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First signs of carbon sink saturation in European forest biomass

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European forests are seen as a clear example of vegetation rebound in the Northern Hemisphere; recovering in area and growing stock since the 1950s, after centuries of stock decline and deforestation. These regrowing forests have shown to be a persistent carbon sink, projected to continue for decades, however, there are early signs of saturation. Forest policies and management strategies need revision if we want to sustain the sink.

We argue that three warnings of saturation of the European forest biomass carbon sink can already be observed, after decades of increasing sink strength[1–4]. First, the stem volume increment rate is decreasing and thus the sink is curbing after decades of increase. Second, land use is intensifying, thereby leading to deforestation and associated carbon losses. Third, natural disturbances are increasing and, as a consequence, so are the emissions of CO_2.

Slow-down in stem volume increment

Early evidence for the biomass sink becoming saturated was derived from several sources. The international statistics on the forest resources of Europe are regularly compiled by the Food and Agricultural Organization (FAO) of the UN and the UN Economic Commission for Europe (UNECE). Every 5 to 10 years, data from thousands of locations sampled during national forest inventories provide updates of the trend in stem volume increment (Fig. 1). The rising trend from 1960–2005 has mainly been ascribed to improvements in forest management practices since the Second World War, an increasing share of forests in productive age classes until 1980[5], area expansion and site recovery after litter raking, combined with environmental changes, such as nitrogen deposition and CO_2 enrichment[6,7]. Some of the upward trend in the earlier decades could also be due to better inventories and data[8].

However, the rising trend has recently reversed: the latest *State of Europe's Forests* report[9] reveals that between 2005 and 2010 the total stem volume increment for the whole European area declined by 13 million m^3 over 178 million ha. Stem volume increment is defined as average annual volume of gross increment over the given reference period minus average annual volume of natural mortality of trees, but including all stem volume harvested or affected by natural disturbances using the minimum diameters defined for growing stock. The total increment was calculated for European Union member states (excluding Romania, Ireland and Malta because of a lack of data), plus Norway, Switzerland and the Balkan countries: Albania, Serbia, and Bosnia and Herzegovina.

The downturn cannot be attributed to a reduction in forest area, as available area for wood supply has slightly increased. Nor can it be ascribed to harvesting intensity. Harvesting showed a small peak in 2007, but this does not explain the decline in increment, as harvested volume is accounted for in the report[9]. Thus, it is most likely that the decline in increment, which was registered mostly in central western Europe, can be ascribed to a combination of the development of older age classes after 1980[5] and high growing stock: European forests are increasingly mature, with older age classes accounting for a greater area. Other important factors could be the reduction in nitrogen deposition[10] and the adverse effects of decreased summer relative air humidity[11] due to climate change. The international statistics showing this decline in increment are supported by other studies that reveal growth decreases across various sites in Europe[12,13].

Figure 1 shows how well the increasing growth trend agrees with the increasing carbon sink development, and when increment declines, the sink curbs as well. Increment is a driver for the sink strength but need not result in a net sink, as natural losses and harvest may be larger than the increment. But for European forests, increment and sink size are well correlated. At present, increment exceeds harvest in Europe by some 260 million $m^3\ yr^{-1}$ (ref. 9) and the forest still acts as a sink, but the increasing trend in the sink (visible in Fig. 1 between 1960 and 1990), has stopped and has started to curb. This seems to be caused by a combination of increment decline and harvest increase, and indicates a sensitive balance between these two factors, and their effect on the net sink. More intensive harvesting (for example, for bioenergy), as is often projected by studies, will further reduce the sink[14,15].

This trend of a saturating sink is not universal across Europe. When we further analyse the sink trend by region, (Fig. 1b), we see distinctly different trends in the forest biomass sink since 1990. In the West-Atlantic and Alpine areas the sink seems to have saturated, whereas in the North and South, the sink is modestly increasing. The Eastern European countries show an intermediate trend, where the sink decreased until 2002, and is now increasing again.

Deforestation

The second warning sign of a sink under pressure is the intensive land use and associated land-use changes in Europe. Until recently, net forest area was increasing by about 700,000 ha yr^{-1}, but between 2005 and 2010 a net expansion of only 500,000 ha yr^{-1} was found[9]. A decreasing trend in net forest area expansion was also reported by European countries to the UN Framework Convention on Climate Change (UNFCCC), from about 400,000 ha yr^{-1} during

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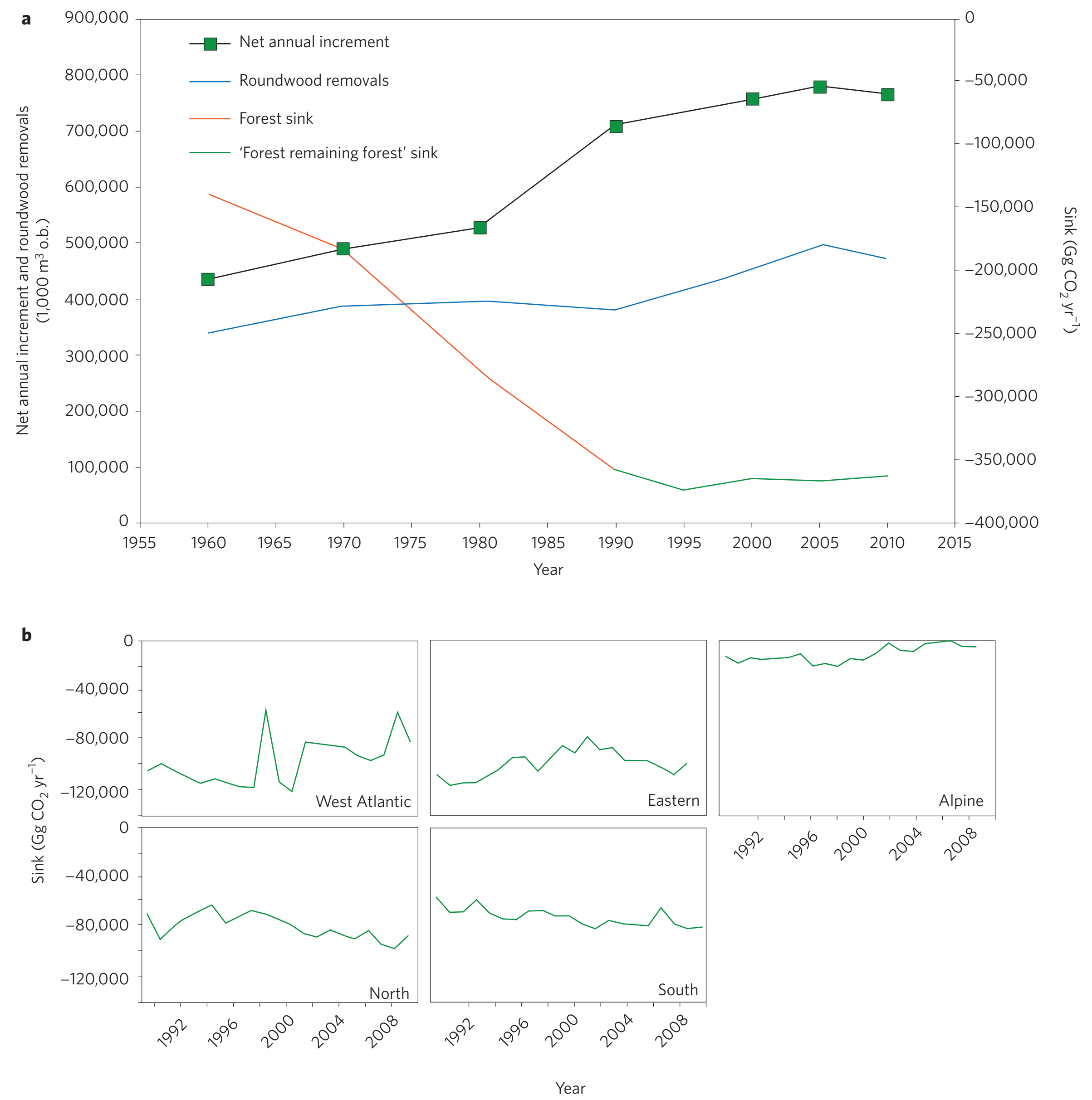

Figure 1 | Trends in increment, removals and sink strength for European forests. a, Net annual stem volume increment since 1960 for the European forest available for wood supply in 29 countries[9,28–32]. The blue line depicts harvesting as roundwood removals including bark (o.b.)[28–31,33]. Where statistics provided numbers excluding bark, we added 12% for bark, following ref. 34. The development of the forest biomass sink for the forest area from 1960-1990 (red line) is based on ref. 2, then from 1990–2010 the green line depicts the forest biomass sink data as submitted in 2012 by countries to the UNFCCC (where 'forest remaining forest' indicates that forest land-use has not changed over the reporting period). The 1990–2010 sink line has the effect of the natural disturbances included, but not the effect of deforestation. **b**, The forest biomass sink in more detail for five European regions over the past two decades, showing distinct differences in the trends. Country groupings are: West Atlantic: Belgium, Denmark, France, Germany, Ireland, Luxembourg, The Netherlands and the UK; North: Finland, Norway, Sweden; Eastern: Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania and Slovakia; South: Croatia, Greece, Italy, Portugal, Slovenia and Spain; Alpine: Austria and Switzerland. The sink is depicted in the international convention, that is, greater negative values indicate a larger sink.

1990–2005 to about 300,000 ha yr^{-1} from 2005–2010[16]. However, the gross expansion of forest is partly countered by gross deforestation[17,18], and this often remains unnoticed in the statistics of net forest area change. Forests are thus shifting across the landscape.

We had two sources of material available for studying deforestation across Europe: the remotely sensed CORINE Land Cover (CLC) data sets for three years[17] that classify the European area into 44 land-cover classes; and the national reports under the Kyoto Protocol[16], which detail deforestation since 1990. Overlaying the 1990, 2000 and 2006 CLC data sets revealed an average annual loss of forest and woodlands of 98,000 ha for all countries together. The country submissions to the Kyoto Protocol in 2012 (for 1990–2010) indicate an average yearly gross deforestation of about 97,000 ha. Figure 2 shows these gross deforestation numbers by source and country. Generally there is good agreement between the two sources; however, in a few cases (for example, France and Spain) large differences in the estimates are visible. These discrepancies are mainly related to the different criteria used to assess deforestation under land-cover (CLC) and land-use (Kyoto Protocol) approaches. Furthermore, the uncertainty of such estimates is high.

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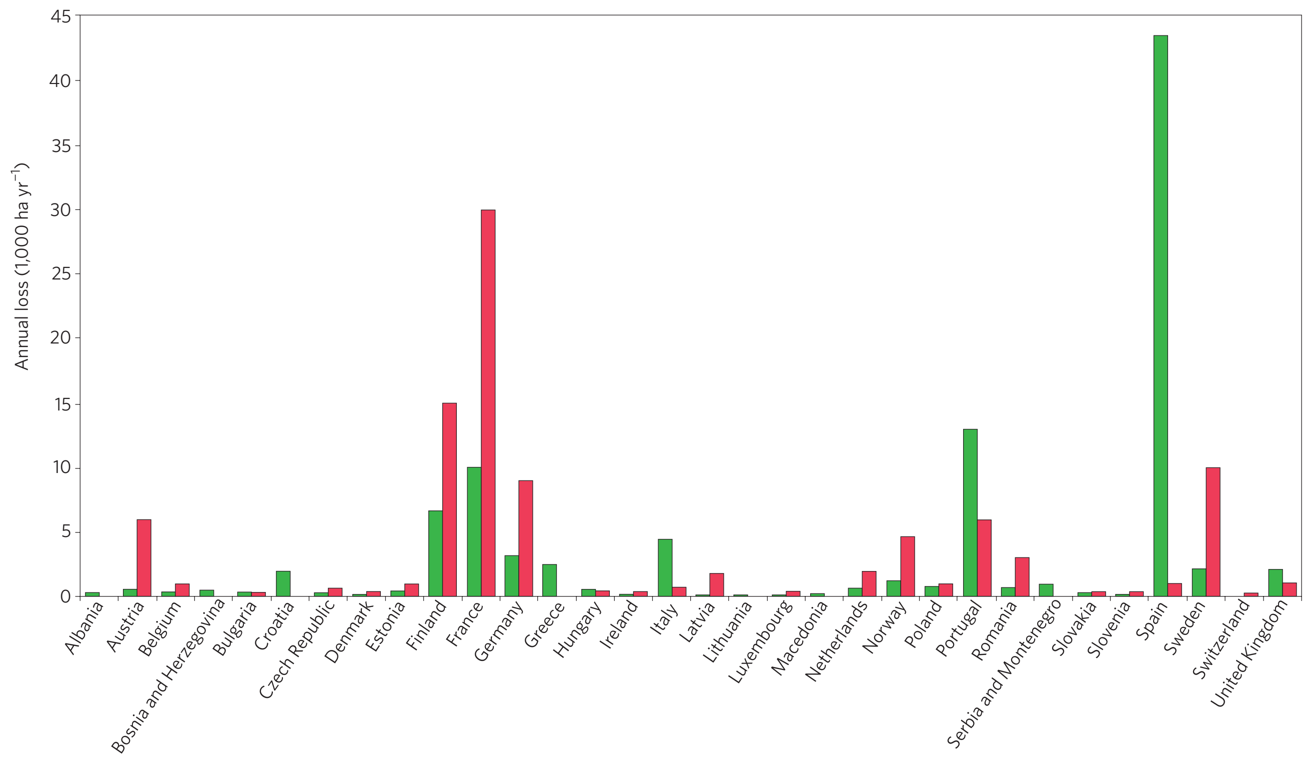

Figure 2 | Average yearly gross deforestation in 1990–2010. Green bars indicate the average forest loss based on the CLC from 1990, 2000 and 2006[17]. Red bars reflect the reports to the Kyoto Protocol on deforestation between 1990 and 2010[16].

As deforestation in Europe is characterized by small and scattered events, it is not easily captured by sampling approaches.

The area affected in Europe is relatively small, but a hectare of lost forest means a large immediate efflux of carbon (around 65 tonnes ha^{-1}; refs 3,9). Although lost forests are often offset by afforestation elsewhere, it takes decades for a hectare of new forest — which sequesters 1–2 tonnes of carbon per hectare — to compensate for the carbon lost through deforestation. For Europe, the deforestation causes an upfront loss of 25.7 Mt CO_2 yr^{-1} in total, roughly 6% of the sink in the remaining forest. In terms of biodiversity, a hectare of lost (old) forest can in no way be compensated for by a hectare of planted seedlings on former agricultural land elsewhere.

The main factors driving deforestation are urban sprawl and the expansion of transport, commercial and industrial infrastructure. Natural disturbances (such as storms or fire) that are sometimes followed by non-sustainable logging and intensive agriculture[18,19] also contribute. Maintenance of a significant net expansion would depend on several factors, mainly related to availability of land[14].

Increased disturbances

The third indicator relates to the growing stock and its vulnerability to disturbances. Except for a brief period in the late 1950s and early 1960s when harvest equalled increment, the growing stock of European forests has increased steadily over the past six decades. It is currently over 24 billion m^3 in the EU, or 137 m^3 ha^{-1} (ref. 9); this is probably the highest since early Medieval times[20]. Seven countries have an average of over 250 m^3 ha^{-1}. An old forest with high growing stock volumes per hectare will be increasingly susceptible to damage[21]: fire, storms and insects are the most harmful, and will have great consequences in terms of growing stock affected and the amount of carbon released. From a database on disturbances with thousands of records[21], it is clear that damages are increasing rapidly (Fig. 3).

This is further evidence that in the foreseeable future we may reach maximum stocking in Europe. On average, about 500,000 ha of forests across Europe are affected by fire each year. Fires are becoming more frequent — especially in the Mediterranean region — and storms have resulted in the largest disturbance damage to European forests, particularly when followed by other causes, such as fire or insects[22].

Uncertainties and interrelations

How certain are we about the trend lines in Fig. 1? The uncertainty in the increment becomes smaller as we approach the present. Over time, more and more countries have improved their inventories and have made large steps towards harmonization[8], thus reducing the overall uncertainty. Nowadays, the root mean square errors at the national level approach 1–2% of the increment, and international compilations are of good quality[9]. The uncertainty in forest biomass sink strength reported by EU member states to the UNFCCC is typically under 20% (ref. 23). This is a relatively high number because the sink is the difference between two large numbers (increment minus losses), and calculation of whole tree biomass carbon requires further processing of increment volume numbers with biomass expansion factors and basic wood density, for example. The uncertainty in the sink trend, however, (Fig. 1), is significantly lower because of the correlation of errors over time. Enormous efforts have also been made to improve the quality and the completeness of the reporting to the UNFCCC.

In our analyses we have included 29 countries, and the foremost characteristic of European forests is the large diversity between countries in terms of state of the forest, management practices and policies. Therefore it is worthwhile to look at the differences between countries, because the main trend of the increment line could be determined by a few countries with large forest area. The six largest forest countries included in our analysis cover 106 million ha or 60% of the total forest area in Europe. Out of these six, Germany and

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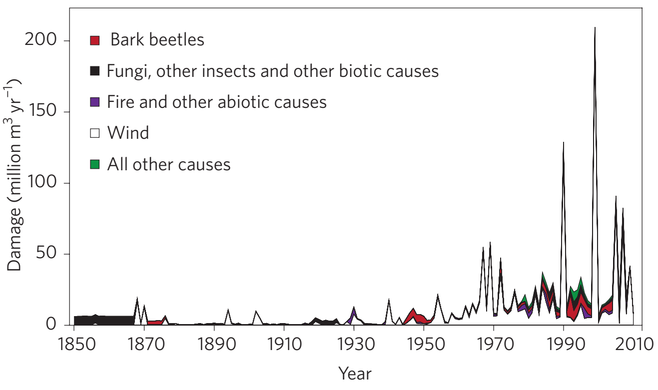

Figure 3 | Volume of damage (in stem volume) caused by different types of natural disturbance from 1850 to 2010[21,35].

France determine to some extent the decline of the increment line after 2005 in Fig. 1.

To calculate a whole tree biomass increment from the stem volume increment, the latter needs to be converted by biomass expansion factors to cover increment in branches, roots and foliage. However, to arrive at a net sink calculation, natural losses, harvest and other losses — for example, deforestation — need to be subtracted as well. Therefore the trend in increment can be, but does not necessarily need to be, in line with the trend in the net sink. Despite this, the trends in Fig. 1 between increment and net sink are in agreement.

In the managed forests of Europe, where 63% of the increment is harvested[9], it is the increment minus harvest that determines the net sink. The decline in increment of the mature forest and an increasing harvest — further enhanced by deforestation and by increased natural disturbances — seem to be causing the curbing of the sink strength. Climate-induced declines in productivity are also a matter for concern, as they are reported to be increasing and are associated with stronger drought limitations[11–13].

Implications

The signs of a forest carbon sink becoming saturated in Europe should be heeded. The managed forests in Europe are apparently closer to maximum stocking than was previously thought. Luyssaert *et al.* [24] reported a significant sink provided by old forests on the basis of a set of ecological sample plots and eddy flux tower sites, which often represent unmanaged forests. Whereas the contention that carbon stocks could still double in the coming century[4] was based on comparing the current carbon stock in European forests with the stock often found in old forests. In managed European forests, however, carbon sink saturation seems quite imminent. This is not a sign of forest decline, but rather an indication that these forests are reaching a dynamic equilibrium with the current intensity of management, tree species and age-class distribution. In a large area of managed forest, increment and growing stock are determined by management intensity, tree species choice and rotation length. Although management measures such as improved planting stock, fertilization and drainage of sites can stimulate increment, the large-area average growing stock is usually lower in a managed forest than in natural forest on that site[25]. Thus many European forests are reaching their maximum large-area growing stock under current management intensity. It has taken these forests some seven decades to reach this point. The growing stock is still increasing in many countries, but the first indications that maximum stocking is being reached are apparent.

The way forward

A biospheric carbon sink is a temporary phenomenon; it will eventually saturate. However, the onset of the saturation (or the rate of sink decline), can be influenced by management in many ways: for example, by tree species, rotation length, age-class distribution, amount and type of harvesting and so on. The Intergovernmental Panel on Climate Change concluded that "in the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fibre or energy from the forest, will generate the largest sustained mitigation benefit"[26], but this would need to be applied in different ways throughout Europe, depending on the state of the forest. Countries should be less focused on the forest biomass sink strength and consider a mitigation strategy (adapted to national circumstances) to maximize the sum of all the possible components: carbon sequestration in forest biomass, soil and wood products, and the effects of energy and material substitution of woody biomass. Furthermore, other climate forcings (that is, biophysical effects) may also affect the climate mitigation potential of forests.

Best practices in forest management for carbon sequestration should consider the diversity of forest types and management systems across Europe, and aim to fulfil all the functions of the forest under a sustainable management scheme, while taking into account the trade-offs between functions. Where exactly to take which measure is up to the national and local policymakers and forest owners.

In relation to carbon sequestration, spatially diversified policies and management could aim to:

- Conserve high carbon-stock densities in old forests that are not at a high risk of disturbance, and allow them to turn into naturally developing forest. As older forests contain more deadwood and habitat niches than intensively managed forests, this would protect existing carbon stocks and benefit biodiversity, while constraining the average rates of increment.
- Harvest mature forests that are at high risk of disturbance and already have low productivity. This intensifies the carbon sink only in the long term, but society should realise that these forests temporarily need to go through a net emission phase in the forest biomass.
- Conserve high carbon-stock forests on sensitive sites, high soil carbon sites and steep slopes.
- Improve the management and protection of fire-prone forests to safeguard their carbon stocks.
- Switch to continuous-cover forest management, if economic and forest management conditions allow. This favourably adjusts the ratio of productive to unproductive timespans in the management cycle.
- Optimize silvicultural techniques (such as planting, tending and harvesting) to arrive at a carbon-efficient management scheme in forests that are grown primarily for timber, and stimulate the recycling of forest raw materials and wood products.
- Shorten forest management cycles and intensify management where the primary goal is biomass for bioenergy.
- Continue afforestation schemes in Europe — particularly in less forested parts — while concomitantly curbing gross deforestation. The latter would deliver immediate gains by avoiding emissions.

The above show that there is no 'one size fits all' in carbon sequestration[27]. A change in the mindset on integrated land-use management is needed to achieve effective carbon mitigation: forests should be valued for all of the environmental services they provide. When management schedules are being revised, the trade-offs with other forest goods and services should be carefully considered. Manifesting the multifunctionality of forest, including its carbon sink capacity, goes beyond the boundaries of the forest sector. Integrated land-use is necessary to achieve an overall balance of functions, incorporating carbon sequestration, both within and outside forests.

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Tackling the challenges outlined above will require better coordination of the policies that affect forest and forest management at the national, EU and pan-European levels (for example, on energy, biodiversity and rural development, as well as the new Common Agricultural Policy, the Forest Strategy and Forest Europe policies). Only then will the multifaceted carbon mitigation functions of forests be fully exploited.

At the FOREST EUROPE Ministerial Conference on the Protection of Forests in Europe — held in Oslo from 14–16 June 1, 2011 — European ministers responsible for forests decided to begin negotiations for a legally binding agreement on forests in Europe, and they are now discussing its contents. However, they should be aware of a changing paradigm regarding European forests, and consider, in their deliberations, the early warning signs that the forest carbon sink is becoming saturated.

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Author contributions

G.N. did the Fig. 1 analyses, interpretations, and wrote large parts of the paper. M.L. and P.J.V. contributed to interpretation and writing of the manuscript. K.G. provided the deforestation data based on CLC in Fig. 2, and wrote parts of the section on deforestation. P.D. contributed to writing and provided data from UN-ECE/FAO sets. R.M. contributed to interpretations, writing, and provided data from UN-ECE/FAO sets. G.G. contributed to interpretations, writing, and provided data from UNFCCC datasets.

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Competing financial interests

The authors declare no competing financial interests.

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