[80], which may occur as part of greenhouse-forced climate change with a contribution from the reduction in the cooling influence of atmospheric aerosols as pollution becomes cleared[81]. In models which incorporate interactive vegetation and the carbon cycle, a drying of the local climate is magnified by feedbacks acting at both regional and global scales[82]. The loss of forest cover leads to changes in evaporation and the surface energy balance, which further reduce precipitation especially inland, and changes in carbon uptake

[78] Sitch et al (2003)
[79] Reproduced from Scholze *et al*. (2006)
[80] Good *et al.* (2008)
[81] Cox *et al.* (2008)
[82] Betts *et al.* (2004)

and release play a part in a larger global carbon cycle feedback accelerating the rate of global climate change[83] which again magnifies the regional drying in Amazonia[84]. In one model[85] the drought conditions experienced in western Amazonia in 2005[86] are simulated to occur every one in two years after the 2020s, and in three-quarters of years by the 2050s. According to this model, the average precipitation over Amazonia may be reduced by 60% by 2100 compared to pre-industrial, and the annual mean temperature of the region may warm by approximately 10 °C, nearly twice the global mean warming of 5.5 °C. Tree cover across large areas of Amazonia is simulated to be either reduced to savanna proportions or replaced entirely with shrubs and grasses. In part of the basin, even grasses can no longer be supported and the simulated land cover becomes semi-desert.

However, it is important to note that even in this extreme scenario, the forest loss due to climate change does not become significant until the second half of the 21st Century. In contrast, direct human-induced deforestation would impact the forest significantly much sooner under a business-as-usual scenario (Box 3)

Even under climate change, tropical forests as a whole are expected to remain an overall net carbon sink in the absence of direct human-induced deforestation

According to climate and vegetation modelling studies, rainforest areas in Africa and SE Asia do not appear to be threatened by detrimental climate change over the coming century[87]. Climate and vegetation models indicate that tropical forests are expected to increase their overall carbon storage over the 21st Century, contributing to the terrestrial carbon sink and offsetting some anthropogenic CO_2 emissions. Nevertheless, climate change may weaken this offset. One caveat is that large-scale vegetation models do not include detailed ecological processes which have been hypothesised to lead to a reduction in tropical carbon storage, through the increased competitiveness of fast-growing, low-carbon content species against slow-growing, high-carbon content species[88].

Severe impacts of climate change on tropical forests may be more likely if the forest is already affected by forestry activities. Forest degradation may therefore increase the likelihood of climate-carbon cycle feedbacks accelerating CO_2 rise.

Areas of tropical forest have experienced drier conditions in the past as a result of natural variations in climate, but have remained intact. For example, in the early mid-Holocene period (8000-4000 years before present) the southern Amazon was substantially drier than the present day, but there is little evidence of large-scale replacement of forest by savanna except at the margins[89]. The palaeo-ecological evidence suggests that tropical forests may have some resilience to drier conditions,

[83] Cox *et al.* (2000)
[84] Betts *et al*. (2004)
[85] The HADCM3LC coupled climate-carbon cycle model including aerosol forcing, driven by the IS92a emissions scenario Cox *et al*. (2008)
[86]Marengo *et al.* (2008)
[87] Betts (2000); Cramer *et al.* (2001); IPCC AR4 WG2 Chp 4 Fischlin *et al*. (2007)
[88] Phillips *et al.* (2008)
[89] Mayle & Power (2008)

provided that there are few sources of ignition for fire. The impact of climate variability on fire appears to be affected by the presence of humans; in the Amazon over most of the last 2000 years, peaks in fire activity coincided with peaks in solar forcing, but the fire peaks declined after an indigenous population crash circa 1700[90]. It therefore appears that climate change can increase the vulnerability of the forest, but the presence of humans leads to the actual impact.

A similar relationship has been demonstrated in recent years, with analysis of the patterns of drought, land use and fire showing that leakage of fire from agricultural areas during droughts is a major influence on the forest[91]. Fire frequency has been shown to be higher within a few km of a forest edge[92], so the introduction of new forest edges through patchy deforestation and road-building would be expected to increase fire risk in the remaining areas of forest. It therefore appears that severe impacts of climate change on tropical forests are more likely if climate change occurs in comjunction with other direct human stresses such as forest fragmentation and the use of fire.

[90] Bush et al. 2008
[91] Aragao *et al.* (2007)
[92] Laurance & Williamson (2001)

Box 2 Amazon forest die-back" – physically plausible but highly uncertain

The Amazon die-back result from HadCM3LC appears to be qualitatively plausible but at the extreme end of the range of results from multiple models. Feedbacks from the die-back itself play a part in generating the large magnitude of the climatic drying, and these are not included in most other climate models. Drying also occurs in the HadCM3 model when these feedbacks are not included, and most other climate models in the IPCC multi-model ensemble show some degree of drying in Amazonia but to a lesser extent than HadCM3 (Figure 1). The baseline model HadCM3 appears to be more skilful than most other models in simulating the present-day climate of Amazonia, and it has been suggested that models such as HadCM3 which simulate a future drying also agree better with observed precipitation trends in Amazonia[93].

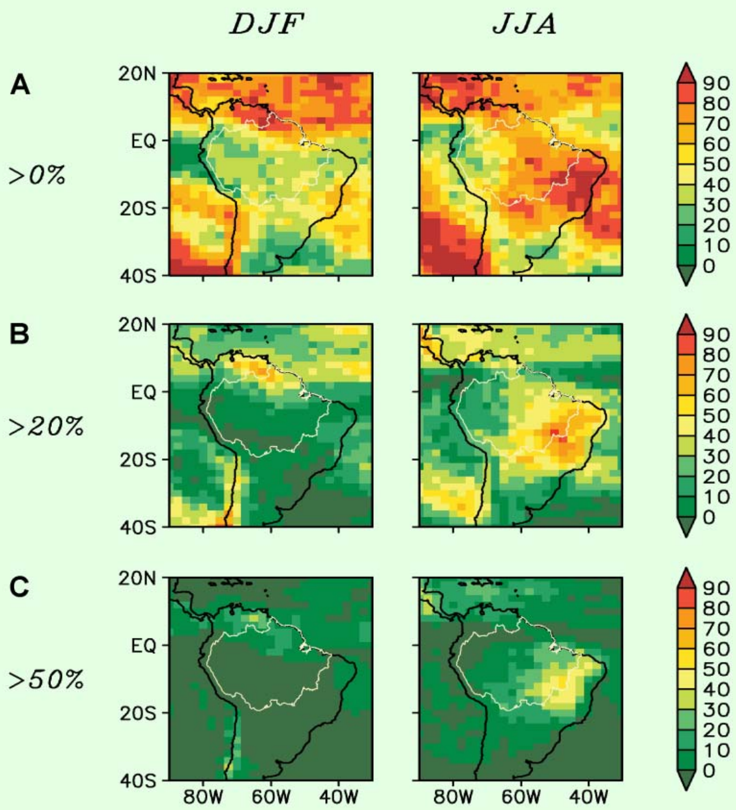


Figure 1. Level of agreement amongst the IPCC climate models on simulated future changes in precipitation over South America.[94]

[93] Li *et al.* (2008)
[94] Reproduced from Malhi *et al.* (2008)

Box 2. continued.

Forest degradation under a drying climate also appears to be qualitatively supported by other models and experimental data[95]. Overall, it appears that the some degree of Amazon forest loss due to climate change remains a physically plausible possibility but is not certain (Figure 2). It may be that a more likely scenario is a less severely-drying climate which may exert lesser impacts on the forest in the absence of other stresses such as those arising from direct human-induced deforestation or degradation. Under such a scenario, the risk of "forest die-back" could be increased by the introduction of fire associated with forestry activities[96].

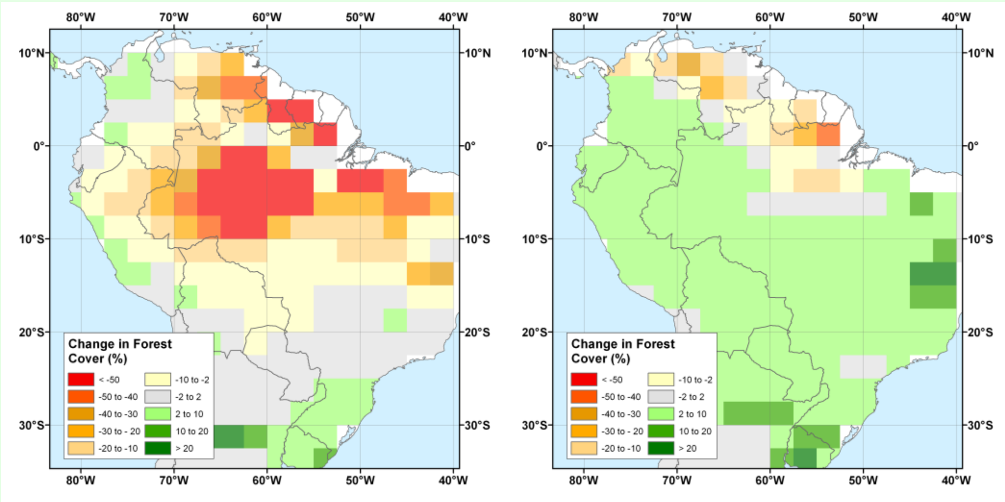


Figure 2. Changes in forest cover as a result of climate change in Amazonia from 2000 to 2100 simulated by two different versions of the Hadley Centre coupled climate-carbon cycle model. The model versions differ in the values assigned to key parameters in the terrestrial carbon cycle calculations

95 Cramer *et al.* (2001); Scholze *et al.* (2006); Brando *et al.* (2008)
96 Malhi *et al.* (2008)

Box 3: Comparing rates of deforestation and climate-driven "die-back" in Amazonia

The scenario of almost total Amazon forest die-back with the fully coupled HadCM3LC model driven by the A2 emissions scenario appears to be the most extreme scenario of climate-driven forest loss[97]. However, even in this extreme case, the climate change-driven dieback does not become significant until approximately 2050. In contrast, scenarios of direct human deforestation[98] imply significant forest loss well before this date.

In the Hadley Centre scenario with climate change but no deforestation[99], forest cover is maintained for at least the next 20 years, and then begins to decline gradually in parts of Amazonia. Until the 2020s, changes in the carbon balance within Amazonia are small, but outside Amazonia to the east, west and south there are increases in forest carbon. The total forest carbon store of South America increases by 3.61 GtC from the 2000s to the 2020s, and then continues to rise more gradually to a total increase of 4.53 GtC by the 2050s, although with carbon stores decreasing in northern Amazonia from 2020. The greatest reduction in carbon by the 2050s is in northern Amazonia.

In contrast, the scenario with both climate change and the Soares et al.[100] deforestation projection show a net loss in South America carbon from the outset (Figure 1). By the 2010s, forest area and carbon is being lost from central, eastern and southern Amazonia, and by the 2020s, total South American forest carbon has reduced by 7.34 GtC. By the 2050s all parts of Amazonia have lost forest cover and carbon in addition to that lost as a result of climate change, with a total reduction in South American forest carbon of 27.06 GtC. Unlike the "climate-only" scenario, the greatest loss of carbon due to deforestation is in the eastern quarter of Amazonia.

It is therefore clear that until the 2050s, the deforestation rates projected by Soares et al[100] would exert a much greater impact on Amazonian forest cover and carbon emissions than would the regional climate change projected by HadCM3LC under IS92a. Despite the beginnings of carbon emissions in northern Amazonia due to climate change, total South America forest carbon still increases as a result of CO_2 fertilization when no human-induced deforestation takes place. However, the Soares et al[100] projection converts this net sink into a much larger net source. Taking into account both the emissions of 27 GtC from deforestation and the loss of the 5 GtC sink, the impact of deforestation is to increase net global cumulative emissions by 32 GtC over 50 years.

[97] Cox *et al.* 2004
[98] For example the SRES and Soares et al scenarios
[99] Cox *et al*. (2008)
[100] Soares *et al.* (2006)

Box 3. continued

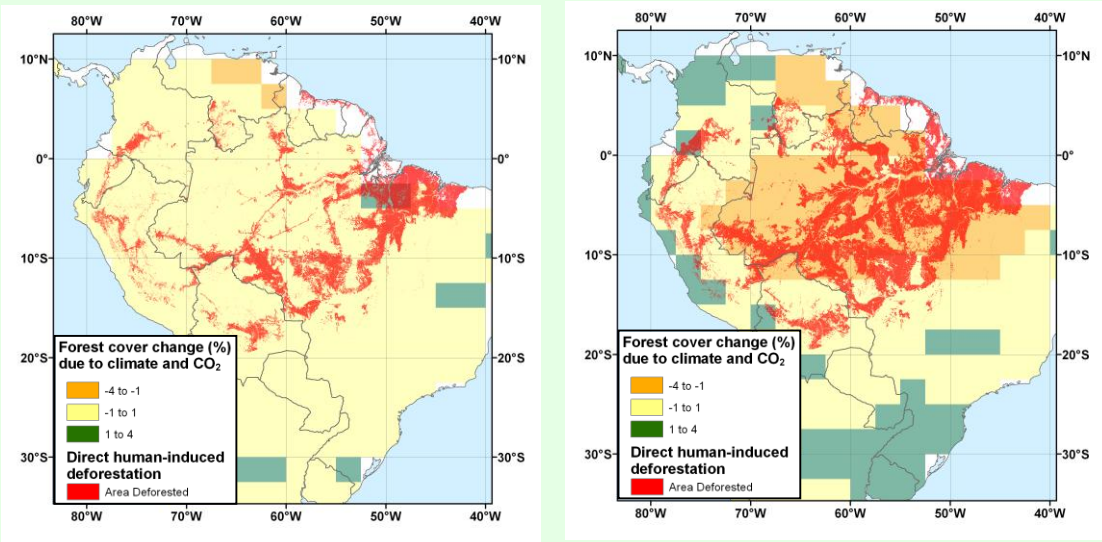


Figure 1. Changes in forest cover due to changes in climate and CO_2 concentration (green, yellow and orange), simulated by the HADCM3LC coupled climate-carbon cycle model[101], by 2020 and 2050 relative to 2000, in comparison with a projection of direct human-induced deforestation[102].

[101] Cox *et al* (2000)
[102] Soares *et al*. (2006)

PART 5: IMPLICATIONS OF DEFORESTATION FOR CO_2 RISE AND CLIMATE CHANGE IN THE CONTEXT OF FOREST CARBON SINKS AND CLIMATE IMPACTS

If the forest carbon sink is strong, total tropical deforestation could increase the 21st Century CO_2 rise significantly. As well as directly emitting CO_2, deforestation could reduce the land carbon sink exerting an additional impact on the CO_2 rise.

A climate-carbon cycle modelling study[103] suggests that total tropical deforestation would increase the CO_2 rise between 2000 and 2100 by 299 ppm, in addition to the rise of 350 ppm which is simulated when tropical forests are not removed. The loss of the tropical forests therefore increases the CO_2 rise by 85% in this simulation (Figure 13). Fossil fuel emissions over the 21st century are projected as 6600 Gt of CO_2, and emissions from total tropical forest loss are just over 1450 Gt of CO_2 [104]. The large contribution to CO_2 rise here occurs despite the cumulative deforestation emissions being only 24% of fossil fuel emissions, because the CO_2 rise is also accelerated by the loss of the tropical forest carbon sink. However, it should be noted that the model used in this study exhibits a land carbon sink approximately twice as strong as the central estimate of other similar models when forest are present [105] and the present-day airborne fraction simulated by this model appears to be below the range inferred from observations [106]. If a similar study were performed with other models, there would be less of a sink to be lost so the impact of deforestation on the CO_2 rise would not be so large. The Hadley Centre coupled climate-carbon cycle model projects that intact tropical forests could sequester up to 58 Gt of CO_2 by 2050, enough to remove 8 years worth of fossil fuel emissions at current rates. Total tropical deforestation would therefore remove this sink.

In the above study[103], the rate of global warming over the 21st Century is increased by 30% as a result of total tropical deforestation (Figure 13). This is a consequence of the increased rate of CO_2 rise; in contrast to other studies[107] the model used in this study does not simulate an additional local warming in the tropics due to reduced evaporation following deforestation.

[103] Bala *et al.* (2007)
[104] House *et al.* (2002)
[105] Friedlingstein *et al.* (2006)
[106] IPCC AR4 WG1 Chp 7 Denman *et al.* (2007)
[107] DeFries *et al.* (2002a); Feddema *et al.* (2005)

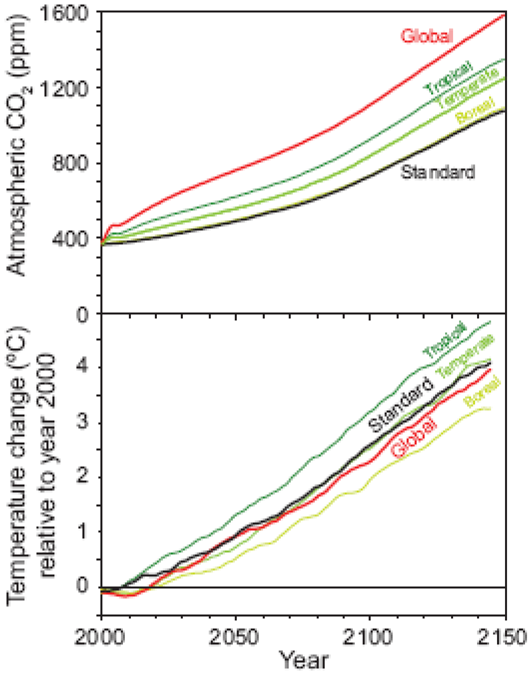


Figure 13. Simulated temporal evolution of atmospheric CO_2 (Upper) and 10-year running mean of surface temperature change (Lower) for the period 2000–2150 in the Standard and deforestation experiments. Warming effects of increased atmospheric CO_2 are more than offset by the cooling biophysical effects of global deforestation in the Global case, producing a cooling relative to the Standard experiment of approx 0.3 K around year 2100. The combined carbon-cycle and biophysical effects from Tropical, Temperate, and Boreal deforestation are net cooling, near-zero temperature change, and net warming, respectively. The sum of the temperature changes in the latitude-band experiments is approximately equal to the temperature change in the Global case, suggesting near-linearity.

The projected atmospheric CO_2 rise due to the IPCC SRES scenarios is greater when land cover change is taken into account

The projected deforestation in the SRES scenarios would also be expected to weaken the land carbon sink and hence accelerate CO_2 rise. Deforestation in any given location would not only lead to a direct emission, but would also remove the potential for a future sink (Figure 14). The sink loss due to global land cover change in the A2 scenario has been estimated to increase CO_2 rise by 4-46ppm over the 21st century[108].

[108] Gitz & Ciais (2004); Sitch *et al.* (2003)

a) b)

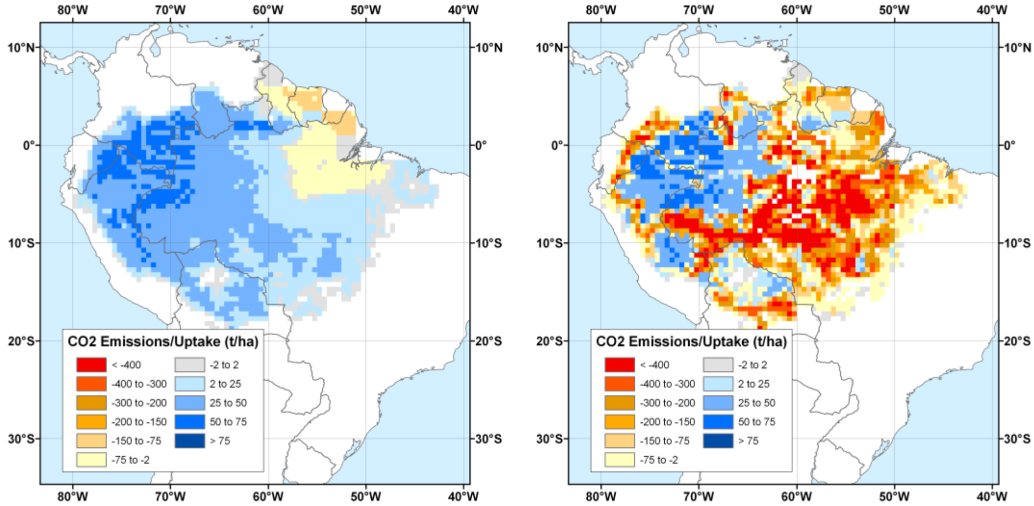


Figure 14. Carbon sinks and emissions in Amazonia due to (a) climate change and CO_2 rise alone[109], and (b) climate change, CO_2 rise and deforestation[110], at 2050 relative to 2000.

Loss of the tropical forest carbon sink would reduce the ability to reduce CO_2 concentrations following the overshoot of a stabilisation target

The slowing of the CO_2 rise for stabilization, or the reversal of the rise following the overshoot of a stabilization target, would both depend on the strength of carbon sinks. Tropical forests could therefore be key to stabilization or recovery after overshoot, and the loss of the tropical forest sink through deforestation could make stabilization or recovery more difficult to achieve.

In a modelling study examining the processes through which CO_2 could be removed from the atmosphere following a cessation of emissions[111], the tropical forest sink was found to be the main mechanism for CO_2 removal provided that climate change had not exerted major impacts. In this hypothetical study, emissions were ceased at 2012[112] and CO_2 concentrations were found to reduce by approximately 20ppm over the following 20 years. A further 20ppm reduction took place over the following 80 years. Approximately one-third of the CO_2 removal was by land ecosystems, and half of this was in the tropics with some areas sequestering over 75 Gt of CO_2 over 40 years. The central African rainforests sequestered nearly 9 Gt of CO_2 from the atmosphere into above-ground biomass over that time, and the SE Asian forests took up over 2 Gt of CO_2 above-ground (Figure 15). With the forests removed, this uptake could not take place which implies that the reduction in atmospheric CO_2 concentration would be slower[113].

[109] Determined using HADCM3LC
[110] Deforestation scenarios from Soares *et al.* (2006)
[111] Jones *et al.* (2006)
[112] 2012 is the end of the first commitment period under the Kyoto agreement
[113] Examined with a simple climate model of Huntingford & Cox (2000) parallel to main simulation

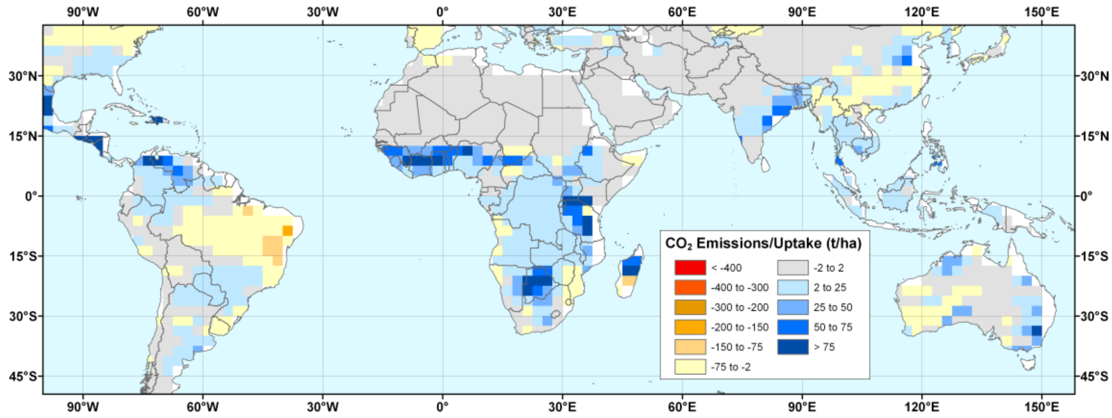


Figure 15. Uptake of carbon in tropical forest vegetation by 2050 following a cessation of CO_2 emissions in 2010[114]

[114] HADCM3LC

PART 6: FURTHER INTERACTIONS BETWEEN FOREST COVER AND CLIMATE CHANGE

The type of vegetation covering the landscape affects climate through the water cycle and the exchange of energy between the land and atmosphere

As well as influencing climate through the emission or uptake of CO_2, changing forest cover can also affect climate by modifying the physical properties of the Earth's land surface. One key property of the land surface influenced by the nature of vegetation cover is the albedo, which is the proportion of solar radiation reflected back into space. A low albedo means that very little solar radiation is reflected while more is absorbed by the surface, which acts to warm the land. A forested landscape generally has a low albedo of around 10-20%. In contrast, a high albedo means that a high proportion of solar radiation is reflected back to space while less is absorbed, so the surface receives less warming from the sun. High albedo landscapes include grasslands, croplands, with albedos of around 40-50%, and deserts which can have even higher albedos if the sand is light coloured. Snow cover can significantly increase surface albedo as snow is highly reflective; a snow-covered landscape can have an albedo of 80% or more. In snowy conditions, forests generally retain a low albedo as the trees usually extend above the snow surface so their dark colouring remains exposed[115]. Snow-free foliage is considerably darker than snow, but even if large quantities of snow are held on the canopy, multiple reflections within the canopy scatter rather than reflect shortwave radiation, which also reduces the landscape albedo[115].

Another key land surface property is the transfer of moisture from the soil to the atmosphere through evaporation. Water on the surface of the land or on vegetation tends to evaporate back to the atmosphere, and this exerts a cooling influence on the land surface and also contributes moisture to the atmosphere which may later be available for precipitation. A forested landscape generally promotes evaporation for a number of reasons. The large total area of leaf surfaces can intercept significant quantities of precipitation and keep them available for evaporation, rather than falling through to the soil where they may filter into soil. Also, a forested landscape exerts frictional drag on the low-level wind which enhances turbulence, which again enhances evaporation. Moreover, evaporation in this context is largely transpiration, which is the drawing-up of moisture from soil by plant roots and the evaporation of this water out into the atmosphere through microscopic pores in the leaf surface. Since trees generally have deeper roots than crops and grasses, they can access moisture deeper in the soil and hence extract more moisture and return it to the atmosphere via transpiration. Reduced evapotranspiration following deforestation can result in a decrease in cloud formation which in turn affects planetary albedo[116]. Removal of forest cover would therefore be expected to lead to decreased evaporation and a reduction in the absorption of solar radiation. When resulting from large-scale changes, these changes in land surface properties can significantly influence regional climates and wider-scale atmospheric circulations.

[115] Harding & Pomeroy (1996)
[116] Bala *et al.* (2007)

The relative importance of these processes depends on local conditions and can vary with season and location; in cold regions, evaporation rates are lower but the presence of snow can lead to a large contrast between the albedo of forested and non-forested landscapes. Considering the effects on landscape properties alone (and neglecting CO_2 uptake), the presence of forests in cold regions with substantial winter snow can therefore exert an overall warming effect on their local climate. In the moist tropics, however, while the contrast in albedo between forest and non-forest can still be significant, the difference in evaporation can be much more significant. The presence of tropical forests can therefore exert an overall cooling effect on local climate.

Past deforestation in the mid-latitudes regions has acted to cool these regions by increasing the surface albedo. Nevertheless, this cooling may be smaller than the warming effect of the contribution of deforestation to the past CO_2 rise.

Deforestation of the boreal and temperate forests exerts a cooling influence on climate because of the overriding influence of the increased surface albedo in the snow-covered periods of winter and spring[117]. Indeed from the global perspective, most deforestation until the mid-20th Century had occurred in the temperate regions exerting an overall local cooling effect[118]. Since changes in surface albedo are a direct perturbation to the radiation balance of the Earth, they can be directly compared with the enhanced greenhouse effect arising from the increased concentrations of greenhouse gases through the metric known as radiative forcing[119]. Broadly speaking, this is a measure of an initial change to the energy absorbed or emitted by the planet prior to any feedbacks which may amplify or dampen the effect, and is considered a useful first-order indicator of the relative effect of different processes on global average temperature[120]. An increase in the concentration of greenhouse gases exerts a positive radiative forcing (i.e. a warming influence) while an increase in surface albedo exerts a negative radiative forcing (a cooling influence, Figure 16).

Global deforestation since 1750 is estimated to have exerted a radiative forcing of -0.2 +- 0.2 Wm^{-2} through increased surface albedo in mid-latitudes (Figure 16), and a positive radiative forcing of and a positive radiative forcing of 0.2 to 0.57 Wm^{-2} (with greater confidence towards the lower end of the range) through its contribution to past CO_2 rise[121] (Figure 16). However, uncertainties in both figures are large and one computer modelling study suggests that the overall effect on temperature has been a cooling due to the dominance of the increase in surface albedo[121]. It is worth noting that these models do not take into account the impact of deforestation and associated disturbance on boreal peatland and permafrost carbon stores. These impacts are likely to significantly increase the historical carbon emission estimates due to deforestation in the mid to high latitudes.

117 Douville & Royer (1996); Brovkin *et al.* (1999); Govindasamy *et al.* (2001)
118 Brovkin *et al.* (1999)
119 IPCC TAR WG1 Chp 6 Ramaswamy *et al.* (2001)
120 IPCC AR4 WG1 Chp 2 Forster *et al.* (2007)
121 Brovkin *et al.* (1999)

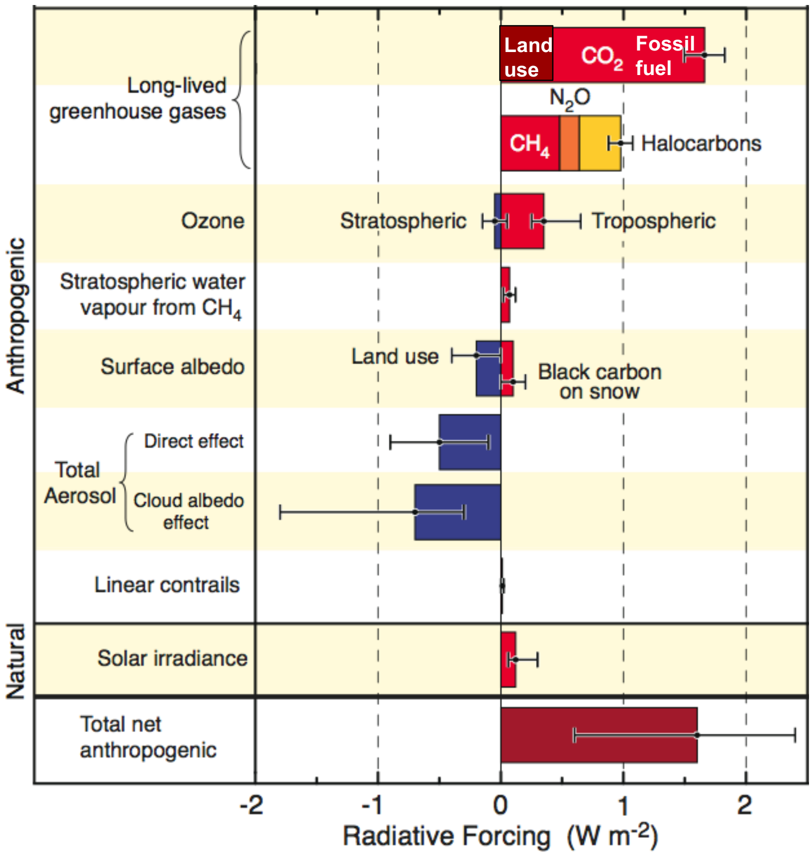


Figure 16. Comparison of global radiative forcings (RFs) of climate at the present day relative to 1750. Land use contributes to the positive RF of CO_2 increase through past CO_2 emissions from net deforestation, and also provides a negative RF through increased surface albedo. Copyright IPCC 2007

Afforestation / reforestation in temperate regions would still act to mitigate global warming overall, but the effect of sequestering CO_2 would be partly offset by the warming effect of decreased surface albedo. In some parts of the boreal forests, the warming effect of decreased surface albedo would outweigh the cooling effect of CO_2 sequestration

In more recent decades, land abandonment in Western Europe and North America is leading to reforestation which would cause a warming influence through surface albedo changes along with a cooling influence through enhanced carbon sequestration. The relative importance of carbon sequestration and albedo change due to afforestation or reforestation depends on the location, and in particular the strength of forests growth (carbon uptake) and the extent of the snow season. Model results suggest that in the temperate mid-latitudes, afforestation / reforestation would still act to mitigate global warming overall because the sequestration of carbon would still exert a greater negative radiative forcing (cooling influence) than the positive radiative forcing (warming influence) of the decreased surface albedo[122] (Figure 17). However, in the colder parts of the boreal forests, the greater extent of the snow season would mean that the contrast between the albedo of forested and un-forested land would be considerable for much of the year, and thus the annual mean surface albedo change due to afforestation/reforestation would be large (Figure 17). Meanwhile, the rate of carbon sequestration is often small in these regions due to slow rates of growth in low temperatures, so the overall radiative forcing due to afforestation/reforestation could be positive as a result of the dominance of the surface albedo decrease[122]. It is worth noting however that the snow-albedo effect will become weaker in the future as climatic warming will decrease snow season length. Climate induced soil carbon losses may also reduce or even offset projected carbon sequestration due to afforestation in the mid-latitudes[123].

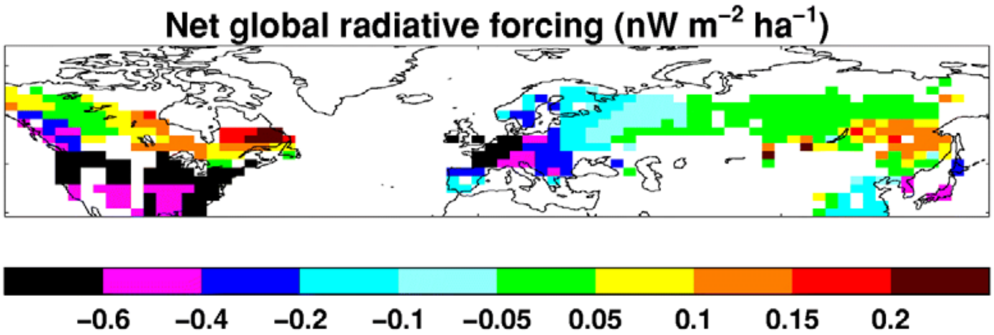


Figure 17. Net global radiative forcing per hectare of forest cover compared to an un-forested state, considering both surface albedo decreases and carbon sequestration over one harvest rotation period. Positive values indicate a net warming effect, i.e.: albedo decrease dominates. Negative values indicate a net cooling effect, i.e.: carbon sequestration and the resulting reduction in atmospheric CO_2 dominates[124].

As well as emitting CO_2, tropical deforestation exerts an additional warming effect by reducing evaporation

A large number of modelling studies have examined the climate sensitivity to total deforestation in tropical regions. There is general agreement among these studies that complete deforestation would cause a warming of surface temperature, due to a reduced level of transpiration from the deforested landscape. The smaller flux of moisture due to reduced transpiration causes a reduction in the ratio of latent to sensible heat fluxes, so the air near the surface is warmed.

Model results suggest that the combined effects of past tropical deforestation may have exerted local warmings of approximately 0.8°C relative to potential natural vegetation[125], and may have perturbed the global atmospheric circulation affecting regional climates remote from the land cover change.

[122] Betts (2000)
[123] Zaehle *et al.* (2007)
[124] Reproduced from Betts (2000)
[125] Bounoua *et al.* (2004)

Large-scale tropical deforestation could impact on regional precipitation, with complex effects but leading to decreased precipitation on average

Tropical forests influence their local rainfall regimes through their role in the water cycle and the surface energy balance (Figure 18). For example, much of the rainfall in the Amazon basin relies the repeated recycling through rainfall-transpiration cycles of water vapour transported in from the Atlantic Ocean[126], so complete deforestation may lead to an overall reduction in the recycling of moisture across the continent. Less moisture would therefore available for precipitation in the centre and west of the Amazon basin[127]. In addition, an increase in surface albedo results in a smaller heating of the surface by the net radiation balance, suppressing convection and hence causing less moisture to be drawn into the region. A reduced frictional drag exerted by the deforested landscape will also act to reduce this moisture convergence. All these mechanisms would be expected to tend to reduce precipitation. However, the influence of land surface changes on regional atmospheric circulations is complex and shifting circulation patterns may bring more precipitation into some parts of deforested regions[128] (Figure 19).

The effects of partial deforestation are particularly complex. High-resolution mesoscale models which resolve the patterns of partial deforestation suggest that the fragmentation of the forest cover may induce small-scale atmospheric circulations which can increase atmospheric ascent and therefore enhance convection. Therefore, partial deforestation may actually increase precipitation locally if the supply of moisture from advection remains unchanged. Once deforestation exceeds a particular threshold, the influence may switch to decreasing precipitation[129].

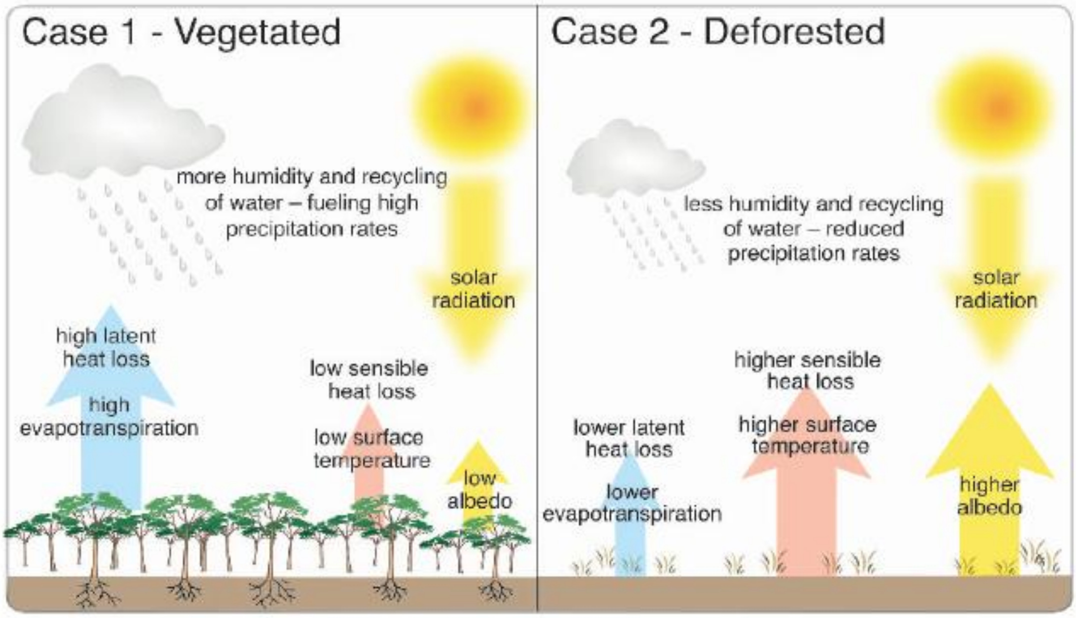


Figure 18. Comparison of water cycle and surface energy balance with and without tropical forests.[130]

[126] Salati & Vose (1984)
[127] Da Silva *et al.* (2008)
[128] Correia *et al.* (2006)
[129] Avissar & Werth (2005)
[130] Reproduced from Foley *et al.* (2003)

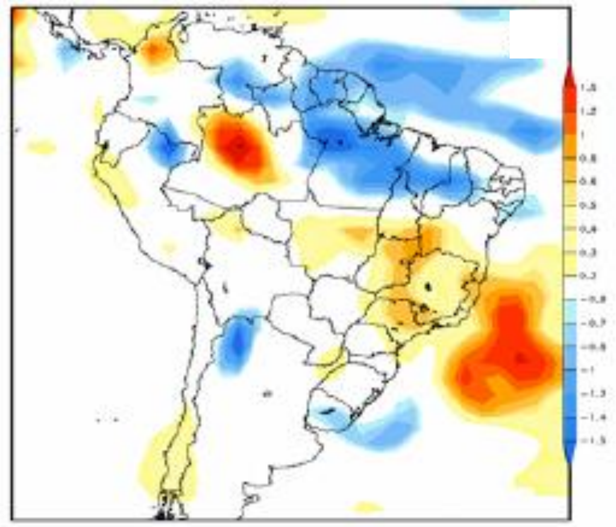


Figure 19. Changes in precipitation resulting from the Amazonian deforestation scenario of Soares et al (2006)[131]

Large-scale tropical deforestation may modify climates around the world by altering the atmospheric circulation

Large-scale deforestation in the tropics may also exert more far-reaching effects, with changes in the near-surface energy balance modifying the large cells of ascending and descending motion near the equator. Changes to these may cause shifts in the atmospheric circulation which propagate across the globe. Climate model simulations suggest that complete deforestation of Amazonia could lead to increased precipitation in Europe through this mechanism[132].

Feedbacks from the oceans may enhance the effects of land cover change on climate, particular in the less continental forests of SE Asia. For example, a climate model study[133] suggested that in the Indonesian Archipelago, the impacts of deforestation on wind speeds may be sufficient to modify ocean up-welling and cause warming over the surrounding ocean surfaces, in addition to the warming caused over land by reduced evaporation. This amplified warming may impact global-scale atmospheric circulations.

At the global scale, most historical deforestation has taken place in mid-latitudes so the overall biophysical effect has been a cooling through increased surface albedo. However, since most future deforestation is projected to take place in the tropics, biophysical effects would add a further warming to that expected from CO_2 emissions

Since the dominant historical land cover change has been deforestation in mid-latitudes, the overall effect on global annual mean temperature is likely to have been an overall cooling due to increased surface albedo in winter and spring. Estimates of

[131] Correia *et al*. (2006)
[132] Gedney & Valdes (2000)
[133] Delire *et al.* (2001)

global temperature responses from past deforestation vary from 0.01 K to –0.25 K[134], with a greater consensus on the cooling, which means that the warming effects of CO_2 rise may have been partly slowed by the changing land surface character. However, since the mid-latitudes trend is now towards reforestation and tropical deforestation is becoming increasingly significant at the global scale, both these trends would be expected to exert a further warming in addition to that arising from increasing CO_2 concentrations. Some climate model simulations including land cover changes from the SRES scenarios suggest that both mid-latitude reforestation and tropical deforestation would lead to local warming effects[135] , with local warming of approximately 2°C due to tropical deforestation in addition to any warming expected from increased CO_2 concentrations. Models including land cover change in response to climate change similarly suggest a further local warming due to forest loss[136]. A small number of models suggest that the landscape change due to tropical deforestation would still exert a cooling[137], but the majority of studies examining large-scale tropical forest loss suggest a warming. It should be noted that most climate model simulations assessed in the IPCC 4th Assessment Report do not include the landscape effects of land cover change; only one model (HadGEM1[138]) included these effects.

Tropical deforestation could also affect climate through aerosol emissions

The process of deforestation usually involves burning of large areas of forest, which releases soot aerosol to the atmosphere. This can exert a positive radiative forcing (warming influence) by absorbing solar radiation. If deforestation occurred in regions which were also drying due to climate change, the resulting increased exposure of the soil surface in dry and windy conditions could lead to the deforested regions becoming new sources of dust emission to the atmosphere[139]. The overall effects of this on the climate would be complex[140] and have not yet been investigated in depth.

[134] IPCC AR4 WG1 Chp 2 Forster *et al.* (2007)
[135] DeFries *et al.* (2002); Feddema *et al.* (2005)
[136] Cox *et al.* (2004)
[137] Brovkin *et al.* (1999); Bala *et al.* (2007)
[138] See Stott *et al.* (2006)
[139] Betts *et al.* (2008)
[140] Woodward *et al.* (2005)

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