TROPICAL FORESTS, CLIMATE CHANGE AND CLIMATE POLICY

One sentence summary: New science underscores the value and timeliness of a promising climate policy initiative to reduce emissions from tropical deforestation.

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Tropical deforestation released 1.4 GtC yr^{-1} (range: 0.9 – 2.2) *(1,2,3,4)* throughout the 1990's, accounting for 17.3% (range: 12.0 – 28.0) *(5,6)* of total annual anthropogenic greenhouse gas emissions. Without the implementation of policies and measures to slow deforestation, the clearing of tropical forests will likely release an additional 87 – 130 GtC by 2100 *(7),* corresponding to the carbon release from more than a decade of global fossil fuel combustion at current rates. Drought-induced tree mortality, logging and fire may double these emissions *(8,9)*. Despite this, the Kyoto Protocol provides no incentives for reducing emissions from the loss and degradation of tropical forests. In a significant step to address this deficiency, the United Nations Framework Convention on Climate Change (UNFCC) recently launched a two-year initiative *(10)* to assess key technical and scientific issues and "policy approaches and positive incentives" for reducing emissions from deforestation and forest degradation in developing countries. If successfully negotiated and implemented, this new "L2" policy process could help to preserve one of the largest terrestrial carbon stocks (428 GtC, or 17.2% of total terrestrial carbon) *(6)*, a potentially important carbon sink (up to c. 2 GtC yr^{-1}, or 25 % of total annual anthropogenic emissions*) (11*), a globally important source of biodiversity *(14)*, and a key resource for the livelihoods of millions of people in forest-rich developing countries *(15)*.

Two important kinds of evidence underscore the value and timeliness of the L2 policy process. First, it is increasingly clear that deep emissions reductions will be necessary to avoid "dangerous anthropogenic interference" with the climate, the goal of the UNFCCC. A substantial contribution from decreased deforestation and forest degradation could complement industrial emissions reductions, greatly increasing the prospects for solutions that are technically and politically feasible. Second, new information on the function of tropical forests through the 21st century highlights their potential role as carbon sinks, if deforestation is managed. Without effective action to slow climate change and deforestation, however, remaining tropical forests face an increased risk that they will become significant sources of carbon to the atmosphere.

Current science is already sufficient to demonstrate the large benefits for a world on a trajectory of low greenhouse gas (GHG) emissions *(16)*. The L2 policy process can make important contributions towards achieving these reductions. For example, following a pathway consistent with stabilizing atmospheric CO_2 concentrations at 450 ppm would require limiting total emissions of CO_2 from 2010 to 2100 to only 44% (range: 17-65%) of those under mid-range business-as-usual scenarios (SRES A2 and B2 Scenarios (*17*); *online supporting text*; Fig. S1). Limiting global temperature increases to 2ºC, the target adopted by the European Union *(18)*, could well require even more ambitious reductions *(*Fig. S2*; 19; online supporting text)*. Reducing deforestation rates 50% by 2050 and then maintaining them at this level till 2100 would avoid the direct release of up to 50 GtC this century - equivalent to seven years of recent annual fossil fuel emissions, and up to 12% of the total reductions that must be achieved from all sources through 2100 in order to be consistent with stabilizing atmospheric concentrations of CO_2 at 450 ppm (*online supporting text*; Figs. S3-S5; Fig. 1). Although this contribution may seem modest, the magnitude and difficulty in achieving emission reductions necessary to avoid dangerous climate change places a high value on every incremental reduction.

Perhaps even more important, reducing deforestation, forest degradation, and industrial emissions to achieve such a stabilization target may prevent the release of substantial portions of remaining tropical carbon pools to the atmosphere through fire, dieback, and loss of sink capacity resulting from global warming and warming-induced shifts in the water balance. The experience of the 1997-1998 El Niño Southern Oscillation Event (ENSO) demonstrates how climate change can interact with land use change to put large areas of tropical forests and their carbon at risk. The extended dry conditions triggered by the ENSO across much of the Amazon and Southeast Asia increased tree mortality and forest flammability, particularly in logged or fragmented forests *(20)*. In the Amazon, a record number of accidental fires burned 40 million ha of standing forests, releasing c. 0.2 +- 0.1 GtC *(21)*. In Indonesia, where draining and clearing forests greatly increased the flammability of peatlands, fires released 0.8-2.6 GtC of carbon *(22)*. Estimates based on remote sensing, biogeochemical modeling and inverse analysis identify a *global* fire emissions anomaly for the 1997-1998 ENSO of 2.1 +- 0.8 GtC *(23)*, with additional long-term effects, as the mortality of trees, especially the large canopy trees, remains elevated for years after the ENSO event *(24,25)*.

Global warming may be putting tropical forest regions at risk of more frequent and severe droughts, even in non-ENSO years. Over the last five years, a number of Amazon basin droughts have been uncoupled from ENSO events but have coincided with some of the warmest global average temperatures on record. For example, in 2005, long-term drought in the Amazon basin, which resulted in the lowest water levels in Amazon River in 30 years *(26)*, led to the release of an estimated 0.5 GtC of carbon to the atmosphere, through the combined effects of reduced forest growth and increased tree mortality *(27)*.

Between 204 and 396 GtC is potentially at risk of release from tropical forest ecosystems *(28, 29)*. In recent decades, carbon losses from tropical deforestation may have been partly or largely offset by a tropical sink (*11*). Forest sinks are, however, unlikely to continue indefinitely, and continued warming will likely diminish and potentially even override any fertilization effects of increasing CO_2. Climate change might also adversely impact tropical forests by reducing precipitation and increasing evapotranspiration, making them drier, more susceptible to fires, and more prone to replacement by shrublands, grasslands, or savanna ecosystems (*30*), which store much less carbon. In the Amazon Basin, continued deforestation may disrupt forest water cycling, amplifying the negative impacts of climate change (*online supporting text*).

A key early paper *(31)*, based on a model that couples climate and carbon cycle components, projected that business-as-usual increases in carbon dioxide and temperature could lead to dramatic dieback of forests in the Eastern Amazon and replacement by grasslands, starting as soon as 2050. Such profound sensitivity of tropical forests to climate change would compromise the long-term value of avoided deforestation, with dieback releasing much of the carbon originally conserved. New results involving 11 coupled climate-carbon cycle models and the mid-range A2 emissions scenario *(17)* indicate that the early result was probably extreme. Ten of the 11 models project that tropical forests continue to act as carbon sinks throughout the century, although the strength of the sink declines (*32*; Fig. 2). Aggressive efforts to reduce emissions would likely reduce the rate of decline and risk of reversal of the tropical sink. Under a 450 ppm stabilization scenario, for example, Amazon emissions for the one (HadCM3L3) model showing dieback under business-as-usual are reduced 43 GtC, or 45%, through 2100 *(33)*.

Initiated at the behest of several forest-rich developing countries, the L2 process offers a unique opportunity to engage their participation in the international effort to avert dangerous climate change. A number of specific mechanisms, including carbon market financing to help developing countries meet voluntary commitments for reductions in forest-sector emissions below historic baselines, are being proposed and debated *(34,35)*. In some tropical forest countries it may be possible to reduce emissions from types of deforestation and forest degradation that provide little or no short-term benefits to local and regional economies. For example, reducing accidental fire in standing forest and eliminating forest clearing on lands that are inappropriate for agriculture are two promising low-cost options for reducing greenhouse gas emissions in Brazil *(36)*. Other measures are unlikely to be implemented at large scales without financial incentives that become plausible within the framework of the L2 policy process *(37)*. In forests slated for timber production, for example, widespread adoption of sustainable forestry practices can both directly reduce emissions and reduce the vulnerability of logged forests to further emissions from fire and drought exacerbated by global warming (*38*). On forested land that is suitable for agriculture, land-use regulations on private property and protected area networks can help reduce deforestation in some countries (*36*).

Beyond protecting the climate, reducing tropical deforestation has the potential to eliminate many negative impacts that may compromise the ability of tropical countries to develop sustainably. Negative impacts associated with deforestation and forest degradation include reduction in rainfall *(39)*, the loss of biodiversity *(14)*, human health impacts from biomass burning pollution *(40)*, and the unintentional loss of productive forests *(21)*. Providing economic incentives for the maintenance of forest cover can help tropical countries avoid these negative impacts and meet development goals, while also complementing aggressive efforts to reduce fossil fuel emissions. Industrialized and developing countries urgently need to support the L2 policy process and develop effective and equitable compensation schemes to help tropical countries protect their forests, reducing the risk of dangerous climate change and protecting the many other goods and services that these forests contribute to sustainable development.

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41. We thank S. Brown, S. Schwartzman, and B. Schlamadinger for comments on previous versions of this manuscript.

FIGURES

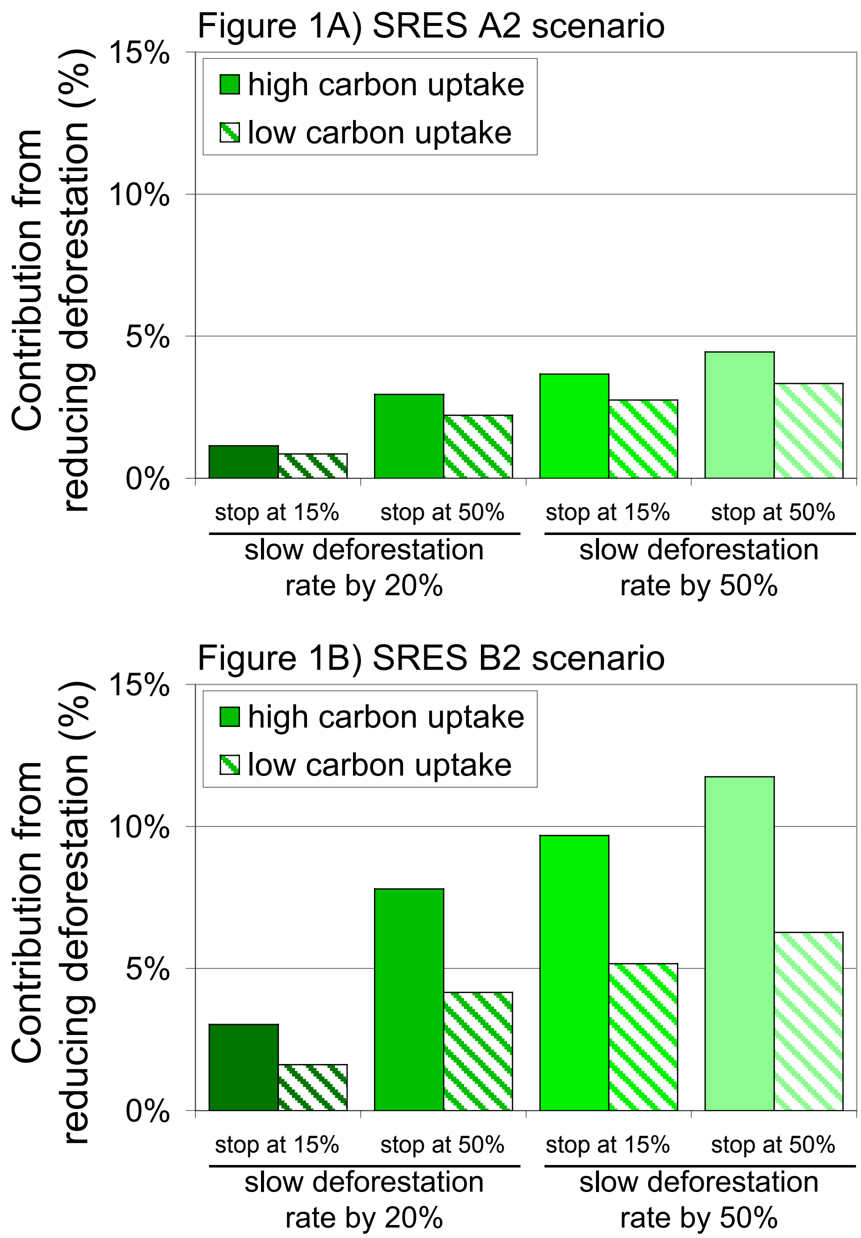

Figure One. The contribution of reduced tropical deforestation towards achieving a 450 ppm stabilization pathway (see *online supporting text* and Figs. S3-S5 for a full description of methodology supporting this figure). The deforestation scenarios are defined by two variables. First, current day deforestation rates are reduced by either 20%

or 50% by 2050, and then maintained at these levels until 2100. Second, deforestation stops entirely once forest cover has been depleted to either 15% or 50% of forest cover present at the year 2000. The analysis considers both a low- and a high future carbon uptake scenario by oceans and terrestrial ecosystems as described by Working Group III of the IPCC. **1A)** The contribution of reduced deforestation under the SRES A2 mid-range emissions scenario, which predicts cumulative carbon emissions of 1785 GtC from 2010 to 2100. Allowable emissions for the WRE-450 stabilization pathway range from 297 to 667 GtC over the same period, meaning that the cumulative emission reductions required are 1118-1488 GtC. **1B)** The same as (1A), but using the SRES B2 mid-range emissions scenario, which predicts cumulative carbon emissions of 1090 GtC between 2010 – 2100, and would require emission reductions of between 423-793 GtC to be consistent with a 450 ppm stabilization pathway.

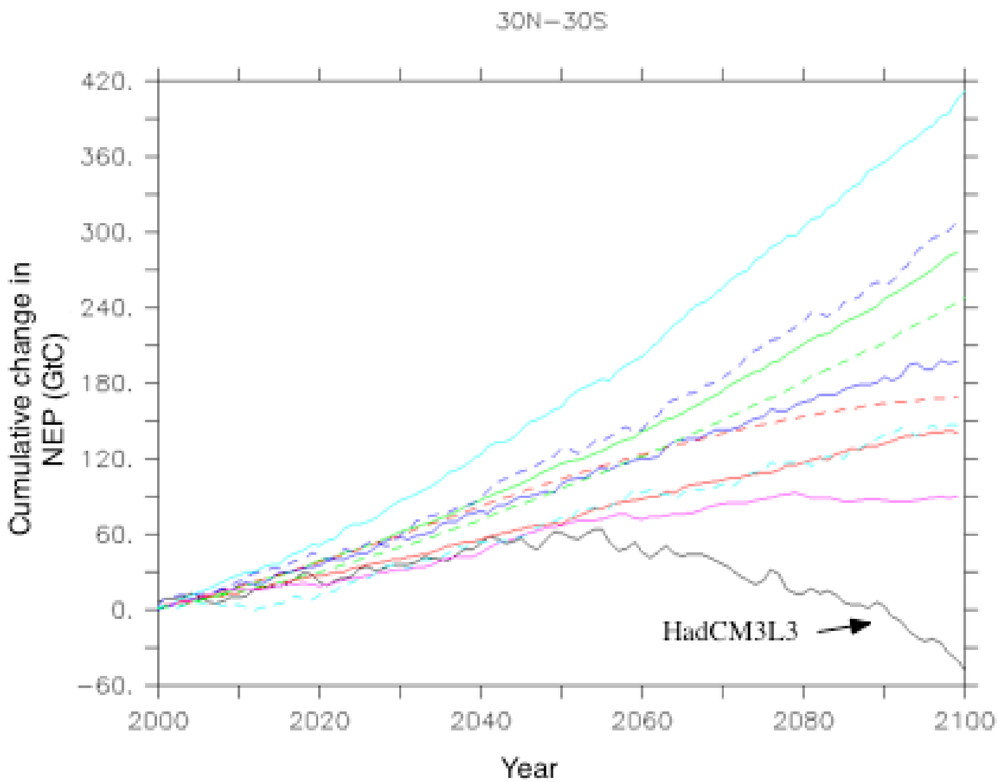

Figure Two. Cumulative change in Net Ecosystem Productivity (NEP) in the tropics from 2000 to 2100 for the eleven models participating in the Coupled Climate-Carbon Cycle Model Intercomparison Project . Models use the SRES A2 emission scenario, which assumes that atmospheric CO_2 concentration will exceed 550 ppm by mid-century, and reach 850 ppm by 2100. Results show the combined effects of climate change and CO_2 fertilization. Projected land-use emissions are included in the simulations, but land use *per se* is not modeled, and does not influence the distribution of natural vegetation. Most models show that sink strength declines over time, with one model (HadCM3LC) projecting that tropical forests become net sources of carbon. [Key to models:

HadCM3LC (solid black), IPSL-CM2C (solid red), IPSL-CM4-LOOP (solid yellow), CSM-1 (solid green), MPI (solid dark blue), LLNL (solid light blue), FRCGC (solid purple), UMD (dash black), UVic-2.7 (dash red) and CLIMBER (dash green), BERN-CC (dash blue). See *(32)* for full description.]

Supporting Online Material

SOM Text
Figs. S1 – S5
References

SOM Text

Cumulative carbon emissions reductions required to meet WRE-450 target

Cumulative carbon emissions from 2010-2100 allowed under the WRE-450 stabilization scenario were calculated as follows. First, the IPCC allowable emissions from 2001 to 2100 range from 365 to 735 GtC, based on uncertainty in rates of carbon uptake by the ocean and terrestrial biosphere *(S1)*. The mid-range estimate of emissions from 1991-2000 under the "S" concentration profiles is 630 GtC *(S2)*. Subtracting estimated global emissions of 57.6 GtC *(S3)* for 1990-1999 from 630 GtC gives a mid-range estimate of 572 GtC from 2000 to 2100. The next step is to adjust the range and mid-point from 2000 to 2010. Global emissions from 2000 to 2003 total 27.79 GtC. SRES-projected emissions in 2010 are 8.4 GtC *(S4)*. Filling in estimated global annual carbon emissions between 2004 and 2010 by linearly interpolating between 2003 values and SRES-projected 2010 emissions gives total cumulative emissions from 2000 to 2009 of 74.9 GtC. Subtracting this value from the cumulative emissions allowed from 2000 to 2100 gives a mid-point of allowable carbon emissions from 2010 to 2100 of 498 GtC, with a range of 297 to 667 GtC. For comparison, total cumulative carbon dioxide emissions for the A2 and B2 SRES emission scenarios over the period 2010 to 2100 are 1785 and 1090 GtC respectively (Fig. S1).

Emissions reductions from slowing deforestation

Houghton (2005) *(S5)* estimates projected emissions from tropical deforestation as follows. First, deforestation rates and emissions during the 1990s have been estimated based on satellite imagery *(S6)* and based on sampled country inventory data *(S7, S8)*. For simplicity, Houghton (2005) assumes deforestation rates and associated emissions stay constant for each country until remaining forested area in that country reaches 15% of the forest area in 2000. At that point, deforestation is assumed to halt as the remaining forested area is already protected or is located in a region that is not cost-effective to clear (Fig. S3).

To illustrate the potential reductions in projected carbon emissions that could be obtained through substantial measures to reduce tropical deforestation, we re-calculated the carbon emissions that would result from (a) a linear reduction in deforestation rates to 20% and 50% below 1990s rates by 2050, and (b) stopping deforestation when 50% of forested area relative to 2000 was still remaining, rather than just 15% as in the Houghton (2005) estimates. Figure S4 compares the baseline (average FAO and Achard) emissions calculated by Houghton (2005) with the emissions based on slowing deforestation rates and increasing the remaining forest area at which deforestation halts. Slowing rates to 50% below 1990's rates by 2050 results in more than 50% of the forested area still remaining by 2100 for most tropical countries, where deforestation halts before 2100 due to ongoing reductions in the rate of deforestation rather than the limit on remaining forest area.

How much of a contribution to global carbon reductions could the reductions in deforestation emissions examined here make? Currently, annual global emissions slightly exceed 7 GtC yr^{-1} *(S4)*. Deforestation reductions from 2010 to 2100 have the potential to offset up to c. 50 GtC, which is equivalent to up to seven years of global emissions at present-day levels (Fig. S5). While large relative to current global emissions, such reductions are modest relative to the total reductions in emissions that would be needed through 2100 to stabilize at 450 ppm CO_2 (Fig. 1). For example, under low carbon uptake and a conservative slowing in the rate of deforestation (20% by 2050), deforestation would account for roughly 2 to 5% of total reductions relative to any scenario. Under higher carbon uptake, if the A2 scenario is used as a business-as-usual baseline, deforestation would still achieve less than 5% of total reductions required to reach stabilization at 450 ppm. Under the B2 scenario, however, deforestation could account for up to almost 12% of necessary reductions.

The Impact of Deforestation on Amazon Rainfall

When global climate models simulate Amazon deforestation, they typically find that precipitation decreases approximately linearly with increasing amounts of deforestation. Maximum precipitation reductions of 5–30 % are seen at complete deforestation *(S10, S11)*. However, meso-scale models, with finer spatial resolution, fail to find the same pattern *(S12)*. Instead of a uniform decrease in precipitation, they show complex patterns of change, with some areas increasing and others decreasing, but not necessarily a marked decrease in overall precipitation.

Supporting figures

Figure S1

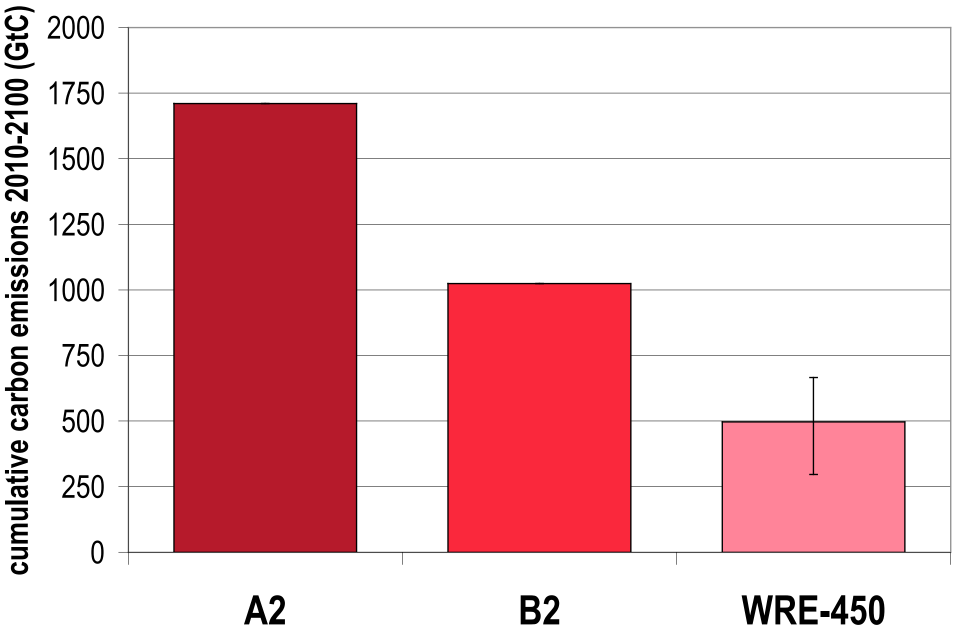

Figure S1 Caption
Cumulative carbon emissions for the SRES mid-range A2 and B2 marker scenarios, as compared with emissions under the WRE-450 stabilization pathway. The range in cumulative emissions under the WRE scenario represents uncertainty in carbon uptake by the ocean and terrestrial biosphere.

Figure S2

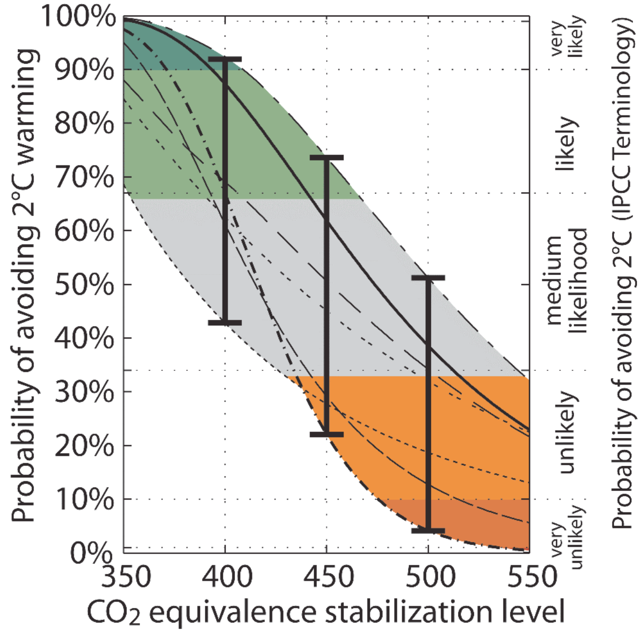

Figure S2 caption

Probability of avoiding (i.e., remaining below) a global 2^{o}C warming target as a function of CO_2-equivalent stabilization levels. Uncertainty range is determined by current estimates of climate sensitivity (re-drawn from (*S12*)). CO_2 concentrations are currently at approximately 385 ppm, while CO_2-equivalent concentrations, which include other gases such as CH_4, N_2O, SF_6 and CFCs, are approximately 425 ppm.

Figure S3

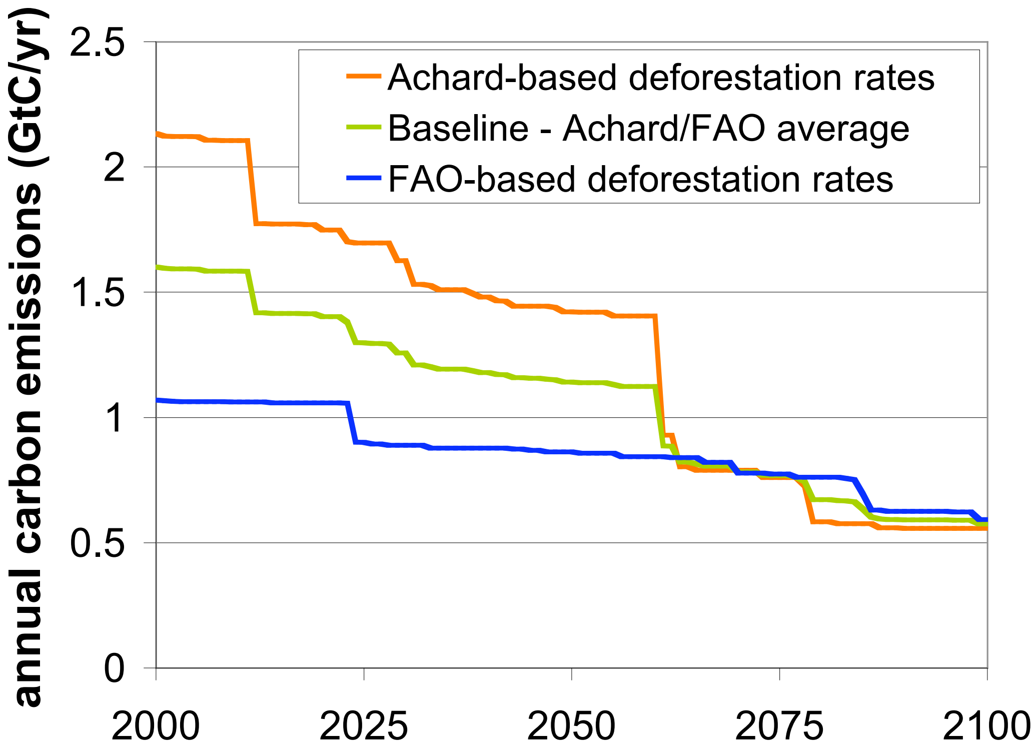

Figure S3 caption

Annual emissions of carbon from tropical deforestation summed over Africa, Asia & Latin America, based on Achard et al., 2004 (*S6*) (orange), FAO (*S7*) (blue) and the average of the two estimates (green), which we use as the baseline for this analysis. Emissions assume that rates of deforestation for the 1990s continue in the future, after Houghton (2005) (*S5*). Deforestation is estimated to halt when a country's forest area reaches 15% of its original forested area relative to 2000.

Figure S4

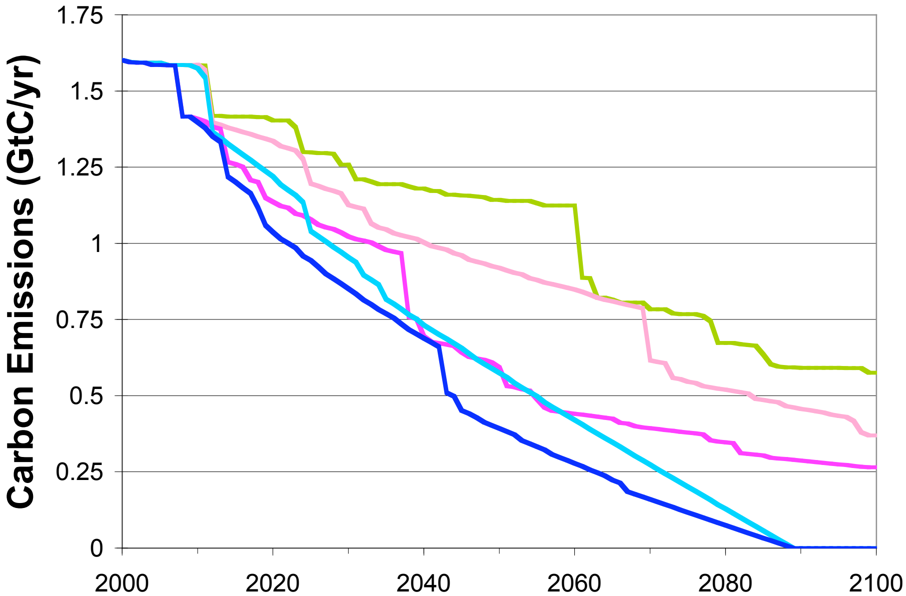

Figure S4 caption

Baseline global emissions from deforestation as estimated by Houghton, 2005 (*S5*) (green). The pink lines show the emissions based on a 20% slowing in deforestation rates by 2050 relative to 1990s average, stopping at 15% of remaining forest area by individual country (light pink) or 50% of remaining area (dark pink). Similarly, the blue lines show emissions corresponding to a 50% slowing in deforestation rates by 2050 stopping at 15% (light blue) or 50% (dark blue) of remaining forest area by individual country.

Figure S5

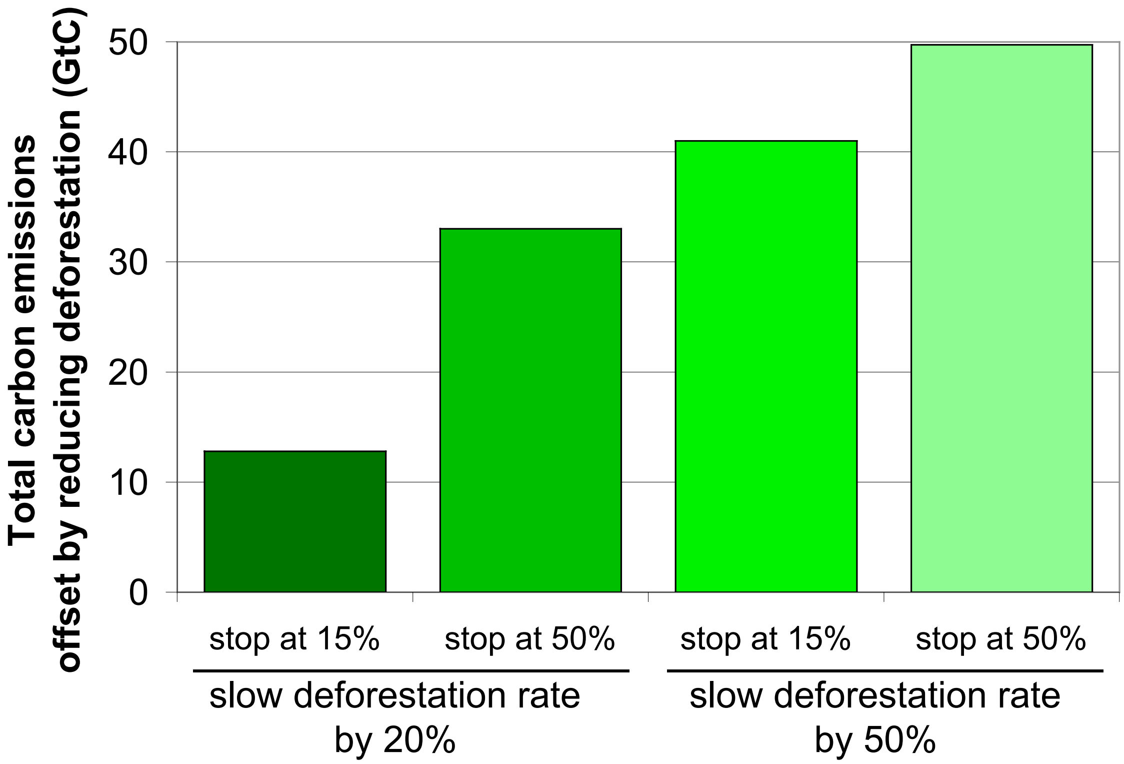

Figure S5 caption

Cumulative carbon emissions that could be offset by 2050 by reducing deforestation emissions through reducing the deforestation rate by 20% or 50% below 1990s levels, and by halting deforestation when 15% or 50% of the forested area in 2000 is reached.

Supporting References

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