Modeling the Role of Remaining Tropical Forests in Climate Change Mitigation

AVOID:
Avoiding dangerous climate change

AVOID is a DECC/Defra funded research programme led by the Met Office in a consortium with the Walker Institute, Tyndall Centre and Grantham Institute

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Date: 17/09/2013

AVOID is an LWEC accredited activity

Non-technical summary

At the time this study was carried out, land use change (LUC) resulting from deforestation and other smaller sources contributed ~17% of global anthropogenic greenhouse gas emissions, whilst more recently (29) the deforestation component alone has been estimated to contribution 11% of the global total. SRES baselines assume LUC emission decrease and reverse, whereas deforestation is continuing unabated. Hence the AVOID project analyses, being based on SRES baselines, likely under-estimate future emissions from deforestation.

This study focuses on tropical deforestation, assuming that action is taken to reduce emissions from other land use change. We find that in the absence of tropical deforestation, rapid emissions reductions of 80% between 2000 and 2050 in fossil fuel and other sectors would deliver a 65% chance of staying below the 2°C threshold. If tropical deforestation instead continues at current rates, the chance falls to 34%. To compensate for the additional climate change caused by continued current rates of tropical deforestation, a doubling of global mitigation efforts (from 3% to 6% per year) would be required to maintain the same 65% chance to avoid temperature rise in excess of 2°C above pre-industrial levels. Only deforestation rates between 0 and 0.8GtC/yr have a greater than evens chance of constraining temperature change to 2°C. Failing to reduce deforestation also increases the difficulty of avoiding a 3°C increase in global temperature. Tackling deforestation could avoid an increase in CO_2e concentrations of up to 100 ppm and concomitant temperature rise of 0.6°C.

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EXECUTIVE SUMMARY

A large body of research suggests that climate changes caused by anthropogenic emissions of greenhouse gases to the earth's atmosphere will result in impacts that increase significantly with rising global mean temperatures (*1, 2*). To minimize potentially severe impacts, the UNFCCC has set a goal of limiting global warming to 2°C above pre-industrial levels.

Land use change (LUC) currently contributes ~17% of global anthropogenic greenhouse gas emissions (*10*). Studies based on the SRES scenarios are largely optimistic about deforestation futures (*14*). Tropical deforestation forms the largest component of deforestation emissions (*11*). The baseline future emissions used in most published climate projections are those of the SRES (*14*), in which 21st century LUC emissions are generally projected to decrease and then reverse from a source to a net sink (-22 to 181 GtC across the SRES). These scenarios are most likely optimistic about deforestation futures, as global deforestation rates continue unabated (*11, 22*) and reforestation in temperate countries may ultimately be offset by carbon release due to projected increases in forest fire frequency and warming-enhanced decomposition (*15, 16*). Hence, analyses using SRES baselines, such as the AVOID project analyses, probably under-estimate future emissions from deforestation.

The UN Framework Convention on Climate Change is currently assessing options for including the reduction of emissions from deforestation and degradation (REDD) in future climate agreements. The question is, how critical is reducing tropical deforestation, and by how much, to constraining ΔT to 2°C or even 3°C?

Whilst it has been previously argued that reducing deforestation would lower atmospheric CO_2 concentrations, (*12, 13*) this work is the first to explore how this affects the attainment of

specific mitigation targets, and how different combinations of emission reductions in fossil fuels interact with different rates of deforestation, here focusing on solely on one key component, tropical deforestation. In this study we show that avoiding tropical deforestation has a critical role in the ability to constrain global temperature rise to 2C above pre-industrial levels.

We show that with rapid emissions reductions of 80% between 2000 and 2050 in fossil fuel and other sectors, including deforestation outside the tropics, that if tropical deforestation is halted, the probability of staying below the 2°C threshold is 65%. However, in contrast if tropical deforestation instead continues at current rates, the chance to stay below the 2°C threshold falls to 34%, and that of staying below a 450 ppm CO_2-equivalent target for greenhouse gas concentrations falls from 37% to 4%.

To compensate for the additional climate change caused by continued current rates of tropical deforestation, a doubling of global mitigation efforts (from 3% to 6% per year) would be required to maintain the same chance to avoid temperature rise in excess of 2°C above pre-industrial levels.

If strong policies for avoiding tropical deforestation are not implemented, society's best efforts to achieve stabilization levels of 450ppm CO_2e, and the opportunity to limit warming to 2°C, are jeopardized, even in the presence of some of the strongest measures being contemplated to reduce fossil fuel emissions. Continued deforestation at current rates (FAO) reduces the probabilities of not exceeding a 2°C threshold from 65% (in the absence of continued tropical deforestation) to 34%, and also reduces the probabilities of not exceeding a 450ppm CO_2e target from 37% to <5%. We also calculated the annual fossil-fuel and non-tropical-forest LUC emission reduction rates required to 'compensate' for continued tropical deforestation and still stabilize at 450 ppm CO_2e by 2100: we found that emission reduction rates had to be increased to 6-7% to 'compensate' for tropical deforestation rates of 1.6-2.2 GtC/yr respectively (these correspond to the two estimates of current deforestation rates that we used (12, 22, 23). These emission reduction rates of 6-7% are significantly larger than most of those appearing in the literature.

Failing to implement avoided/reduced deforestation policies (e.g., REDD) also increases the difficulty of constraining concentrations to 550ppm CO_2e and limiting ΔT to 3°C. We also found that near-total tropical deforestation in the 21st century would eliminate the 10-year transition period which is allowable in scenario 550N requires during which emission reduction rates in the fossil fuel and non-forest LUC sectors slowly ramp up from 0 of 2.5%/year in 2020: in order to still stabilize at 550 ppm CO_2e, the 2.5%/yr emission reductions in non-tropical forest sectors would need to commence immediately.

Recent research (*25*) suggests that climate changes such as atmospheric warming, precipitation changes and concomitant increases in drought may be largely irreversible, at least on human timescales, and thus avoiding increases in GHG concentrations and ΔT is essential to preventing climate change impacts. All emission reduction pathways examined in this study demonstrate that reducing tropical deforestation could avoid an increase in CO_2e concentrations of up to 100 ppm in 2100, and a concomitant increase of up to 0.6°C of temperature rise. Signs that ocean sinks may be saturating (*26*), and that tropical forests may play a more important role in storing carbon than previously thought (*27*), would suggest that our figures may be conservative.

Fossil fuel use is the predominant driver of increasing greenhouse gas emissions. If these are reduced through strong climate policies, and tropical deforestation continues at current rates, emissions of CO_2 from land use change become proportionally much more important. Near total avoidance of tropical deforestation (e.g., through REDD policies) is thus a key component for achieving stringent stabilization and temperature targets and avoiding the impacts that accrue with warming. Such policies potentially yield many co-benefits, including the delivery of ecosystem services and biodiversity conservation.

INTRODUCTION

Climate change impacts in both human and natural systems are projected to increase with global mean temperature rise (ΔT) (*1*, *2*). To minimize the severity of climate impacts and also to reduce the potential for breaching 'tipping points' in the earth system *(1,3,4)*, many countries and other stakeholders have variously proposed implementing policies to limit ΔT to no more than 2°C (all temperatures given relative to pre-industrial levels); or for limiting greenhouse gas (GHG) concentrations to 350-450 ppm CO_2 or 450-550 CO_2 equivalent concentrations (CO_2 e) (*5, 6*, *7*, *8*). Stabilizing GHG concentrations at 445-490 ppm CO_2 e would potentially limit equilibrium ΔT to 2-2.4°C but will require reductions in GHG emissions of 50-85% relative to current levels (*9*). Present day GHG emissions contain a sizeable contribution from land use change (LUC), amounting to ~17% of global greenhouse gas emissions in 2004 (*10*), and continuing deforestation could ultimately lead to estimated releases of 450 - 800 GtC; 395 GtC from tropical forests (*11*). In 2012, the UNEP Emissions Gap Report (29) estimated that 11% of global anthropogenic emissions originated from tropical deforestation. The baseline future emissions used in most published climate projections are those of the SRES (*14*), in which 21st century LUC emissions are generally projected to decrease and then reverse from a source to a net sink (-22 to 181 GtC across the SRES). Similarly, GLOCAF assumes that by 2050 deforestation and afforestation combined produce a small net sink in the GLOCAF baseline. These scenarios are most likely optimistic about deforestation futures, even though there has been some recent decline in deforestation rates (*11*, *22*, *30*) and as reforestation in temperate countries may ultimately be offset by carbon release due to projected increases in forest fire frequency and warming-enhanced decomposition (*15, 16*). Hence, analyses using SRES baselines, such as the AVOID project analyses, probably under-estimate future emissions from deforestation.

Previous work used emission budget estimates to argue that reducing deforestation could contribute to climate protection (*12*). Additional work modeled the response of the carbon cycle and atmospheric CO_2 concentration to deforestation against a single reference emissions-scenario in the absence of other climate mitigation policies (*13*). We advance beyond these works by investigating multiple scenarios looking at the influence of tropical deforestation upon ΔT in conjunction with stringent fossil fuel mitigation. Specifically, we use a probabilistic modeling approach to examine how potential future scenarios of avoided deforestation enhance or inhibit society's ability to meet various GHG concentration and temperature targets over the 21st century. Our approach includes both retaining existing forest stocks and reducing deforestation rates.

The UN Framework Convention on Climate Change is currently assessing options for including the reduction of emissions from deforestation and degradation (REDD) in future climate agreements. Therefore, an investigation of the role of avoided deforestation in mitigation policy is timely.

AIMS

This study sets out to answer the following question:

"How critical is reducing tropical deforestation, and by how much, to constraining global mean temperature rise above pre-industrial levels (hereafter referred to as ΔT) to 2°C or even 3°C?"

METHODOLOGY

Emissions scenarios

To examine the trade-off between reductions in fossil fuel emissions and emissions from tropical deforestation, we created sets of future emission scenarios for fossil fuel burning and land use change arising from factors other than tropical deforestation, and sets of emissions scenarios for tropical deforestation, and combined them.

We used an emissions scenario generator (*18*) to produce trajectories of emissions from fossil fuel emissions (and other sectors) including LUC from other than tropical deforestation.

Prior to the calculations presented here, it was first necessary to identify the constraints on the values of parameters date mitigation starts (TS), transition time (TT) and rate of emissions of reduction (R) in the emission scenario generator, necessary to meet the two stabilization targets for GHG concentrations in the atmosphere without 'overshooting' these concentrations. This was implemented by systematically searching combinations of TS and TT in units of 10 years, combined with values of R at 0.5%/yr intervals. Values of TS were slowly brought forward in time, or TT reduced slowly to zero, or R slowly increased, until stabilization was obtained without overshooting the target concentration. For each scenario we plotted temporal trajectories of the most likely value of CO_2e concentrations. Stabilization was deemed to have been achieved if the most likely value remained below the target during 2100-2150 and was not continuing to rise towards the end of this time period. Table 1 summarizes three of the combinations of values of TS, TT, and R that were shown not to deliver stabilization at 450ppm CO2e even if tropical deforestation ceases in 2010. Similarly, relaxation of the parameters in the 550N scenario demonstrated that later or less stringent mitigation as represented by these parameters would not deliver stabilization at 550 CO_2e as a most likely outcome.

Table1. Combinations of parameter values of TS, TT, and R in the emissions scenario generator that do or do not deliver stabilization of greenhouse gas concentrations at 450ppm CO2e, detailing the OS450 and 450N scenarios.

Parameter combination	Used in study	TS (year)	TT (years)	R(%/yr)	Stabilization?
1	No	2020	0	3	No
2	Yes as OS450	2010	10	3	No
3	No	2010	0	2.5	No
4	Yes as 450N	2010	0	3	Yes

To discover the relationship between R and the scenarios being discussed by policy makers, we referred to the largest percentages of emission reductions cited in the literature, that refer to an 80% reduction of global emissions by 2050 relative to 2000 levels (*9*). Some policy makers have also referred to potential 80% cuts in national emissions by 2050. Assuming that the emission reductions take the form of a simple geometric progression, the emission reduction rate is given by the 50th root of 0.2, that gives approximately 3%/yr. The most extreme scenario referred to in (*9*) refers to an 85% reduction by 2050. Hence immediate implementation of emission reductions in fossil fuel and other sectors (including LUC outside tropical forests) at the maximum rates found in the literature is necessary to achieve stabilization at 450 ppm CO_2e.

We also examined an emission reductions scenario with emission stabilizing at 450 CO2e in 2100 after initially exceeding it and rising to 475 ppm (450OS). The combination of parameters in the emission scenario generator corresponding to this scenario is shown in Table 1. The emissions in the 450N and 450OS scenarios are shown in Supplementary Figures 4a,b, in order to demonstrate the relationship between the trends in emissions of the various greenhouse gases and aerosols, and to show how the OS scenario has a more gentle onset for emission reductions.

Climate modelling

We use a version of the MAGICC simple climate model to simulate the global average near surface warming and its uncertainty for our full range of emissions trajectories. The specific parameters that we varied are the climate sensitivity (defined as the equilibrium global mean temperature increase for a doubling of atmospheric CO_2), the ocean mixing rate (that determines how quickly the warming at the surface is diffused throughout the ocean), and a climate-carbon cycle feedback factor (that amplifies the temperature dependent climate-carbon cycle feedbacks already in MAGICC ver. 4). Our analysis draws on a widely-used probability distribution of climate sensitivity (*24*). The climate-carbon cycle amplification parameter follows a normal distribution whose parameters were derived to allow MAGICC's atmospheric carbon dioxide concentrations to closely match that of the earth system models in the C4MIP analysis (*20*). Finally, a lognormal distribution of ocean mixing rates was fitted to the general circulation models employed by (*3*). In order to demonstrate the ability of MAGICC to replicate features of more complex earth system models we plotted Supplementary Figure 5, that shows the warming from pre- industrial times to 2100 simulated in the C4MIP models alongside the equivalent tuned MAGICC simulations. For each scenario we implemented 1000 runs of the MAGICC tuned model, using Latin hypercube sampling for climate sensitivity, ocean diffusivity, and a parameter that scales the feedback of climate on to the terrestrial components on the carbon cycle.

In the main text, scenario outcomes with annual 2010-2100 tropical deforestation rates of 0, 2.2 and 3.96Gt/yr are mainly discussed. We considered annual tropical deforestation rates of 0, 0.8, 1.6, 2.2 and 3.96Gt/yr and 3.0 GtC/yr . Lower estimates of current deforestation rates (ref) are 1.6 GtC/yr. Rates of 0.8 GtC/yr represent a partially effective REDD policy; rates of 2.2 GtC/yr match the FAO estimate of current deforestation rates; whilst 3.96GtC/yr reflects the extreme possibility of complete tropical deforestation by 2100.

Assumptions

We assume that CO_2 emissions continue to increase at an historical rate until mitigation begins (2010 and 2020 in the 450N, 550N scenarios respectively). We also apply current rates of tropical deforestation (22) until 2010 in all scenarios. This was the most reliable estimate of tropical deforestation rates at the time the study was carried out, although since then the FAO has provided updated estimates showing a reduction in deforestation rates from 160,000 square km/yr in the 1990s to 130,000 square km/yr in the 2000s. This amounts to a decline of 18% since the 1990s, but since our estimate dates from 2006, the difference between our 'current' rate and the updated 'current' rate will be smaller than this.

Emissions of non-CO_2 GHGs and of SO_2 emissions follow historical trajectories until 2000 and thereafter scale with CO_2 emissions (Supplementary Figure 4a). From 2010-2100 we studied six annual rates of deforestation of 0, 0.8, 1.6, 2.2, 3.0 and 3.96GtC/yr (Table 2). We used the CIAS integrated assessment framework (*17*) to couple an emission scenario generator (*18*) to a probabilistic version of the MAGICC simple climate model (*19*), tuned to represent the spread of uncertainty in the most complex earth system models (*3, 20, 21* , Supplementary Figure 5).

Table 2. Tropical deforestation scenarios explored, 2010-2100

Annual deforestation rate, GtC/yr	Description
0.8 GtC/yr	Very low deforestation rate: would remove 20% of tropical forest cover by 2100
1.6 GtC/yr	Low deforestation rate: lower than latest FAO 2012 estimate: would remove 40% of tropical forest cover by 2100
2.2 GtC/yr	FAO 2006 best estimate of current rate: would remove 55% of tropical forest cover by 2100
3.0 GtC/yr	Increased rate, removing 75% of tropical forest cover by 2100
3.96GtC/yr	Fastest rate possible, removing 100% of tropical forest cover by 2100

At present there is lack of sufficient and consistent data for deforestation emissions of non-CO_2 greenhouse gases and black-carbon aerosols, therefore we made the methodological choice not to try to simulate these species. This means our results may, in fact, underestimate medium-term avoided climate change from reduced deforestation. We also do not include the loss of net primary production that may accompany deforestation. Finally, our modeling approach also could not incorporate local feedback processes induced by deforestation. For example, where there is drying, a local reduction in cloud cover may lead to warming; whereas land clearance may cause a local increase in albedo that may cool (28). Future work will address this limitation using GCMs.

RESULTS

We find that in the absence of any tropical deforestation in the 21st century, [CO_2e] can be stabilized at 450 ppm by 2100 (with no overshoot, i.e., thresholds not exceeded) by reducing emissions from fossil fuel and other sectors, and LUC outside tropical forests, at a rate of 3%/year starting in 2010 (scenario 450N). This delivers a 65% probability of constraining ΔT to 2°C (Figure 1a). The 3% annual reduction corresponds to an 80% reduction emissions between 2000 and 2050 (Supplementary Information) and to some of the highest published possible rates of emission reduction *(9)*. If with these emission reduction rates, tropical deforestation instead continues at rates estimated by the FAO (2.2GtC annually, (*23*)), the probability of staying below 2°C falls to 34% (Figure 1a), with temperatures still rising at the end of the century (Supplementary Figure 1a); whilst [CO_2e] values in 2100 increase by a 5-95% range of 42-85 (most likely 52) ppm (Figure 2b). Furthermore, if tropical deforestation were hypothetically to increase to a 'high' rate of 3.96GtC annually, so that there was complete loss of forest by 2100 (*11),* most likely ΔT in 2100 would increase by 0.6°C (Figure 2a, Supplementary Figure 2a) to 2.4°C, and the probability staying below 2°C in 2100 would fall to only 17% (Figure 1a). Concurrently the probabilities of exceeding 3°C in 2100 would rise to 19%, compared to <5% if tropical deforestation were to cease in 2010 (Figure 1a). In this case [CO_2e] would most likely rise to 544 ppm implying an increase of close to 100 ppm (5-95% range 75-155 ppm) in 2100 as a result of the complete tropical deforestation (Figure 2b). Cumulative distribution functions reveal that probabilities of staying below 450 ppm CO_2e in 2100 in this 450N scenario decline rapidly as deforestation rates increase, from 37% with zero net deforestation to <5% with the loss of all tropical forests (Figure 1b). Calculations take into account carbon sequestered by subsequent land uses (*11*).

We also find that in the absence of tropical deforestation in the 21st century, [CO_2e] may be stabilized at the higher level of 550 ppm by 2100 with emission reductions beginning more gently in 2010, increasingly linearly during a ten-year transition period to a rate of 2.5%/year by

2020 (scenario 550N). This delivers probabilities in 2100 of staying below 3°C of 82%, and of staying below 2°C of 18% (Figure 1c). If current rates of deforestation instead continue, probabilities of remaining below 3°C decline to 65% , and further to 50 % respectively under high rates of deforestation (Figure 1c) with temperatures still rising in 2100 (Supplementary Figure 1b). Most likely [CO_2e] values rises from 545 to 649 ppm (Figure 2d), whilst probabilities of staying below 550 ppm CO_2e in 2100 decline from 39% through 12% to < 5%, depending on deforestation amount (Figure 1d).

Thus even in the context of strong non-forest sector mitigation, we find that only zero or low deforestation rates of 0.8 GtC/yr (Figure 1a) have a greater than evens chance of constraining temperature change to 2°C, or are likely to result in stabilization of GHG concentrations by 2100. We find that the potential to avoid increases in ΔT and [CO_2e] in 2100 in these strong mitigation scenarios 450N and 550N through action to reduce or halt tropical deforestation ranges from 0.47-0.88°C (most likely 0.59°C) and 75-155 ppm (most likely 95 ppm) in the 450N scenario; and 0.42-0.76°C in the 550N scenario (most likely 0.55°C) and 81–170 ppm (most likely 104 ppm) in the 550N scenario.

The most likely and 5-95% values of [CO_2e] and ΔT evolve with time in the 450N and 550N emission reduction scenarios with the various tropical deforestation rates studied. The probability distributions and 5-95% ranges of temperature and concentration outcomes increase in a skewed fashion both with the rate of deforestation and with time, with larger climate changes becoming disproportionately more likely for higher deforestation rates because of the asymmetric nature of probability distributions of climate sensitivity (*24*) and the non linearity of the climate-carbon cycle feedback *(20).* (Supplementary Figures 1a-d, 2a).

Scenarios with tropical deforestation rates of 0.8 GtC/yr showed concentration and temperature trends intermediate between those of the zero tropical deforestation case and the low estimate of continued current rates case (1.6 GtC/yr) and represents a partially effective REDD policy, whilst rates of 3.0 GtC/yr showed trends intermediate between continued FAO estimate of current rates case (2.2 GtC/yr) and the complete tropical deforestation case with losses of 3.96GtC/yr. (Table 2) The implications for the lower rates of continued current tropical deforestation rates of 1.6GtC/yr were for slightly lower temperature and CO_2e outcomes than for the higher FAO estimate of 2.2 GtC/yr. The outcomes of these simulations are shown in Figures 1a-d, 2a-d, and Supplementary Figures 1a-d, 2a-b and 3a-b.

We studied a variant of emission reduction scenario 450N, with overshooting of a 450 CO_2e threshold (Supplementary Methods) and obtained similar results (Supplementary Figures 2b, 3a, b). Whilst numerical probabilities of breaching thresholds were generally slightly higher using 450OS than 450N, the pattern and relative influence of increasing deforestation rates remained very similar. Our conclusions are thus robust to some variation in the pathway to stabilization.

In the future work is planned to examine the spatial implications of this work, both in relation to the effect that forest cover has on the earth's albedo and also to consider the implications of policies to preserve forests in various regions. This is beyond the scope of the current research.

CONCLUSIONS

If strong policies for avoiding tropical deforestation are not implemented, society's best efforts to achieve stabilization levels of 450ppm CO_2e, and the opportunity to limit warming to 2°C, are jeopardized, even in the presence of some of the strongest measures being contemplated to reduce fossil fuel emissions. Continued deforestation at current rates (FAO) reduces the probabilities of not exceeding a 2°C threshold from 65% (in the absence of continued tropical deforestation) to 34%, and also reduces the probabilities of not exceeding a 450ppm CO_2e target from 37% to <5%. Even if deforestation rates have fallen by as much as 20% since the FAO report in 2006 was produced, the probability of not exceeding a 2°C threshold would still fall from 65% (in the absence of continued tropical deforestation) to approximately 38% (Figure 1a), meaning that a 50% probability of not exceeding a 2°C threshold is not achieved without action to reduce tropical deforestation. In the AVOID results, baseline scenarios assume exogenous declines in tropical deforestation rates.

We also calculated the annual fossil-fuel and non-forest LUC emission reduction rates required to 'compensate' for continued tropical deforestation and still stabilize at 450 ppm CO_2e by 2100: we found that emission reduction rates had to be increased to 6-7% to 'compensate' for tropical deforestation rates of 1.6-2.2 GtC/yr respectively (these correspond to the two estimates of current deforestation rates that we used (12, 22, 23). These emission reduction rates of 6-7% are significantly larger than most of those appearing in the literature.

Failing to implement avoided/reduced deforestation policies (e.g., REDD) also increases the difficulty of constraining concentrations to 550ppm CO_2e and limiting ΔT to 3°C. We also found that near-total tropical deforestation in the 21st century would eliminate the 10-year transition period which is allowable in scenario 550N requires during which emission reduction rates in the fossil fuel and non-forest LUC sectors slowly ramp up from 0 of 2.5%/year in 2020: in order to still stabilize at 550 ppm CO_2e, the 2.5%/yr emission reductions in non-tropical forest sectors would need to commence immediately.

Recent research (*25*) suggests that climate changes such as atmospheric warming, precipitation changes and concomitant increases in drought may be largely irreversible, at least on human timescales, and thus avoiding increases in GHG concentrations and ΔT is essential to preventing climate change impacts. All emission reduction pathways examined in this study demonstrate that reducing tropical deforestation could avoid an increase in CO_2e concentrations of up to 100 ppm in 2100, and a concomitant increase of up to 0.6°C of temperature rise. Signs that ocean sinks may be saturating (*26*), and that tropical forests may play a more important role in storing carbon than previously thought (*27*), would suggest that our figures may be conservative. Our results hold irrespective of recent welcome declines in deforestation rates below the FAO estimate of 2.2CtC/yr, as larger declines would be necessary to offset the warming. Recent reported declines in deforestation rates are insufficient to significantly affect these conclusions.

Fossil fuel use is the predominant driver of increasing greenhouse gas emissions. If these are reduced through strong climate policies, and tropical deforestation continues at current rates, emissions of CO_2 from land use change become proportionally much more important. Near total avoidance of tropical deforestation (e.g., through REDD policies) is thus a key component for achieving stringent stabilization and temperature targets and avoiding the impacts that accrue with warming. Such policies potentially yield many co-benefits, including the delivery of ecosystem services and biodiversity conservation. Some countries, notably Brazil and Indonesia, have included deforestation reduction in their mitigation pledges under the Cancun Agreements. In particular, Brazil has set a target to reduce deforestation by 80% of the 1996-2005 average by 2012, and in June 2012 announced record low deforestation levels since records began 23 years ago. Our research highlights how necessary such stringent action to reduce deforestation rates is for reaching UNFCCC goals.

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Figure 1a-d Probability of remaining below various CO_2e concentration thresholds (b, b) or below various thresholds for ΔT (c, d) in 2100, in the 450N (a, c) and 550N (b, d) scenarios as potential future deforestation between 2010 and 2100 is raised from zero to the rates shown. In panels (a,c) the fossil fuel and non-forest LUC mitigation scenarios 450N, 550N are such that greenhouse gas concentrations stabilize in 2100 without overshooting at 450, 550 ppm CO_2e respectively when tropical deforestation ceases in 2010.

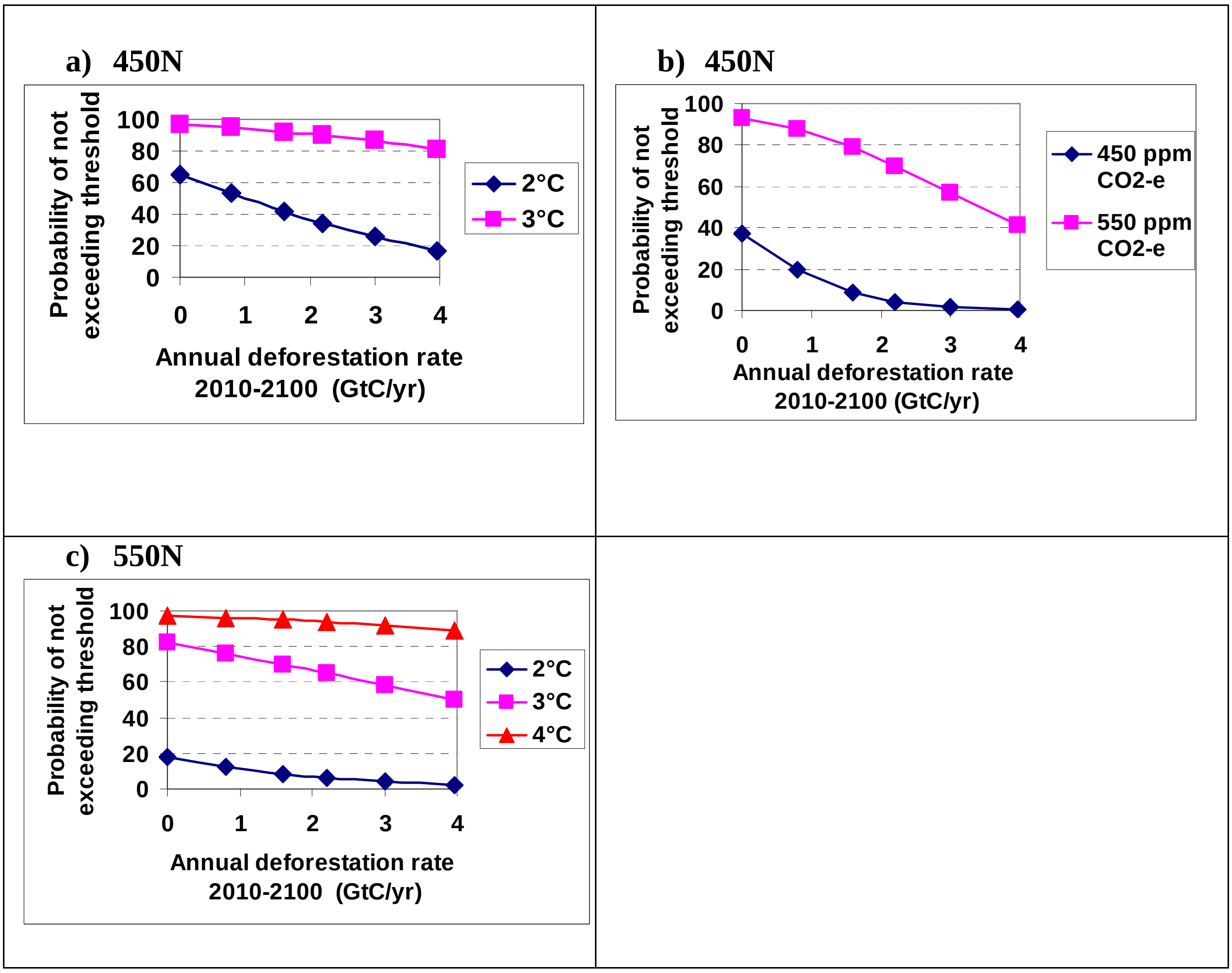
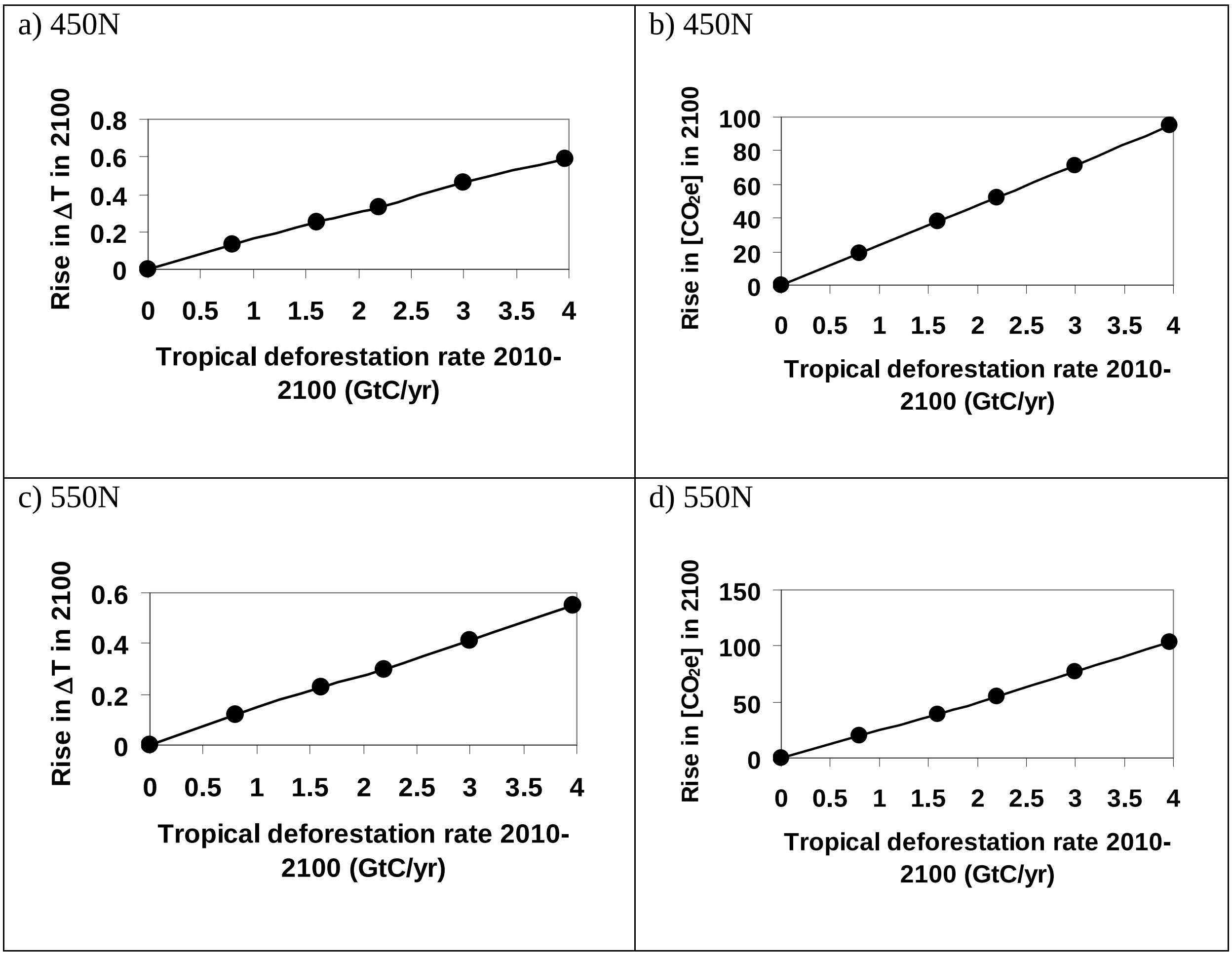
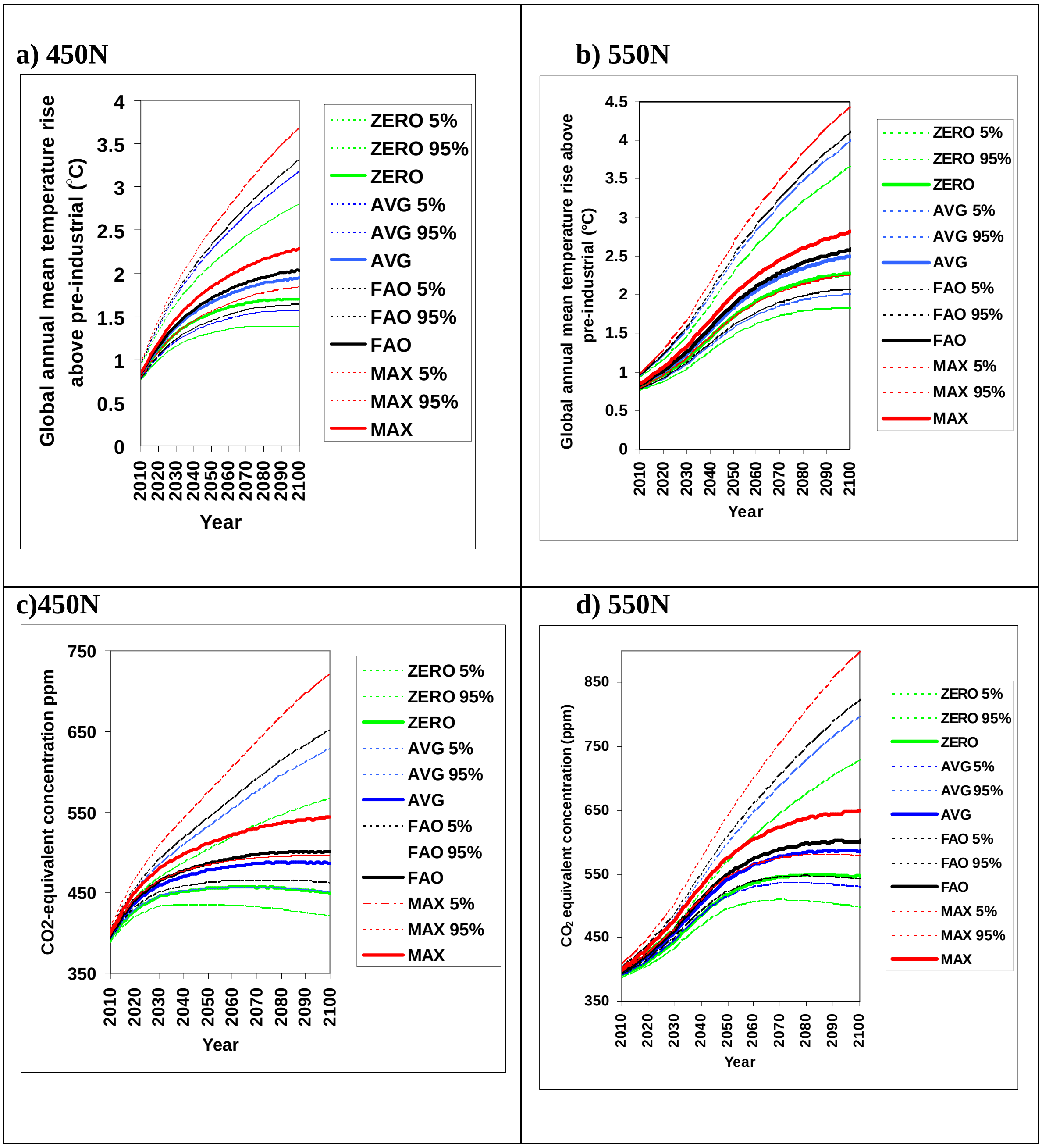


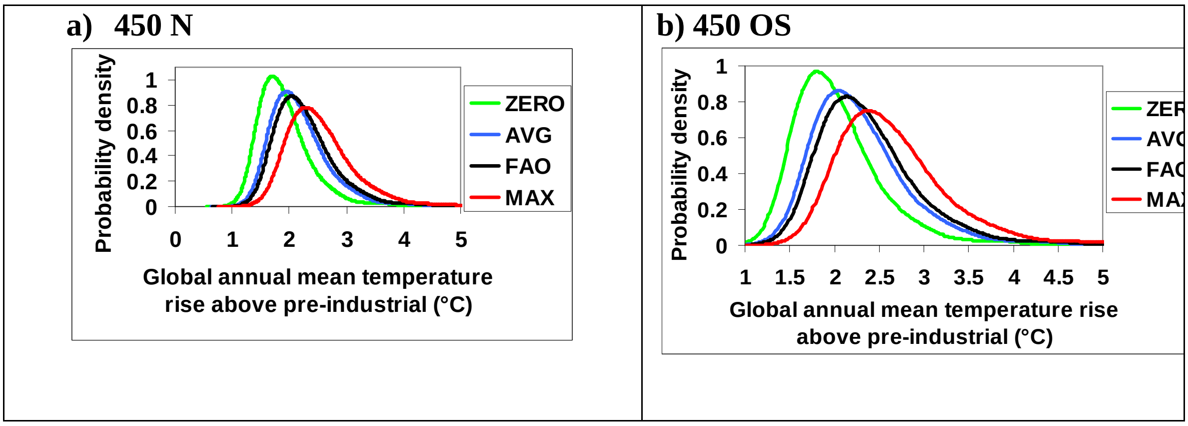
Figure 2a-d Potential additional increases in most likely values in 2100 of (a, b) $CO2_e$ and (c, d) ΔT in emission reduction scenarios in the 450N (a, c) and 550N (b, d) scenarios as potential future deforestation between 2010 and 2100 is raised from zero to the rates shown. In panels (a,c) the fossil fuel and non-forest LUC mitigation scenarios 450N, 550N are such that greenhouse gas concentrations stabilize in 2100 without overshooting at 450, 550 ppm CO_2e respectively when tropical deforestation ceases in 2010.



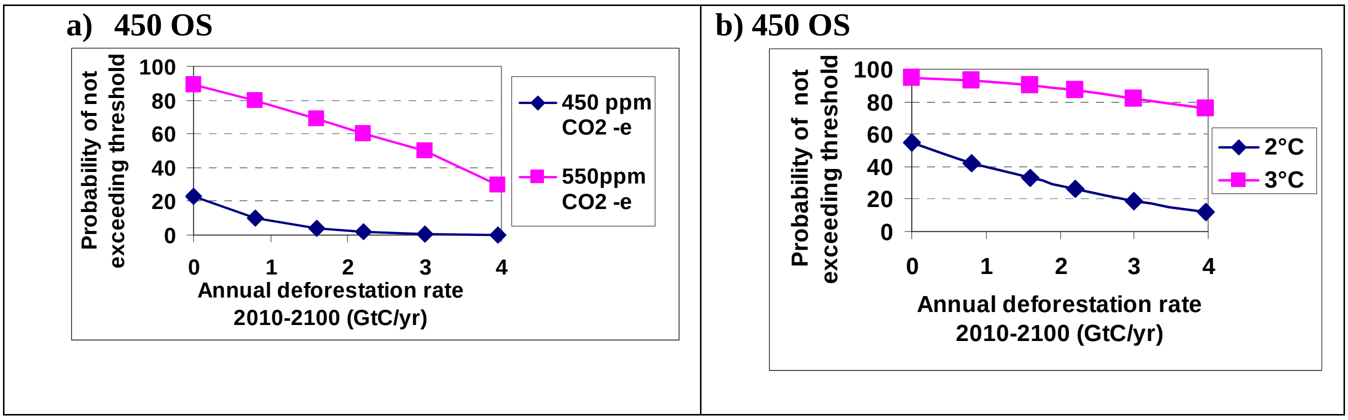
Supplementary Figures



Supplementary Figure 1a-d Most likely value, 5% and 95% percentiles for ΔT outcomes(a,c) and CO_2e outcomes (b,d) in scenarios with strong mitigation of fossil fuels combined with 2010-2100 annual deforestation rates of 0 (ZERO), 1.6 (AVG), 2.2 (FAO) and 3.96 (MAX) GtC/yr.

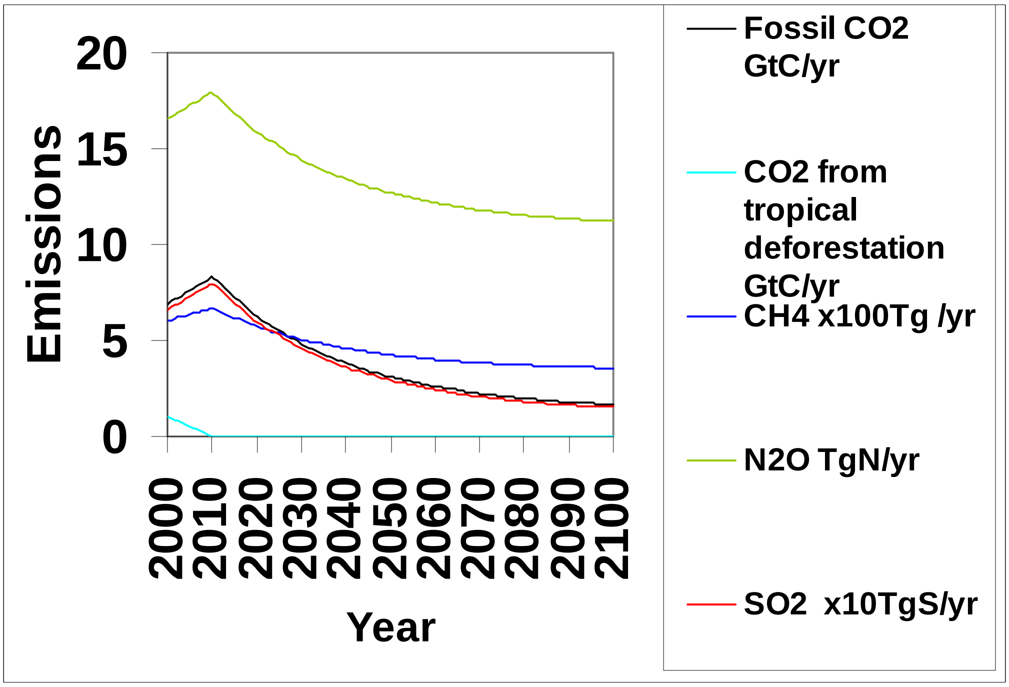


Supplementary Figure 2a-b. Simulated probability distribution in 2100 of global annual mean temperature rise in scenarios in (a) 450N and (b) 450OS with strong mitigation of fossil fuels combined with a range of annual tropical deforestation rates between 2010-2100 (for legend see Supplementary Figure 1a-d)

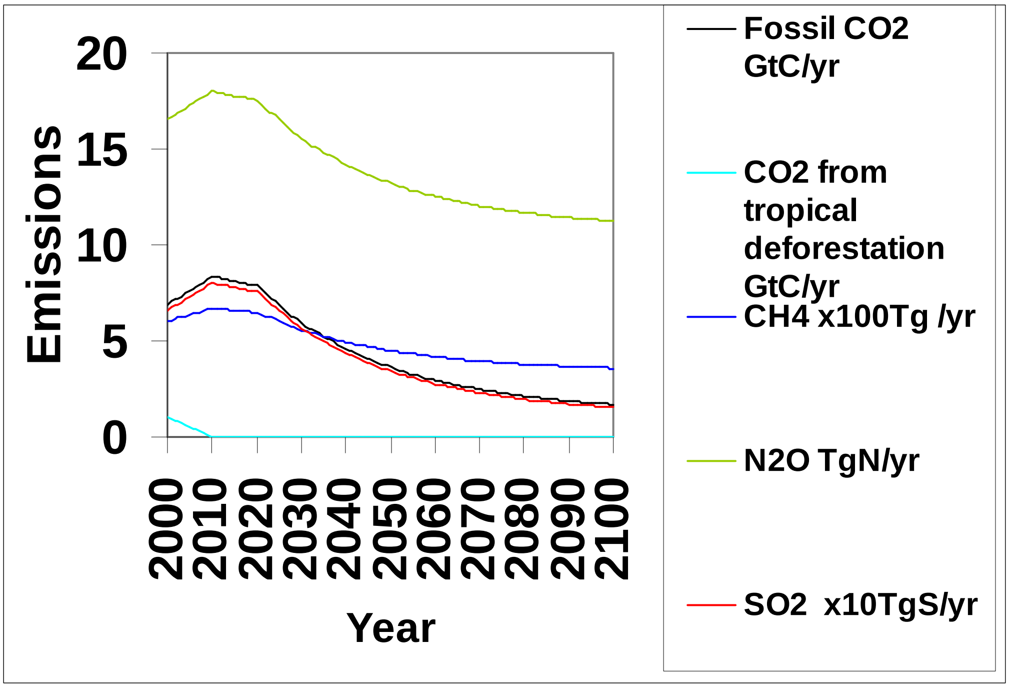


Supplementary Figure 3a-b Probability of remaining below various CO_2e concentration thresholds (a) or thresholds of temperature rise (b) in 2100, in the 450OS scenario as potential future deforestation between 2010 and 2100 is raised from zero to the rates shown.

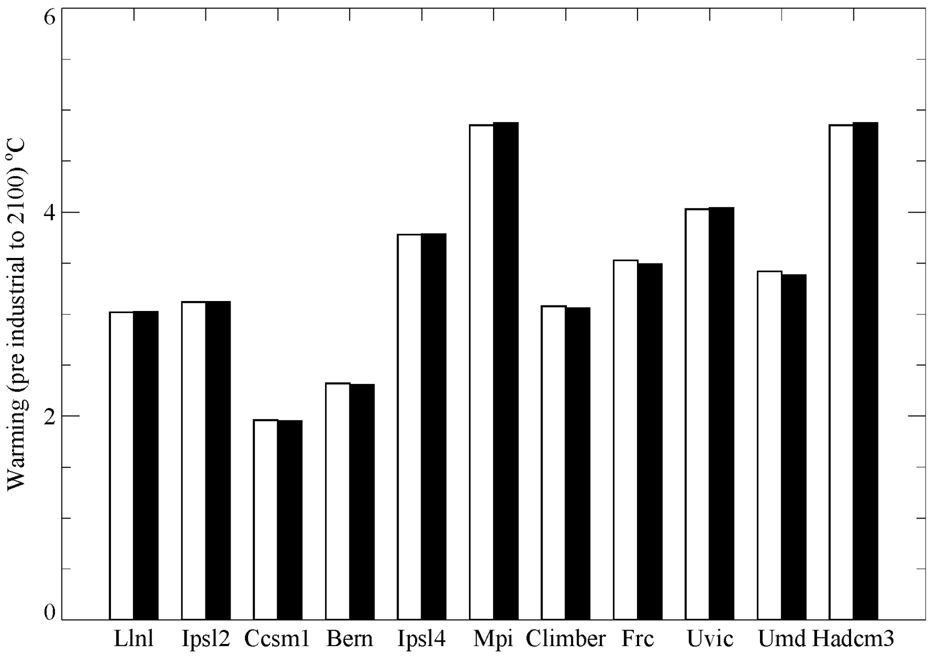
In Figures 3a,b and 5a,b: in emission reduction scenarios 450N, 450OS respectively, when tropical deforestation ceases in 2010, greenhouse gas concentrations stabilize at 450 ppm CO_2e by 2100 (without, with) 'overshooting' the value of 450 prior to 2100.



Supplementary Figure 4a. Greenhouse gas emissions in the 450N scenario



Supplementary Figure 4b. Greenhouse gas emissions in the 450OS scenario



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Supplementary Figure 5. An inter-comparison of the MAGICC model's ability to reproduce the global warming projected by the more complex models that took part in the C4MIP study. The white bar shows the projection made by MAGICC for a CO_2-only version of the SRES A2 scenario when appropriate parameter values are chosen. The black bar shows the more complex model results for the same scenario.