Fearnside, P.M. 2003. Climate change impacts in tropical forest: Unfinished controversies over detection and attribution. pp. 48-51 In: C. Rosensweig, O. Canziani, M. Parry, M. Harrison and P. van de Linden (eds.). *IPCC Workshop on the Detection and Attribution of the Effects of Climate Change, Goddard Institute for Space. Studies, New York, USA, 17-19 June, 2003*. Intergovernmental Panel on Climate Change (IPCC) Working Group II Technical Support Unit, UK Meteorological Office, Exeter, UK. 81 pp

Climate Change Impacts in Tropical Forest: Unfinished Controversies Over Detection and Attribution

Philip M. Fearnside[1]

The impact of the current level of climate change on tropical forests is a matter of considerable controversy, with estimates ranging from massive uptakes to massive emissions of carbon by standing tropical forest. The amount of monitoring data, although much greater than what was available only a few years ago, is still inadequate to resolve some of the controversies. Other parts are a matter of interpretation of the data at hand. Of course, not all interpretations, and not all data sets, are equal in terms of their consistency.

Early eddy flux correlation studies from towers in Brazilian Amazonia indicated substantial (> 5 Mg C ha^{-1} yr^{-1}) uptakes of carbon by the forest (Grace *et al.*, 1995). However, additional towers and subsequent refinements of the method indicate much lower rates of uptake: 1-2 Mg C ha^{-1} yr^{-1}, according to ongoing research by the Large-Scale Biosphere-Atmosphere (LBA) project (Pesquisa FAPESP, 2003). An important reason for high estimates from measurements using towers is believed to be lateral movement of CO_2 at night: carbon flux into the forest as photosynthesis proceeds during the day was fully captured by the sensors at the top of towers that project above the canopy, but at night much of the CO_2 released by respiration concentrates near the forest floor and flows downhill in a sort of "river" of gas, thus escaping measurement, making net flux calculated by difference of inflow and outflow at the top of the tower misleading. Towers in different locations show substantial differences, some of which can be explained by topography and drainage and other factors, and some of which remain unexplained. Uptake has been presumed to be the result of response to CO_2 enrichment.

Corroborating information is inconsistent, as is the interpretation of the information. Biomass changes as measured in monitored plots has generated controversy. An analysis of existing data sets by Phillips *et al.* (1998) indicated uptake over recent decades, especially in Amazonia. However, the largest and longest-running series of monitored plots, with 36 ha of plots located ≥ 100 m from a forest edge, showed no change in biomass at all over the 1980-1997 period (Laurance *et al*., 1997). The conclusion by Phillips *et al*. (1998) that plots were showing net gains in biomass was largely based on significantly higher frequency of plots showing gains rather than losses; however, this is the pattern that would also be expected in small plots were the forest in complete equilibrium, since large trees occasionally fall and die, causing large declines in a few plots, while most plots will show gradual growth by the remaining trees instead (Fearnside, 2000). The Phillips *et al*. (1998) study has also been questioned on the basis of possible bias from inclusion of tree girth measurements that include buttress growth (Clark, 2002; Clark and Clark, 2000; Clark *et al*., 2001; see also reply by Phillips *et al*., 2002).

The recent discovery of large emissions of CO_2 from water in the Amazon River (Richey *et al*., 2002) has been suggested as an explanation of the inconsistency between the tower measurements indicating carbon uptake by the forest while plot measurements indicate little or none. Carbon could be taken up by the forest but, instead of being stored as wood in the trees it would be released into the soil where it would travel through groundwater as dissolved organic carbon, later to be oxidized to CO_2 after reaching the streams and rivers. The problem with this explanation is that the CO_2 flux from the water only accounts for one side of the carbon balance for the aquatic ecosystem; estimates of the input of carbon to the water from fixation by macrophytes and phytoplankton need to be included before conclusions can be drawn. Recent measurements of

[1] National Institute for Research in the Amazon, Amazonas, BRAZIL

net primary production of flooded canarana meadows in the *várzea* (Amazonian floodplain) indicate massive fixation of carbon in these ecosystems (M.T. Piedade *et al*., unpublished).

The effects of climate changes on standing tropical forests have been indicated for both substantial uptake of carbon and substantial losses. Increasing temperature is expected to lead to carbon loss; when extrapolated to future climate scenarios, these losses become catastrophic: the Hadley Center's HadCM3 model (Cox *et al*., 2000) indicates climate change decimating Amazonian forests by 2080, as does the earlier HadCM2 version (Arnell *et al*., 2002) while slightly less dieback is shown by a subsequent version of the model: HadCM3LC (Cox *et al*., 2003). It should be emphasized that the same climate changes, on a more modest scale, are already occurring. Of particular importance is the increased frequency of El Niño events already observed (Nicholls *et al*., 1996: 165), which would be especially important as an anthropogenic climate change impact if a causal relationship with global warming is accepted (*e.g*., Timmermann *et al*., 1999; Trenberth and Hoar, 1997). Modeling results in Amazonia indicate droughts during El Niño events lead to net releases of carbon during these periods, while forests absorb carbon in non-El Niño years (Tian *et al*., 1998); releases during the 2002-2003 El Niño have been documented by LBA tower measurements near Santarém (Pesquisa FAPESP, 2003).

The importance of temperature is indicated by results from the La Selva research station in Costa Rica, an area without significant limitation from moisture stress. Clark *et al*. (2003) found that night-time temperatures are critical at La Selva: in hot years, trees grow less and the forest emits CO_2. The emissions correlate with atmospheric measurements of CO_2 concentrations. The amounts emitted are substantial; if extrapolated to all tropical forests, annual emissions are as high as 6.7 Pg C in El Niño years.

Other results appear to be inconsistent with this. Modeling results by Nemani *et al*. (2003) indicate large uptakes of carbon in most tropical forest areas (including Costa Rica) during the same time period that Clark *et al*. (2003) found a large release. These models consider the critical factor to be irradiation in tropical forest area: warming results in greater cloud cover, producing diffuse light that increases photosynthesis. However, Clark *et al*. (2003) found no response of the forest to changes in irradiation in Costa Rica, with fluctuations of up to 35% between years during the period of observation. The study (Clark *et al*., 2003) is based on a meticulous long-term data set (the only one with annual measurements) and an "intimate knowledge of trees" (Kaiser, 2003).

The Hadley Center results contain assumptions that both exaggerate and understate the impacts of climate change on tropical forests, whether present or future. On the side of exaggeration, trees in Amazonian forests have very deep roots (*e.g*., Nepstad *et al*., 1994), giving them more resistance to drought than the simulated trees (P. Cox, pers. comm., 2002). On the side of understatement, the predictions of substantial dieback of Amazonian forest (Cox *et al*., 2000, 2003) are based on the effects of climate change alone, without the interactions with direct human-induced changes such as logging, forest fragmentation and edge formation through the expansion of deforestation, and the increasing number of ignition sources and prevalence of ground fires in the forest.

Logging greatly increases the flammability of forest and the consequent probability of ground fires by opening the canopy and leaving large amounts of dead wood to serve as fuel (Cochrane and Schulze, 1999). Ground fires, especially in El Niño years, have affected large areas of forest, which then become more susceptible to subsequent fires, which are hotter and more destructive than the first fire (Barbosa and Fearnside, 1999; Cochrane, 2003; Cochrane *et al*., 1999; Nepstad *et al*., 1999, 2001). Fragmentation and edge formation cause similar increases in large-tree mortality, increasing the flammability of the forest (Nascimento and Laurance, 2003). Road building over the past decades, and expected increases in roads and other infrastructure for which plans have been announced, imply great increases in all of these risk factors (Laurance *et al*., 2001; Nepstad *et al*., 2000). Climate changes included in the Hadley model, such as increased temperature and increased frequency of droughts, would have much greater impact on the forest under these altered conditions. It should be emphasized that these changes apply not only to future projections, but also to the present and to the last two decades.

In summary, controversies concerning the impact of present climate change on tropical forests remain unfinished. The possibility of substantial impacts that damage the forest and introduce positive feedback effects into the climate system are sufficiently large that these impacts should be an important consideration in defining policies that affect both land-use change and global greenhouse gas emissions. The need for more research is obvious, but policy changes should not be held hostage to the results of further research.

ACKNOWLEDGMENTS

I thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for support (Proc. 470765/2001-1).

References

Arnell, N.W., M.G.R. Cannell, M. Hulme, R.S. Kovats, J.F.B. Mitchell, R.J. Nichols, M.L. Parry, M.T.J. Livermore and A. White. 2002. The consequences of CO_2 stabilisation for the impacts of climate change. *Climatic Change* 53(4): 413-446.

Barbosa, R.I. and P.M. Fearnside. 1999. Incêndios na Amazônia brasileira: Estimativa da emissão de gases do efeito estufa pela queima de diferentes ecossistemas de Roraima na passagem do evento "El Niño" (1997/98). *Acta Amazonica* 29(4): 513-534.

Clark, D.A. 2002. Are tropical forests an important carbon sink? Reanalysis of the long-term plot data. *Ecological Applications* 12: 3–7**.**

Clark, D.A. and D.B. Clark. 2000. Landscape-scale variation in forest structure and biomass in a tropical rain forest. *Forest Ecology and Management* 137: 185-198.

Clark, D.A., S. Brown, D. Kicklighter, J.Q. Chambers, J.R. Tomlinson, J. Ni, and E.A. Holland. 2001. Net primary production in tropical forests: an evaluation and
synthesis of existing field data. *Ecological Applications* 11: 371-384.

Clark, D.A., S.C. Piper, C.D. Keeling and D.B. Clark. 2003. Tropical rain forest tree growth and atmospheric carbon dynamics linked to interannual temperature variation during 1984-2000. *Proceedings of the National Academy of Sciences* 100: 5852-5857.

Cochrane, M.A. 2003. Fire science for rainforests. *Nature* 421: 913-919.

Cochrane, M.A., A.A. Alencar, M.D. Schulze, C.M. Souza, D.C. Nepstad, P. Lefebvre and E.A. Davidson. 1999. Positive feedbacks in the fire dynamic of closed canopy tropical forests. *Science* 284: 1832-1835.

Cochrane, M.A. and M.D. Schulze. 1999. Fire as a recurrent event in tropical forests of the eastern Amazon: Effects on forest structure, biomass, and species composition. *Biotropica* 31(1): 2-16.

Cox, P.M., R.A. Betts, M. Collins, P. Harris, C. Huntingford and C.D. Jones. 2003. Amazonian dieback under climate-carbon cycle projections for the 21st century. Hadley Center Technical Note No. 42, Hadley Centre, Wallingford, U.K.. 29 pp. (http://www.meto.gov.uk/research/hadleycentre/pubs/HCTN/HCTN_42.pdf).

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* 408: 184-187.

Fearnside, P.M. 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change* 46 (1/2): 115-158.

Grace, J., J. Lloyd, J. McIntyre, A.C. Miranda, P. Meir, H.S. Miranda, C. Nobre, J. Moncrieff, J. Massheder, Y. Malhi, I. Wright and J. Gash. 1995. Carbon Dioxide Uptake by an Undisturbed Tropical Rain Forest in Southwest Amazonia, 1992 to 1993. *Science* 270: 778-780.

Kaiser, J. 2003. An intimate knowledge of trees. *Science* 300: 566-567.

Laurance, W.F., M.A. Cochrane, S. Bergen, P.M. Fearnside, P. Delamônica, C. Barber, S. D'Angelo and T. Fernandes. 2001. The Future of the Brazilian Amazon. *Science* 291: 438-439.

Laurance, W.F., S.G Laurance,. L.V. Ferreira., J.M. Rankin-de-Merona, C. Gascon and T.E. Lovejoy. 1997. Biomass collapse in Amazonian forest fragments. *Science* 278: 1117-1118.

Nascimento, H.E.M. and W.F. Laurance. 2003. Biomass dynamics in Amazonian Forest fragments. *Ecological Applications* (in press).

Nemani, R.R., C.D. Keeling, H. Hashimoto, W.M. Jolly, S.C. Piper, C.J. Tucker, R.B. Myneni, S.W. Running. 2003. Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. *Science* 300: 1560-1563.

Nepstad, D.C., J.P. Capobianco, A.C. Barros, G. Carvalho, P. Moutinho, U. Lopes and P. Lefebvre. 2000. Avança Brasil: Os Custos Ambientais para Amazônia. Instituto de Pesquisa Ambiental da Amazônia (IPAM), Belém, Pará, Brazil. 24 pp. (http://www.ipam.org.br/avanca/politicas.htm).

Nepstad, D.C., C.R. Carvalho, E.A. Davidson, P.H. Jipp, P.A. Lefebvre, G.H. Negreiros, E.D. Silva, T.A. Stone, S.E. Trumbore and S. Vieira. 1994. The role of deep roots in the hydrological cycles of Amazonian forests and pastures. *Nature* 372: 666-669.

Nepstad, D.C., G. Carvalho, A.C. Barros, A. Alencar, J.P. Capobianco, J. Bishop, P. Moutinho, P. Lefebvre ,U.L. Silva Jr. and E. Prins. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecology and Management* 154(3): 395-407.

Nepstad, D.C., A.Veríssimo, A.A. Alencar, C.A. Nobre, E. Lima, P. Lefebvre, P. Schlesinger, C. Potter, P. Moutinho, E. Mendoza,. M. Cochrane and V. Brooks. 1999. Large-scale impoverishment of Amazonian forests by logging and fire. *Nature* 398: 505-508.

Nicholls, N. and 98 others. 1996. Observed climate variability and change. pp. 133-192 In: J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.). *Climate Change 1995: The Science of Climate Change*. Cambridge University Press, Cambridge, U.K. 572 pp.

Pesquisa FAPESP. 2003. Fluxo invertido: Após sucessivos ocorrências do El Niño nos anos 90, a Floresta Nacional do Tapajós libera mais gás carbônico do que absorve. *Pesquisa FAPESP*, No. 88: 50-51.

Phillips, O.L., Y. Malhi, N. Higuchi, W.F. Laurance, P.V. Núñez, R.M. Vásquez, S.G. Laurance, L.V. Ferreira, M. Stern, S. Brown and J. Grace. 1998. Changes in the carbon balance of tropical forests: Evidence from long-term plots. *Science* 282: 439-442.

Phillips, O.L., Y. Malhi, B. Vinceti, T. Baker, S.L. Lewis, N. Higuchi, W.F. Laurance, P. Núñez Vargas, R. Vásquez Martinez, S. Laurance, L.V. Ferreira, M. Stern, S. Brown and J. Grace. 2002. Changes in growth of tropical forests: evaluating potential biases. *Ecological Applications* 12(2): 576–587.

Richey, J.E., J. Melack, A. Aufdenkampe, V. Ballester and L. Hess. 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2. *Nature* 486: 617-620.

Tian, H., J.M. Mellilo, D.W. Kicklighter, A.D. McGuire, J.V.K. Helfrich III, B. Moore III and C. Vörösmarty. 1998. Effect of interanual climate variability on carbon storage in Amazonian ecosystems. *Nature* 396: 664-667.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif and E. Roeckner. 1999. Increased El Niño frequency in a climate model forced by future greenhouse warming. *Nature* 398: 694-696.

Trenberth, K.E. and T.J. Hoar. 1997. El Niño and climate change. *Geophysical Research Letters* 24(23): 3057-3060.