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Global Warming: How Much of a Threat to Tropical Forests?

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Abstract

Tropical forests are a key part of debates on climate change science and policy because of the prospect of large areas of Amazonian forest not surviving projected climate changes under "business as usual" scenarios, the substantial contributions that deforestation and other landscape modifications make to climate change, and the potential role of efforts to counter deforestation as part of a strategy to mitigate climate change in the coming decades. Because half of the dry weight of the trees in a tropical forest is carbon, either deforestation or forest die-off releases this carbon in the form of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4), whether the trees are burned or simply left to rot.

Tropical forests are vulnerable to projected changes in precipitation and temperature. These changes could therefore threaten the biodiversity of these forests and the traditional peoples and others who depend upon the forests for their livelihoods. Also threatened are the environmental services supplied by the forests to locations both near and far from the forests themselves. Greenhouse-gas emissions provoked by forest die-off due to climate change are part of a potential positive feedback relationship leading to more warming and more die-off. The Amazon forest is a focus of concern both because of the particularly severe impacts of climate changes predicted for this area and because the vast extent of this forest gives it a significant role in either intensifying or mitigating future climate change (see: http://philip.inpa.gov.br).

CLIMATE-FOREST INTERACTION IN AMAZONIA

SCENARIOS

Modeled scenarios for future climate in tropical forest areas vary widely, creating corresponding uncertainty regarding both the impacts of climate change and the climatic benefits of keeping the forests standing. However, the wide range of possible outcomes can easily be misleading from a policy perspective for three reasons. First, the range of things that have ever been written or said about these predictions is always much wider than the true range of scientific doubt: studies become obsolete and their predictions of the future are discarded (even by the studies' own authors), yet the ghost of these results can continue to haunt not only popular but also scientific discussion of the topic for years or decades (see Fearnside, 2000a for examples in the case of impacts of Brazilian deforestation). Second, there is a strong tendency to fall victim to the "Goldilocks fallacy," where, when presented with a range of numbers, one naturally assumes that one in the middle will be "just right"; such an assumption is fallacious because it is the quality of the data and of the reasoning used to interpret the data that will determine which of various possible results is the best, and this may well be at either the high or the low end of a range of available estimates (see Fearnside and Laurance, 2004). Third, the existence of uncertainty commonly provokes the response of "let's wait and see what the experts decide," when this uncertainty should instead lead to even more vigorous action based on the precautionary principle (*e.g.*, Schneider, 2004). At any moment in time, there is always one best value for each parameter in each calculation (together with an associated range of uncertainty), and we must act on the current information. Decisions must be based both the current best value and an allowance for avoiding risks of major impacts from the high ends of the uncertainty ranges.

The case of predicted climate change and their impacts on Amazonian forest is a highly relevant example. In 2000, the Hadley Center model of the UK Meteorological office (UKMO) was updated to include various feedbacks that made it predict a catastrophic dieoff of Amazonian forest by the year 2080 under a business-as-usual scenario (Cox *et al*., 2000). Other global climate models, which lacked the same feedbacks, did not indicate any such catastrophe (see review by Nobre, 2001). Over the next five years, testing of the various models proceeded at Brazil's Center for Research in Weather and Climate (CPTEC). In November 2005 the conclusion was reached that the Hadley Center's Had3CM model provided the best fit to the current climate in Amazonia, lending strong support to this most catastrophic scenario as the most likely (J. Marengo, public statement, 2005).

Global climate models contain substantially more uncertainty in their predictions of changes in rainfall than for temperature. For Amazonia, the key question is the establishment or not of a permanent El Niño. The disastrous consequences that severe El Niño conditions imply for tropical rainforests are evident from the observed effects of the 1982-1983 El Niño, which produced widespread fires in standing forest in Brazil and Indonesia (Malingreau *et al*., 1985), and these events were repeated on an even larger scale in the same countries during the 1997-1998 El Niño (Barbosa and Fearnside, 1999; Fuller and Murphy, 2006).

The first model to show a massive die-off of Amazonian forest as a result of predicted global warming was the Hadley Center model of the UK Meteorological Office (Cox *et al*., 2000, 2004). Under a business-as-usual scenario, the forest is essentially wiped out by the year 2080 (and replaced by a savanna). In 2005, most of the global climate models were revised to include feedbacks that had previously been restricted to the Hadley model, with the result that five out of seven models now show the climate locking into permanent "El Niño-like conditions", meaning that surface water in the Pacific Ocean warms to levels characteristic of El Niño events today. However, only one model (the Hadley model) replicates the connection between these "El Niño-like conditions" and the actual consequences of an El Niño with reduced rainfall and increased temperature in Amazonia. Unfortunately, the connection between El Niño and Amazonian droughts is something that we know from direct observations, not something that depends on the results of computer models. In other words, when other models show the water in the Pacific warming and nothing happening in Amazonia, this indicates that there is something wrong with those models, not that Amazonia is less at risk.

If a high climate sensitivity is assumed, the Hadley Center model indicates Amazonia as expecting an increase in average temperature of 14^{o}C, far the greatest increase of any locality on the planet (Stainforth *et al*., 2005, p. 405). This calculation assumed the equilibrium concentration of CO_2 double the pre-industrial level, a mark that should be reached in approximately 2070 if there is no mitigation of the greenhouse effect. The increase in global mean temperature over pre-industrial levels at this CO_2 concentration is what defines "climate sensitivity." Projected temperature increases by 2100 are approximately 40% higher than the corresponding value for climate sensitivity (*i.e*. 3.5°C as a "most likely" value in 2100 versus 2.5°C for climate sensitivity).

A recent piece of good news is that an analysis of indicators of past climatic changes reduced the estimates for the probability of the true value of climate sensitivity being at the extreme high end of the range of possible values, the point that corresponds to a 95% margin of safety decreasing from 9.7 to 6.2°C (Hegerl *et al*., 2006). Proportionally, the 14°C increase in Amazonia in approximately 2070 under high climate sensitivity would fall to an increase of 8.3°C, which would still be a catastrophe that threatens both the forest and the human population in the area.

The temperatures indicated by Stainforth *et al*. (2005, p. 405) are now out-of-date as representations of the situation under high climate sensitivity in approximately 2070 (the time of doubled pre-industrial CO_2). The revised probability density function for climate sensitivity makes the Stainforth *et al*. (2005) temperatures a close match for what would be expected under high climate sensitivity in 2100. Assuming proportionality, under high climate sensitivity the global mean temperature in 2100 would be 8.7°C above pre-industrial levels and the mean in Amazonia would be 14.7°C above the same baseline.

Establishment of a permanent El Niño would lead to the Amazon forest being killed by the joint effect of increased temperature and decreased rainfall in Amazonia (*e.g*., Betts *et al*., 2004). If a high climate sensitivity is assumed, the Hadley Center model indicates Amazonia as expecting by far the greatest temperature increase of any locality on the planet (Stainforth *et al*., 2005, p. 405). In addition, when programmed with a model similar to that of the Hadley Center, the same result is shown by the Earth Simulator, including peak temperatures exceeding 50^{o}C in Amazonia after 2050. The Earth Simulator is a gigantic array of interconnected computers in Yokohama, Japan that simulates global climate on a scale of 10 km, whereas normal climate models simulate the earth on scales of several hundred kilometers.

Large carbon stocks would be lost if the “permanent El Niño” is allowed to form (Huntingford *et al*., 2004). Fortunately, this catastrophic outcome only applies to a business-as-usual scenario, and restricting emissions to keep atmospheric CO_2 concentrations from rising much above their current levels would avert this disaster (Arnell *et al*., 2002). Reducing emissions globally will require using every existing mitigation option, among which reducing tropical deforestation is one of the most cost effective (Fearnside, 2001, 2003, 2006; Fearnside and Barbosa, 2003; Moutinho and Schwartzman, 2005; Santilli *et al*., 2005).

SYNERGISMS

Climate change is linked through synergisms to other processes that threaten tropical forests. Forest fires have become a major threat to forests both in Amazonia and in Southeast Asia. These forests are not adapted to fire, and the thin bark of the trees make them more susceptible to mortality when fires do occur than is the case for trees such as those in savannas or coniferous forests. In Amazonia, fire entering surrounding forest from burning in agricultural clearings or in cattle pastures was practically unknown to most Amazonian residents prior to the 1982/1983 El Niño event. Nevertheless, severe El Niños in the past had resulted in forest burning as in the “big smoke” of 1926 (Sternberg, 1968) and in four “mega-

El Niño" events over the last 2000 years when forest left charcoal in the soil (Meggers, 1994). But the 1982/1983 El Niño was a change, with substantial areas burning both in Amazonia and in Indonesia (Malingreau *et al*., 1985). The frequency of El Niño is significantly higher since 1976 than it was prior to that year (Nicholls *et al*., 1996, p. 165). Some evidence exists that the explanation for this change in frequency is due to global warming (Timmerman *et al*., 1999, Trenberth and Hoar, 1997), although the Intergovernmental Panel on Climate Change (IPCC) has not yet arrived at a concensus over the existence of such a connection. The "official" status of IPCC recognition of a causal connection between global warming and El Niño would have major policy implications, because El Niños have unambiguous and devastating consequences today, as opposed to predicted consequences at some future time. The 1982-1983 El Niño killed over 200,000 people in Ethiopia and neighboring countries. El Niño impacts include both human mortality in droughts and floods and the environmental losses of forest fires such as those in Roraima (in northern Brazil) and in Kalimantan (Indonesia) in 1997-1998 (Barbosa and Fearnside, 1999; Barber and Schweithelm, 2000). Establishment of a "permanent El Niño" is the critical event in the Hadley Center model simulations that leads to reduced rainfall and greatly increased temperature in Amazonia after 2050 (Cox *et al*., 2000, 2004).

Flammability of Amazonian forest is expected to increase under various climatic scenarios (Cardoso *et al*., 2003). Current El Niño conditions already result in wide areas of the region becoming susceptible to fire (Alencar *et al*., 2004; Nepstad *et al*., 1999, 2004). The logical result of reducing rainfall and increasing temperature is to dry out the litter on the forest floor that serves as fuel for forest fires. Tree mortality increases the amount of litter available to burn, forming a positive feedback loop with fire occurrence (Cochrane, 2003; Cochrane *et al*., 1999). In addition, loss of forest both through deforestation and through dieback from climate change would lead to reduced evapotranspiration in the region, thereby cutting off part of the supply of water vapor needed to maintain large amounts of rainfall in the region—forming another positive feedback relationship leading to forest degradation and loss (Fearnside, 1995).

FEEDBACKS

A positive feedback relationship exists between biomass carbon and global warming. Carbon in the biomass of standing Amazonian forests is released to the atmosphere during El Niño events (*e.g*., Rice *et al*., 2004; Tian *et al*., 1998). These forests can subsequently reabsorb the carbon during La Niña and "normal" years, but the observed shift towards more frequent El Niños, together with the prediction of a permanent El Niño after the middle of the current century, suggest that carbon stocks will be steadly drawn down in the remaining forest. Forest degradation takes place under experimentally induced dry conditions in Amazonian forest that mimic conditions after the rainfall reductions foreseen by models such as that of the Hadley Center (Nepstad *et al*., 2002). In these plots, where plastic sheeting intercepts 60% of the throughfall in the forest over an entire hectare as part of the Large-Scale Atmosphere Biosphere Project (LBA), large trees are the first to die, thus greatly increasing the release of carbon (Tohver *et al*., 2006). Mortality in trees > 30 cm diameter at breast height (DBH) was 9.47%/year in the dry plot, as compared to 1.74%/year in the wet (control) plot. The same occurs at forest edges, where microclimatic conditions are hotter and drier than in the interior of a continuous forest (Nascimento and Laurance, 2004;

Laurance *et al.*, 1997). The carbon released from such events would increase global warming and its effect on the "permanent El Niño", thereby driving further carbon releases from Amazonian forest (*e.g.*, Cox *et al.*, 2000, 2004).

Drying and tree mortality in Amazonian forest are part of another very dangerous positive feedback relationship, this one between climate change and fire. Both reduced rainfall and higher temperatures would increase the flammability of Amazonian forest (Nepstad *et al.*, 2004), leading to more forest fires in standing forest and greater emissions of greenhouse gases. Forest flammability is further increased by an interaction with logging, which greatly increases the risk of fire by its opening the canopy and by the logging operations killing many trees in addition to those that are harvested (Cochrane, 2003; Cochrane *et al.*, 1999; Nepstad *et al.*, 2001). The disastrous potential of fires under a "permanent El Niño" is illustrated by the fires that occurred during recent El Niño events. The Great Roraima Fire of 1997-1998 burned 11.4 – 13.9 X 10^3 km^2 of forest, releasing 17.7 – 18.0 X 10^6 t CO_2-equivalent C by combustion alone (Barbosa and Fearnside, 1999).

Unfortunately, fire risk is virtually never included in forest management plans, which invariably calculate sustainability under the simple assumption that the areas will never burn. Logging is rapidly spreading to formerly inaccessible areas of the forest. Forest management is foreseen as the use to which large areas of forest will be allocated outside of fully protected parks and reserves. Fire risk will increase both in the large areas subject to illegal logging, in legally managed areas on private land and in new areas of public land to be opened for forest management in accord with law enacted in January 2006 allowing 40-year concessions in up to 13 million hectares of "public forests."

An early model indicating the possibility of substantial loss of soil carbon in Amazonia was developed by Townsend *et al.* (1992). The temperature and vegetation changes foreseen by the Hadley Center model (Cox *et al.*, 2000, 2004) are much more severe than those assumed by Townsend *et al.* (1992). A series of simulations using the Hadley Center models and simpler models that represent the behavior of the Hadley Center models with several adjustments to best to represent the observed current values of important parameters, all indicate a dramatic loss of soil carbon (Huntingford *et al.*, 2004). By 2080 approximately two-thirds of the soil carbon is lost; although the authors do not indicate to what depth in the soil this result applies, it appears to represent the top 30 cm. The carbon stock in this layer drops from 60 to approximately 40 tC/ha over the 2000-2080 period, which corresponds to a loss of approximately 20 GtC over the period, or an average of 250 million tC/year.

Soil carbon is not limited to the top 30 cm, and what becomes of carbon stocks at deeper levels could have substantial consequences. Carbon stocks in soil under Amazonian forest average 42.0 tC/ha for 0-20 cm depth, 52.0 tC/ha for 20-100 cm and 142.8 tC/ha for 100-800 cm (Fearnside and Barbosa, 1998). The large carbon stocks in the deep soil undergo an appreciable turnover under present conditions (Trumbore *et al.*, 1995). Conditions altered by climate change could therefore turn these carbons stocks into a veritable timebomb. One factor that would decrease the speed of soil-carbon release in the tropics as compared to releases at higher latitudes is the discovery that carbon in highly weathered tropical soils is less sensitive to release from a given temperature increase than is carbon in many temperate and boreal soils (Davidson and Janssens, 2006).

The future role of soil carbon under global warming has recently become a worldwide concern with the publication of results from a detailed monitoring program in England and Wales (Bellamy *et al*., 2005). This longitudinal study over the 1978-2003 period with four samplings at each of 2179 sampling locations indicated significant loss of soil carbon under both agriculture and undisturbed natural vegetation. This represents a potential positive feedback loop – a "runaway greenhouse effect" that could escape from human control. The more carbon that is released by the soil, the greater the temperature increase from global warming, leading to still more release of soil carbon. Unlike emissions from fossil fuels and deforestation, humans do not have the option of solving the problem by diminishing their own emission, since the magnitude of the soil emission potentially exceeds the fossil fuel emissions of the human population. The study in Britain raises the possibility that we may already have entered into the territory of the "runaway greenhouse," but data from other parts of the world, such as Amazonia, are lacking to either confirm or contradict this. If the 2 trillion tons of carbon in the Earth's soils were being released at the 0.6%/year average rate detected in Britain, the annual emission from this source today would be 12 GtC/year, or 50% more than the approximately 8 GtC/year emission today from fossil-fuel combustion and cement manufacture. Even deforestation, for which global estimates vary from 1.6 GtC/year for 1980-1989 (Schimel *et al*., 1996, p. 79; see review in Fearnside, 2000a) to 2.4 GtC/year for 1990 (Fearnside, 2000b), would not bring the anthropogenic total to this level, meaning that even complete elimination of anthropogenic emissions might be insufficient to avert a runaway greenhouse. This points to both the need for intensified research to quantify soil emissions under different climatic scenarios, and to take immediate action on a scale much larger than that agreed so far under the Kyoto Protocol in order to halt, or even reverse, global warming before damage worsens and escapes from control. The visible damage to Amazonian forests from the 2005 drought brought home to many the ease with which such large-scale processes can escape from human control.

TROPICAL FORESTS AND "DANGEROUS" CLIMATE CHANGE

The United Nations Framework Convention on Climate Change (UN-FCCC), signed by 155 countries at the 1992 "Earth Summit" in Rio de Janeiro, specifies its purpose as stabilizing the atmospheric concentrations of greenhouse gases at levels that avoid "dangerous" interference with the climate system (UN-FCCC, 1992). However, what is "dangerous" is not defined by the UN-FCCC (Article 2), and negotiations to define such a level got off to at least a symbolic start in December 2005. In an illustration with a maximum temperature increase of 2.85 ^{o}C as the median value considered "dangerous," available "conventional" climate-policy controls have been shown to be capable of significantly reducing the probability of reaching this level and incurring its consequences within the current century (Mastrandrea and Schneider, 2004). A wider range of mitigation options would need to be tapped if a lower value for maximum temperature rise (such as 2^{o}C) is adopted as the definition of "dangerous."

The first version of the Hadley Center model indicated that stabilizing atmospheric CO_2 concentration at 750 ppmv would stave off the demise of Amazonian forest (which dominates global vegetation dieback) by approximately 100 years beyond the 2080 crash indicated by simulations without mitigation, while limiting the concentration to 550 ppmv would postpone the disaster by over 200 years (Arnell *et al.*, 2002). Limiting the rise in average global temperature to $2^{o}C$ would be necessary to avoid substantial forest degradation in Amazonia and consequent carbon releases (Huntingford *et al*., 2004). A global average temperature rise of $2^{o}C$ is close to the amount of temperature increase that has been set in motion by emissions that have already occurred (Hare and Meinshausen, 2006). In March 2005 the European Union heads of government adopted $2^{o}C$ as their goal for maximum amount by which global mean temperatures should be allowed to rise above pre-industrial levels. This would require holding the atmospheric concentrations of greenhouse gases to the equivalent of 400 ppmv of CO_2, or, as an alternative to faciliate negotiating such a definition of "dangerous" climate change, by allowing the concentration to overshoot this limit and rise to 420 ppmv, after which the concentration would be reduced to the 400 ppmv limit (Hare and Meinshausen, 2006). A 400 ppmv limit implies a risk of 2-57% (mean = 27%) that the $2^{o}C$ would be overshot; at 350 ppmv this risk would be reduced to 0-31% (mean = 8%) (Hare and Meinshausen, 2006). The concentration of CO_2 passed the 380 ppmv mark in 2006, but the equivalent of appoximately 40 ppmv of CO_2 from the atmospheric loads of CH_4 and N_2O mean that we have already entered into the age of "dangerous" climate change as defined by a $2^{o}C$ ceiling on temperature increase.

The vulnerability of tropical forests to climate change is evident from indications of biomass loss in standing forest from the changes in climate that have already occurred (Fearnside, 2004), combined with the modest amount of change so far relative to what is projected for the next century in a "business-as-usual" world. Global mean temperatures have so far increased by only $0.8^{o}C$ (Hansen *et al*., 2006).

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