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Preface:

Tropical forest makes an approximately neutral contribution to the global carbon cycle, with intact and recovering forests taking in as much carbon as is released through deforestation and degradation. In the near future, tropical forests will likely become a carbon source, due to continued forest loss and the impact of climate change on the remaining forests' ability to capture excess atmospheric CO_2. This will make it much harder to keep global warming below 2° C. Encouragingly, recent international agreements commit to halting deforestation and degradation, but a lack of fundamental data for monitoring and model design makes policy action difficult.

Tropical forests have played a critical role in the changing atmospheric carbon concentrations of the industrial age, acting both as a very significant emissions source as they have been logged or burned, but also as a carbon sink, as the remaining forests have taken in much of the extra carbon added to the atmosphere. To illustrate this, from 1960 to 2015 anthropogenic emissions of carbon totalled 408 PgC, 80% from burning fossil fuel and making cement, and 20% from (largely tropical) land use change[1]. However, the atmospheric CO_2 stock grew by 'only' 180 PgC over that period[2], meaning that 55% of these emissions were taken in by the Earth system, reducing the climate change caused. There are uncertainties around the relative contributions of the three main locations of this sink, namely the oceans, northern hemisphere forests, and tropical forests[1], but likely between a quarter and a third was due to the enhanced growth of trees in tropical forests[3,4,5]. Understanding the size and causes of this sink is crucial for predicting its evolution over the coming century: the tropical land sink is known to be very variable year-to-year[1,6,7,8,9], and reverse to a source in hotter years[10], suggesting there is a real risk that over the coming decades under climate change it will become a major source every year.

The tropical land sink is the least certain major component of the global carbon budget[1]. There are various possible ways of estimating its size (Box 1), but none estimates the sink directly, and all have high uncertainty due to either sparse sampling[5,11,12,13,14,15] or coarse resolution[6,7,10]. As a result, the main way the land sink has been estimated is as the residual of the sum of all other components of the global carbon cycle[1]; however with this method it is not possible to estimate the relative contribution of the northern hemisphere and tropical forests to the sink. Further, some other components of the global carbon cycle are also very uncertain and variable, such as the Land Use Change (LUC) flux[1,16], making accurately estimating trends in the sink very difficult. This uncertainty greatly limits the development and testing of theories and models, and thus means there is a wide divergence of predictions as to how the sink will change under different climate change scenarios and policy interventions.

Considering all sources of evidence, it appears likely that tropical forests are in the process of switching from being approximately neutral, to a net source, as the intact forest sink declines in size[1,3,7,17,18]. This decline is caused by a combination of the decrease in the area of intact forest[19,20], and increasing temperatures and drought reducing trees' ability to respond to higher CO_2 concentrations by growing faster[12,13]. With both forest loss and climate change likely to accelerate over this century, tropical forests are likely to release ever more carbon, making keeping global warming to less than 2° C above pre-industrial levels very difficult[21,22].

The carbon balance of tropical forests

Living tropical trees store 200-300 Pg of carbon[5,23,24,25], about a third as much as is held in the atmosphere[1]. This stock is very dynamic: tropical trees perform about 60% of the the world's photosynthesis, capturing ~72 Pg of carbon from the atmosphere every year[26], but also releasing a similar amount back to the atmosphere through respiration of both the plants themselves and other organisms[17,27]. Given these large fluxes, a small proportional change in either the uptake or release of CO_2 can result in a large net source or sink. There are multiple lines of evidence that over at least the past 50 years these two processes have been out of balance, with tropical vegetation increasing in biomass by >2 Pg C yr^{-1}, about 1 % per year[5,28,29]. It is clearly though that this sink has very high inter-annual variability, driven by temperature and rainfall fluctuations[16,30,31].

The tropics are also the main nexus of global land use change, with deforestation and forest degradation (where some trees are removed but the area retains sufficient trees to be classed as a forest) releasing somewhere between 0.5 and 3.5 Pg C yr^{-1} (refs 7,20,32,33,34,35,36,37). The wide range of estimates is partly due to differences in time period, but mostly caused by differing definitions and included processes, different methods (Box 1), and wide uncertainty bounds.

Comparing different methods, there is consensus that the overall carbon balance of the tropics was approximately neutral over the past decades, with sinks in intact and regrowing forests equal in magnitude to sources from deforestation and forest degradation[4,5,7](Fig. 1). However, it is also clear that in abnormally hot years, such as during strong El Niño events, the tropics becomes a major net source[1,10] (Fig. 1d).

The following section examines the current magnitude of the major sources and sinks. Then the evidence for trends in these over recent decades is considered, along with their likely future pathways, and whether international policy can change these trends.

Carbon sources

Deforestation is easy to map using optical satellite data, with free Landsat satellite data meaning most countries produce their own maps[20], with large scale independent maps also available and broadly consistent[19,39]. Deforestation affects very large areas: about 100 Mha were deforested in the tropics from 2000-2012, about 50% in Latin America, 30% in SE Asia, and 20% in Africa (ref 19 using a forest definition of >25% canopy cover; similar values are found in studies[20,39]). The main drivers of this deforestation differ by location, with large-scale commercial agriculture/pasture and mining dominating in much of Latin America, palm oil and pulp/paper plantations in SE Asia, and smallholder agriculture and only more recently mining and commercial agriculture/plantations driving deforestation in Africa[32].

Estimating the carbon released from deforestation is more difficult than assessing its spatial extent. Often estimates are produced by simply multiplying the area deforested by a single carbon density per unit area value, with the result therefore very sensitive to that single value: normally this is the mean carbon density from a number of local forest inventory plots, but to be accurate they must be numerous and representative of the type of forest deforested. At a pantropical scale recent studies have improved on this by overlaying the deforestation data on continuous maps of carbon density[7,32,35,37], though such methods have errors caused by their carbon data having a coarser resolution than their deforestation data, and the carbon maps having potential large regional biases[25,40]. Overcoming these issues, there has been some consensus in recent years that the flux from gross tropical deforestation in the 2000s was 0.6-0.8 Pg C yr^{-1} (refs 32,35).

In contrast, it is much harder to estimate the area affected, and carbon losses caused, by forest degradation[41,42]. Partly this is because degradation is caused by a wide variety of processes with different impacts, including commercial logging, fuelwood extraction, sub-canopy cultivation, grazing, fire, and edge effects caused by nearby deforestation[41,43]. But further it is because the only remote sensing methods that are sensitive to degradation are coarse resolution, with each pixel containing twenty to thousands of hectares[4,6,7,10,14,15,36,44], and thus far exceeding the <1 ha size of most degradation events[42,45]. This means that estimates inevitably mix the fluxes from deforestation, forest degradation, regrowth of previously disturbed forest, as well as changes in intact forest, into a single combined change per pixel.

There are studies that have used inventory plots to estimate fluxes from degradation[46,47], however these give numbers on a per hectare basis that are hard to scale, as we do not have maps of degradation. High resolution remote sensing from LiDAR[48] or Synthetic Aperture Radar[45], combined with local field biomass plots, can directly map the carbon stock changes from deforestation, degradation and regrowth at a suitable resolution, but so far such studies are rare and have only been used for small areas, so cannot help much with pantropical estimates. They can however show the broad ratio between carbon losses from deforestation and degradation; though this varies widely in space and time, there is a suggestion that at a large scale degradation is responsible for perhaps twice the carbon release of deforestation, with great regional variation[7,45]. Further, there is agreement that degradation is more significant as a proportion of total emissions in Africa than in South America or SE Asia[29,38,41,42].

Tropical peat forests are independently a major potential source of carbon. Peat is carbon-rich partially decayed organic matter, associated with waterlogged and acidic conditions, which exists in layers up to 20 m thick under tropical swamp forests. Recent large discoveries under the forests of the Congo[49] and Amazon[50] basins has increased the known area of tropical peat by 50% to 577,000 km^2 (combining figures from refs[49,51]). These peat forests have very high carbon densities, meaning they have the potential to make an outsized contribution to the global carbon cycle: about 5% of tropical forests overlay peat, but they store 70-130 Pg C (ref 49), significant compared to 200-300 Pg C in all tropical trees[5,23,24,25]. The majority of tropical peat is in SE Asia, which has been extensively cleared and drained in recent decades (over half the area present in 1990 had been deforested or degraded by 2008[52,53]), therefore contributing significantly to land use change emissions by releasing 0.3-0.54 Pg C yr^{-1} (refs 3,16). This large flux is included in the land use change numbers in Figure 1, but excluded from normal values giving the deforestation flux (e.g. refs 7,32,35,37), as such methods exclude below-ground carbon. Further, intact, degraded and drained peatlands in SE Asia have been subject to fires in El Niño years that have released much larger quantities of carbon: up to 2.5 Pg C in a single year, sufficient to cause noticeable anomalies in the atmospheric CO_2 growth rates[10,54]. In contrast, the peatlands of the Congo and Amazon basins were until recently largely undisturbed, so are not currently thought to contribute significantly to the land use change flux[55].

Even undisturbed peatlands are however likely losing carbon due to climate change[3,51,53]. This is hard to monitor because satellites can only see the trees, but the vast majority of the carbon in peat forest ecosystems is instead stored in belowground as peat. Gruelling fieldwork to ascertain peat depths and extract cores for chemical analysis is a necessity to ascertain carbon stocks, but these point estimates are hard to scale to large areas due to great spatial variability[49,53]. Tracking losses is further complicated because of the range of mechanisms through which peats can lose carbon: respiration in peats releases CH_4 as well as CO_2; burning releases CO and C in addition to CO_2; and dissolved and particulate organic carbon is washed away in rivers. There is some data on non-CO_2 emissions: both satellite and modelling datasets suggest that all tropical peatlands are significant methane sources[56], and field data suggests that both intact and disturbed peats in SE Asia have significant fluvial organic carbon transport, which has increased by >30% from 1990-2008[52]. While more baseline data is needed, it seems likely that climate change caused warming and droughts are resulting in peat forests being net sources of carbon[3,29,51,53].

Carbon sinks

The remeasurements of millions of trees in networks of forest inventory plots across the undisturbed forests of Latin America, Africa and SE Asia suggest these forests have all been gaining carbon at a similar rate of ~0.5 Mg C ha^{-1} yr^{-1} over the past decades, adding up to a total sink of a little over 1 Pg C yr^{-1} (refs[5,13,57,58]). Though it has been suggested that artefacts in plot remeasurements could lead to erroneous findings of increasing carbon storage with time[59], there is also considerable evidence of a sink of around this magnitude from independent methods, such as atmospheric inversion studies[4,14,15], satellite data[7,36], and models[17], so there is little doubt that it exists.

Regrowing and disturbed forest are also clearly taking in carbon from the atmosphere, but as with forest degradation, there is little reliable data on the magnitude of this sink. Studies tracking individual field plots show great variation: following total clearance there was no increase in biomass at all after 20 years at a site in Uganda[60], but over 10 Mg C ha^{-1} yr^{-1} throughout the first ten years in moist sites in Latin America[11]. A meta-analysis of 1468 plots in 45 sites found average recovery rates of 3.05 Mg C ha^{-1} yr^{-1} for the first 20 years, and that sites regained 90% of old-growth biomass values after a median of 66 years[11] (though biodiversity does not recover in these timescales[11,42,60]). As we do not have good maps of past disturbance it is hard to turn plot values into tropical estimates, but these data are consistent with inversion studies and satellite observations of a current flux with a similar magnitude to the intact forest sink (i.e. 1 Pg C yr^{-1}), with large uncertainty[3,4,5].

Trends in the sources and sinks

Despite the uncertainties related to individual components, we do have a reasonable understanding of the carbon balance of the tropics in the recent past, with various methods agreeing that the tropics make an approximately neutral contribution to the global carbon budget[3,4,7,36] (Fig. 1). However, we are much less certain about how the system is changing.

While there is general agreement that total forest area is shrinking across the tropics, there is considerable controversy as to whether the rate of loss is rising or falling. Official figures from the Food and Agriculture Organisation (FAO, collated from national statistics) show a decline in annual net forest loss rates since 2000[20,38], whereas satellite-based data see an increase in the loss rate[19] (Fig. 2). Some of this difference can be explained by differing definitions of forest and the precise area compared, but the difference in trend is too large to be explained by these alone. It has long been known that FAO statistics are not ideal for analysing trends[61]: while some tropical countries probably produce very good data, their monitoring capacity is variable[62]. As an example, 14 African countries have reported exactly the same annual change in forest area every year from 1990 - 2015[38], even though other datasets see significant changes in their rates of loss through time[33].

On balance, the evidence from the remote sensing data sources appears more reliable than the FAO data. This is because the data from Hansen et al.[19] is produced consistently across the tropics; detects country-level trends where we have good alternative sources of data, for example correctly seeing the rapid reduction in deforestation in Brazil[63], and the recent rapid acceleration of loss in the Democratic Republic of Congo[64]; and matches well to detailed high resolution data in a study comparing areas with different patterns of forest loss[65]. It is therefore likely that the rate of deforestation in the tropics is increasing.

Over the coming decades, as the global demand for agricultural, timber and mineral commodities, and local population density, continue to grow, it seems likely that the rate of forest loss will continue to increase[32,63,64]. Current areas that are largely undisturbed due to inaccessibility, such as the peat forests of the western Amazon and the Congo, will likely become accessible and suffer deforestation[55]. Eventually the rate of forest loss will stabilise and start to fall, partly because the area of remaining unprotected forest will have greatly decreased, but also because the that once countries reach a sufficient level of economic development and forest loss, policy and civil society drivers result in the remaining forest area stabilising or even increasing[66]. However this point may come only once most forest has been lost, and even once countries reach this point (such as Vietnam, China or much of the developed world), they themselves will export deforestation to less economically developed countries as their economies demand increasing levels of commodities[67]. The case of Brazil makes an interesting case study here: it greatly reduced its rate of forest loss from 2005-2014[19], due to reductions in global commodity prices and policy interventions[63], but the rate has since increased again and could climb faster as the global demand for agricultural and mineral commodities increases, and laws promote development not forest protection[63,68].

Forest degradation is hard to map and monitor: as discussed previously there is little hard evidence about its overall current magnitude, let alone trends, though we suspect it involves a much larger area than deforestation each year[7,44,45,46]. Normally degradation appears to be closely associated with deforestation[44], and it is reasonable to assume in the future as the area of forest that is accessible increases, due to fragmentation caused by deforestation and road building, the area of forest degraded each year will also increase. About 20% of all tropical forest is now within 100 m of an edge, with 84% of these edges anthropogenic, and this proportion will continue to increase as more anthropogenic edges are created each year than closed up[43]. Commercial logging, a major direct cause of degradation but also a driver of increase fragmentation and access roads, also seems likely to increase in impact as ever more logging concessions are granted[41,42]. Degradation due to fire may also increase with time due to climate change, as well as increasing fragmentation[42]. Overall it is hard to believe that the area of forest degraded each year is not increasing, nor that it will stop increasing in the near future.

As the area of degraded forest increases, so does the area of forest with the potential for regrowth; thus the proportion of the forest sink that comes from previously disturbed forest is likely to increase with time[3]. Disturbed forest normally takes up carbon much faster per hectare than undisturbed forest, though with high variability[11,69]. Under climate change the rate of growth that could be achieved by disturbed forest could increase further, due to CO_2 fertilization[17,70]. However, other factors (increased temperature, changing precipitation) could negate this effect: a specific modelling test as to whether land use change increased the land sink under an extreme CO_2 scenario found only one of four models predicted an increased sink, with the others showing no increased sink[70]. Fundamentally the size of the sink from regrowing forest is very hard to model using current knowledge, with a high level of divergence between models[71]. Separately, there is evidence that in the long term, once deforested, land is ultimately normally permanently converted to agriculture, pasture or settlements; and most degraded land is itself ultimately deforested[72]. This pattern is unlikely to change as the global economy and population continue to grow, so ultimately carbon captured in the regrowing sink may not remain captured long.

It is also difficult to predict how the intact forest sink will change with climate change because we know that climate change will have opposing pressures[5] (Figure 3). Theory and modelling studies generally agree that the most likely cause of the sink is CO_2 fertilisation: as atmospheric CO_2 concentrations have risen from ~280 ppm in 1850 to over 400 ppm today fixing carbon through photosynthesis is easier, with CO_2 concentrations in leaves increasing for a given level of stomatal opening (itself limited by water availability)[17]. This effect should continue as CO_2 levels increase[8,17], but climate change will also raise temperatures, increasing soil and plant respiration rates, and droughts and fires will also increase, directly killing trees (Fig. 3). Further, deforestation and degradation will continue to reduce the area of intact forest that can act as a sink. Many studies therefore suggest that climate change could lead to a reduction in the sink strength, and ultimately its reversal into a source[10,73,74,75,76]. There is evidence from networks of field plots that this is already happening, with the sink magnitude decreasing through time[12,13].

However, models do not generally predict a reduction in the land sink, with many predicting the CO_2 fertilisation will offset the negative influence of climate change on ecosystem respiration and tree mortality[8,17,70,77]. For example, six coupled climate models run under the same CO_2 growth scenario found changes in tropical land carbon storage between 1960-2099 ranging from -11 Pg C to +319 Pg C, with a mean of +172 Pg C (Ref 8). The differences between these models is mostly caused by differences in the sensitivity of tropical vegetation to temperature, and the extent to which temperature rises due to non-CO_2 forcings (for example reduction in aerosol concentrations or other greenhouse gases), which do not come with the positive CO_2 fertilization effect[8]. The variability in model prediction of the current size of the intact forest carbon sink[8,71,78,79], and model's lack of critical factors such as mortality of large trees caused by droughts[76], makes it difficult to use model-based predictions for predicting trends in the forest sink. Therefore the best evidence is from field plots[12,13] and satellites[6,10], which show that the intact forest sink is weakening, and becomes a source in unusually hot years, suggesting that it will likely reverse under climate change.

There is so little data on the carbon balance of intact peat forests that it is hard to speculate with confidence how they are changing. But it is likely that increasing temperature and variable precipitation has increased the rate of carbon loss, especially when combined with draining and other disturbance, and that such losses are likely to accelerate in future[49,52,53,55]. However there are high uncertainties, and an increase in basic observations of peat forests are urgently needed.

Modelling the future of tropical carbon

From recent trends, it appears likely that the current major sources of emissions (deforestation and degradation of forests, including peat forests) will at least stay stable or likely increase over the coming decades[32,63,64], whereas the current sinks (from intact and regrowing forest) will likely reduce, and could reverse and become sources[10,73,74,75,76]. Therefore it is very likely that tropical forests will become a net source of CO_2 to the atmosphere in the near future, if they have not already[3]. Estimating the size of this tropical source through time is very difficult though, even when considering a specific scenario of land use and climate change, due to complex feedbacks and interactions between different elements of the carbon cycle, climate change, people, policy and the global economy.

The climate modelling community has produced ever more complex models that include the complex feedbacks between land use change, climate change and intact forest[71]. A noticeable difference between the 4th and 5th Assessment Report of the International Panel on Climate Change (IPCC) is that the latter uses Earth System Models (ESMs) for much of its predictions, rather than Atmosphere-Ocean General Circulation Models (AOGCMs)[29]. ESMs include all the processes of AOGCMs, but add representations of biogeochemical cycles, including the full carbon cycle, and couple these cycles with other components allowing for feedbacks. For example, deforestation in a AOGCM simulation will increase the atmospheric CO_2 concentration, and change the physical properties of the ground surface, but only in an ESM will the smoke and dust released from deforestation, and their subsequent effect on atmospheric chemistry and the rate of photosynthesis of the remaining trees, be modeled[71].

In order to standardise the inputs to modelling climate change under different scenarios to 2100, for is 5th Assessment Report the IPCC developed four Representative Concentration Pathways (RCPs)[29]. These are trajectories of atmospheric greenhouse gas concentration and consequent radiative forcing, and are named after the radiative forcing in the year 2100 relative to pre-industrial levels in W m^{-2}: RCP2.6, RCP4.5, RCP6 and RCP8.5. They are based on underlying assumptions about social and technological development, and the extent to which climate mitigation activities take place, with RCP8.5 assuming annual fossil fuel emissions increase rapidly to about 2070 before eventually stabilising, whereas RCP2.6 assumes emissions peak by 2020 and then decrease rapidly[80]. Ideally it would be possible to provide confident predictions for the size of the forest sinks under these different scenarios, but unfortunately ESMs still have high variability in their predictions of the tropical carbon cycle, and cannot agree as to whether the tropical land surface will gain or lose carbon overall under the different scenarios[8,81]. Much of the uncertainty in tropical land surface prediction (~80%) is caused not by scenario uncertainty but differences in model structure[71], specifically for the tropics dominated by differences in predictions of the effect of specific climate parameters and CO_2 concentration on NPP and vegetation turnover (including structural shifts, wild fires and mortality)[82]. It is thus urgent that we improve our knowledge of how the components of the tropical carbon cycle function, in order to better design and test such models.

Policy impact on tropical forests

The extreme RCPs (RCP2.6 and RCP8.5) assume similar levels of conversion of tropical forest to agriculture[81], with the differences coming largely from the degree of fossil fuel burning. However, in reality big developments in national and international policy since the last IPCC report in 2013 have made reducing tropical deforestation and degradation, and restoring previously degraded and deforested tropical land, a key pillar of reducing climate change. This is sensible, as unless tropical deforestation and degradation is reversed the task of halting the rise in atmospheric CO_2 concentrations would involve decarbonising the global economy at a likely unfeasible rate[21,22], and offers the possibility of a different path for the tropical carbon cycle than continuing current trends.

The Paris Agreement of 2015, now ratified by 176 of the 197 countries of the UNFCCC and having entered into force in 2016, aims to keep increases in global average temperature to ’well below 2°C above pre-industrial levels’. It does not set specify how this should be reached, but includes a strong statement in Article 5 that countries ’*should* take action to conserve and enhance … forests’[83]. In order to assist developing countries with meeting Article 5, it ‘encourages’ all countries to engage in REDD+ (’reducing emissions from deforestation and forest degradation, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries’)[83]. The details of financing and monitoring have yet to be agreed, but there is significant optimism that REDD+ can succeed in increasing the area of forest, and the proportion of it that is undisturbed, compared to business as usual[32,84,85]. Most tropical countries have thanks to ‘REDD Readiness’ funding increased their capacity to monitor changes in their own forests[62], and are submitting Forest Reference (Emission) Levels, official baselines against which future emissions can be compared, and plans for reducing emissions below these levels if funding is provided.

Though the Paris Agreement is ambitious in overall terms, its proposals on forests lack concrete detail, stating only that countries should ‘take action’. However, there are other international agreements involving many or most of the same countries that are more specific. For example, the New York Declaration on Forests, signed by 192 organisations including 40 governments in 2014[86], aims to: “At least halve the rate of loss of natural forests globally by 2020 and strive to end natural forest loss by 2030”. This was ambitious, but some believed it was achievable[32]. More ambitious still, the UN Sustainable Development Goals[87], agreed in 2015, include as Target 15.2 an aim to “By 2020 … halt deforestation”. This was included not just because preventing climate change is a key aim of the SDGs, but because healthy tropical forests are important for the achievement of most of the 17 SGDs[66]. Few believe deforestation can really be stopped so fast, but these international agreements will spur at least some countries to enact policies to greatly reduce their deforestation rates[32,63].

The New York Declaration on Forests further aims to restore 150 million hectares of currently deforested or degraded land by 2020, and 350 million hectares by 2030.

There are worries related to these ambitious targets: there is a risk that natural grasslands will be afforested, leading to a loss of biodiversity and potentially also soil carbon[88], or that agriculture will be displaced by restored forest, leading to more deforestation elsewhere[89]. Also many countries have not committed to meet their goal solely through natural forest (e.g. through leaving degraded land to regenerate naturally, with the greatest ecological and long-term carbon benefits), but instead will plant monocultures of exotic tree species such as teak and rubber. Nonetheless, this overall enthusiasm for restoration of forests should be positive for tropical carbon storage (Fig. 3), and if the sites are chosen well and the restoration type carefully considered, it could be highly beneficial for people and the environment[21,89].

Looking further into the future, the Paris Agreement mandates that by the second half of this century remaining anthropogenic emissions will be balanced by sinks[22]. This will require a large program of capturing carbon directly from the atmosphere and storing it elsewhere[29]. As tropical trees are by far the most efficient carbon capture method known, a proposal called Bioenergy with Carbon Capture and Storage (BECCS) is proposed, which will generate energy through the burning of tropical plantations and store the CO_2 produced belowground[22]. To meet the negative emissions targets needed to keep global warming below 2°C by 2100, models suggest it would need to be implemented on an enormous scale (400 - 800 Mha, for comparison India covers 329 Mha)[22,29]. This would clearly make the tropics a major carbon sink, but with negative biodiversity and ecosystem services consequences.

Overall, these agreements are sufficient to dramatically change current trends, and if fully implemented would increase the forest carbon storage of the tropics markedly over the coming century. However, meeting the targets would involve drastic and coordinated action from people, policy makers and companies globally[32,63].

Safeguarding tropical forest carbon

The evidence suggests that unless the world makes a coordinated effort to change from its current course, deforestation, degradation and climate change will combine to make the tropics a net source of carbon to the atmosphere over the coming decades. This is despite increasing CO_2 levels making it easier for intact forests to photosynthesise and absorb carbon[8,17]. However, if we were able to stop deforestation and forest degradation, leave currently degraded forests to recover, and reforest, as targeted in international agreements, then tropical forests would instead likely become a significant carbon sink, contributing to the Paris Agreement goal of keeping mean global temperatures rises to below 2°C[21,22]. Keeping and restoring these forests would have further immense benefits to human wellbeing, through maintaining their biodiversity and ecosystem services[66]. However, two interconnected problems limit the achievement of these goals. Our spatial information on how forests are changing is poor, and a lack of field experiments means ESMs cannot predict well how forests will respond to different climate and land use change scenarios.

While we monitor deforestation well, we do not have good data on changes within forests. We have techniques that can observe the integrated carbon flux over large regions, but have very little knowledge of the size of the individual processes involved (such as degradation, regrowth, or the impact of droughts and fire). This makes it hard to design and implement policy: for example no country has reliable baseline figures on their rate of forest degradation[62], making it hard to set targets or create policies to reduce degradation under REDD+, nor receive payments even if such policies are successful. This also limits model development and testing.

New satellite mission such as GEDI and OCO-3 (both planned for launch in 2018), and BIOMASS (2021) will help by producing high resolution, globally consistent maps of forest carbon stock changes for the first time. These will not only assist with targeting and monitoring policies, but also allow us to discover the magnitude of the forest sink at an unprecedented resolution (< $1km^2$) and how local conditions and climate fluctuations influence it. However these satellites require pantropical forest inventory and airborne LiDAR data for calibration and validation. REDD+ will assist directly here: already significant funding has been spent on designing and setting up monitoring systems and capacity in developing countries[62]. Unfortunately the data collected is rarely made available to the international scientific community, as publishing such data is against the natural instincts of countries, who wish to protect their sovereignty (there are some exceptions, for example field and LiDAR data from recent carbon stock map of DRC is available at http://panda.maps.arcgis.com). Funders and scientists must persuade countries to be more open, or they will not obtain the full benefits from new satellite missions.

Better maps of forest carbon stocks will make a big difference, removing the current wide spread of figures on the carbon fluxes from tropical forests (Figs 1&2), supporting REDD+ and other policy efforts to reduce forest loss, and enabling the testing of ESMs and theories as to how tropical forests respond to climate fluctuations and disturbance events. However, these data will not improve our understanding of how forests will respond to climate and CO_2 conditions that do not currently exist, understanding that is necessary for improving ESMs. For this we need field experiments, such as those that artificially drought, warm or increase the CO_2 concentration of large tropical forest plots. Such experiments are expensive to run, and take many years to produce useful results[76], and therefore inevitably they are almost nonexistant in the tropics[90]. Their development should be supported by governments, as without them there will be no data to develop and test the critical next generation of ESMs[79].

Figure legends

Figure 1: Tropical forest carbon fluxes assessed using different methods

Annual fluxes (in Pg C yr^{-1}) into and out of tropical forests for different overlapping time periods (a-c) and for a recent El Niño year (d). The net intact forest flux is shown in blue, the net flux in regrowing forest is in pink, and the deforestation and forest degradation flux (including fire) is shown in red. Panels a-c shows there is broad agreement that the tropics have made an approximately neutral contribution to atmospheric carbon stocks in the recent past, but panel d shows that in hot and dry years intact forest can become a carbon source, leading to significant net emissions from the tropics. a) Ref 5: data from networks of forest inventory plots, combined with forest area data from country surveys or ref 38. b) Ref 7: data from annual 463 m resolution optical satellite data, calibrated using LiDAR data and field plots from the mid 2000s. Intact and regrowth fluxes are not separated in this method. The figures in the study have been grossed up from biomass to total carbon stock change (i.e. including dead wood, litter, soil) using the data in Ref 5 Table 2 (adding 16%). c) Ref 4: data derived from looking for overlap between atmospheric inversion, modelling and field plot estimates. d) Ref 10: data from satellites sensitive to atmospheric CO_2 concentrations for the 2015 El Niño year, contrasting sharply with the other estimates shown. Land use change could not be divided into separate regrowth and loss fluxes in this method.

FIGURE 2: Contradiction in major forest area change datasets

Satellite datasets and nationally reported statistics are in agreement about the rate of net tropical forest loss in the early 2000s, but diverge increasingly with time. Orange points and trendline (quadratic OLS): net annual forest loss from a systematic global satellite analysis from the University of Maryland (UMD)[19], Version 1.4. Forest gain is not assigned to a particular year in this dataset, so is here distributed equally across the time period to give net figures. A forest definition of 10% canopy cover in 2000 was used. Green points and trendline (linear OLS): net annual forest area change across tropical countries from the FAO FRA 2015[38], as summarised in ref 20. Forest area is reported at 5-year intervals, the change has been calculated between each interval and then divided by 5 to give annual data. A variety of forest definitions are used by countries when producing these figures, with canopy cover ranging from 10-30%. This means that the total area of forest considered for 2000 is higher in the UMD dataset, and would be expected to lead to consistently slightly higher deforestation for the UMD dataset than the FAO dataset. However this difference in forest definition cannot explain the differences in trend, as only ~5% of losses in the UMD dataset are in forest with canopy cover between 10 and 30 %.

Figure 3: The impacts of climate and land use change on the intact forest carbon sink.

The potential contrasting impacts of climate change and different land use change trajectories on the size of the intact forest carbon sink. Arrows pointing up show how climate change and policy could increase the magnitude of the sink, whereas arrows pointing down show how it will be reduced. All processes will occur to some extent, so predicting how the sink size will change is very difficult.

Box 1: Methods used to assess the tropical forest carbon balance

Forest inventory plots: marked areas of forest where tree diameters are measured and species recorded, enabling estimation of tree mass[91]. Revisiting networks of such plots every ~5 years gives precise estimates of how forest carbon stocks are changing[12,13,57], though uncertainties are increased because plots are rare and unevenly distributed, with some forest types undersampled. There are also plots that are intensively monitored to give insight into the detail of carbon allocation and use efficiency[92], and rare experimental manipulations that test the response of trees to conditions that do not naturally exist[76,93].

Atmospheric inversions: There is a sparse network of towers and marine measurement sites across the tropics that permanently collect greenhouse gas concentration and micro-meteorological data. These are supplemented by ship and aircraft data, and combined with atmospheric transport models to estimate the net flows of CO_2 into or out of the atmosphere at a broad, regional scale[4,14,15].

Satellites can be used to estimate:

- **Forest area** Landsat satellites have been used to produce consistent estimates of forest cover change since the early 1970s. Many countries produce their own maps, and global 30m resolution forest change data are available from 2000 onwards[19]. However loss data are much more reliable than gain, and relating the area-based data to carbon stock changes is difficult.

- **Carbon stocks** A unique LiDAR satellite operating in the mid-2000s collected distributed estimates of tree height in 70 m footprints, which were combined with field plots and other satellite data to make medium resolution (500 m – 1 km pixels) carbon stock maps[23,24], albeit with large uncertainties[40]. These maps enable estimates of emissions when combined with forest area change data[35], or when produced annually[7]. It is also possible to estimate carbon stock changes using passive microwave remote sensing[36], however the resolution (1-2 times coarser) makes it impossible to separate gain and loss fluxes.

- **GHG concentration** Satellites can measure the greenhouse gas concentrations of narrow columns of the atmosphere with a precision of ~1ppm CO_2. These measurements have been used to directly observe the carbon entering and leaving tropical forests, giving information about the size of the tropical forest sink and its reaction to droughts at a continental scale[6,10]. However cloud cover means the observations are sparse in time and space, and the coarse resolution once again means forest loss and gain fluxes cannot be distinguished.

Modelling: Given the difficulty with directly observing forest responses to rising CO_2 concentrations and climate changes, dynamic vegetation models are used directly to predict their responses[8,17]. The latest generation of models, Earth System Models (ESMs), include many more processes and feedbacks than traditional Atmosphere-Ocean General Circulation Models (AOGCMs), increasing their predictive power[71]. Models provide information on processes or time periods where we have no other data, and enable us to synthesise our current knowledge about the Earth system to predict the future under specific scenarios of climate and land use change[22].

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Competing interests

The author declares no competing interests.

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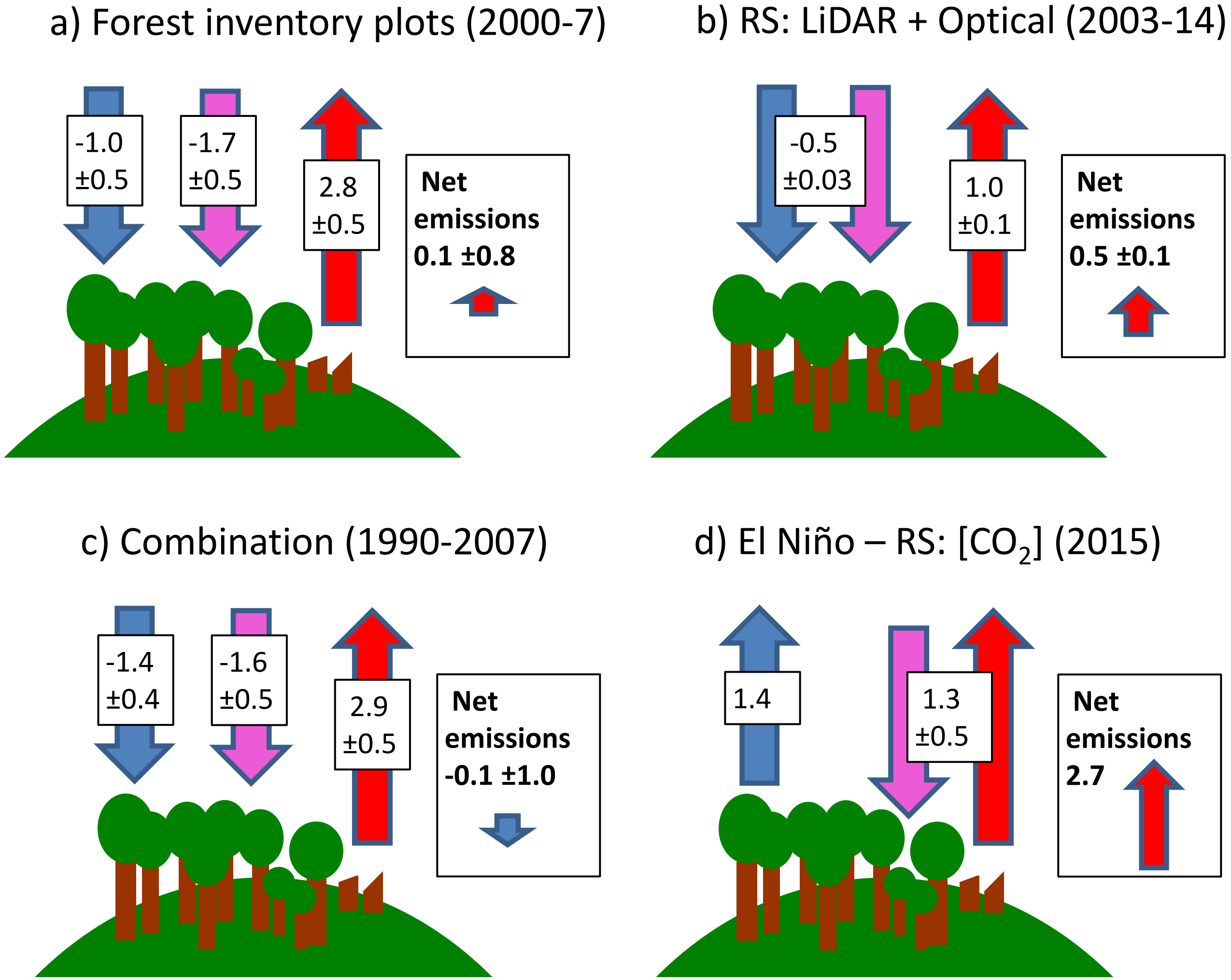
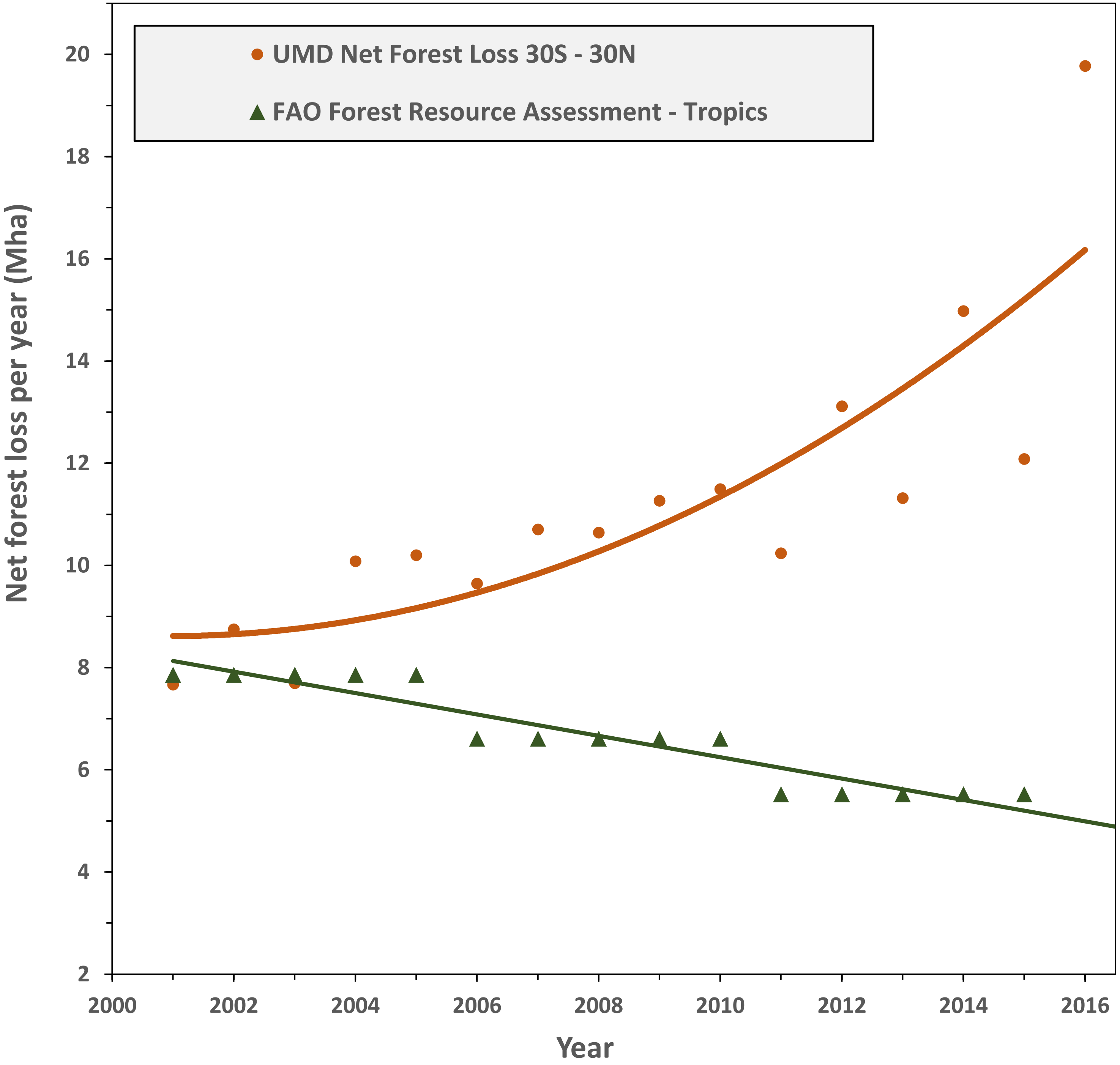

a) Forest inventory plots (2000-7)
-1.0 ±0.5
-1.7 ±0.5
2.8 ±0.5
Net emissions 0.1 ±0.8
b) RS: LiDAR + Optical (2003-14)
-0.5 ±0.03
1.0 ±0.1
Net emissions 0.5 ±0.1
c) Combination (1990-2007)
-1.4 ±0.4
-1.6 ±0.5
2.9 ±0.5
Net emissions -0.1 ±1.0
d) El Niño – RS: [CO2] (2015)
1.4
1.3 ±0.5
Net emissions 2.7

● UMD Net Forest Loss 30S - 30N
▲ FAO Forest Resource Assessment - Tropics
Net forest loss per year (Mha)
20
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8
6
4
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2000
2002
2004
2006
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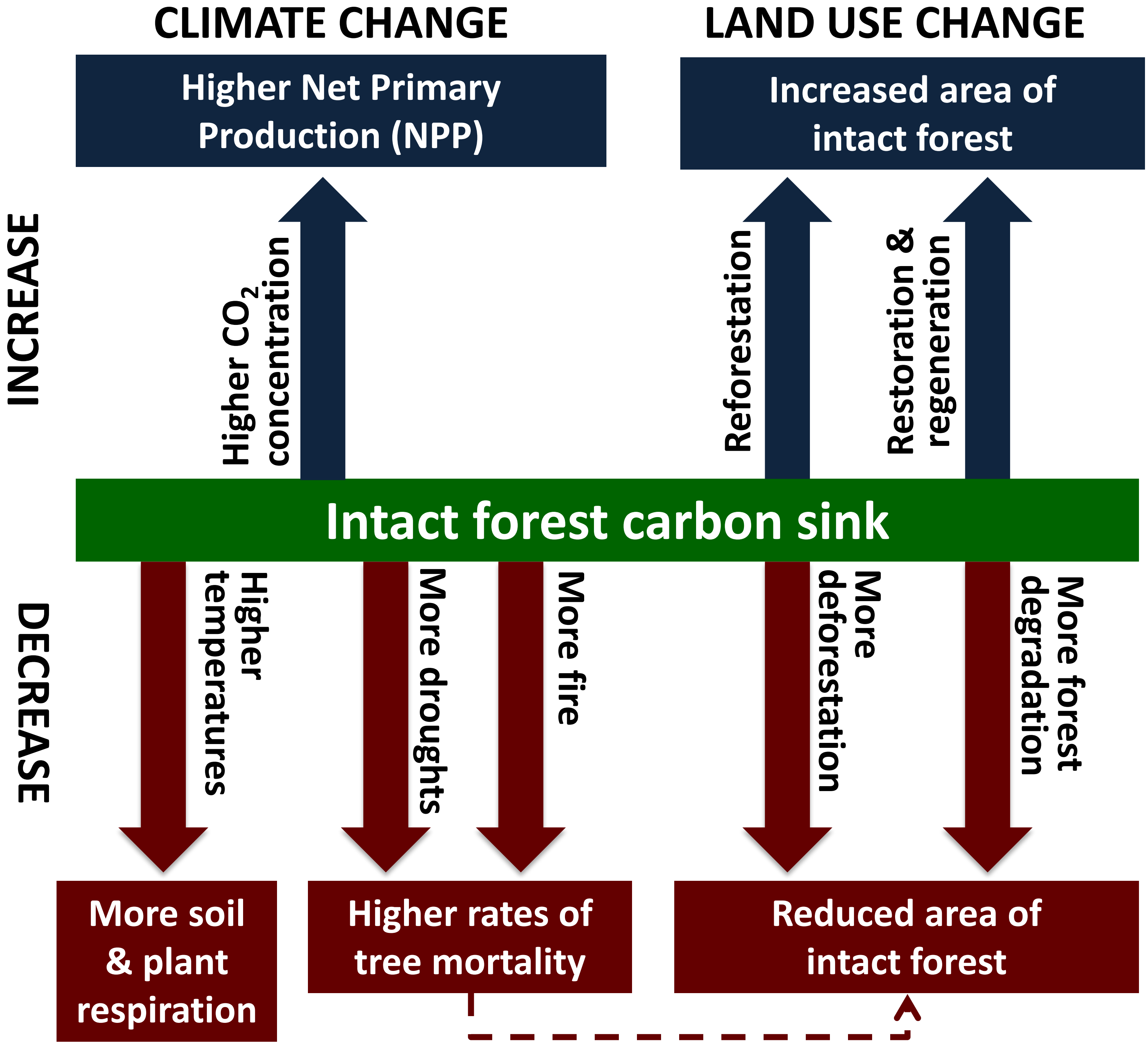
2010
2012
2014
2016
Year



CLIMATE CHANGE

LAND USE CHANGE

Higher Net Primary Production (NPP)

Increased area of intact forest

INCREASE

Higher CO_2 concentration

Reforestation

Restoration & regeneration

Intact forest carbon sink

DECREASE

Higher temperatures

More droughts

More fire

More deforestation

More forest degradation

More soil & plant respiration

Higher rates of tree mortality

Reduced area of intact forest