Title: Quantifying forest degradation requires a long-term, landscape-scale approach

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Forests are spatially and temporally dynamic, such that forest degradation is best quantified across whole landscapes and over the long term. The European Union's Forest Degradation policy, which focuses on contemporary primary forest conversion to plantations, ignores other globally prevalent forestry practices that can flip forests into a degraded state.

Two major recent policy developments aim to eliminate or reduce forest degradation. The European Union's Deforestation Regulation[1] (EUDR) aims to prevent forest degradation through import bans on forest products originating from degraded forests. The core goal of EUDR is to reduce carbon emissions and biodiversity loss[1]. An objective of the 2023 COP28 United Nations Climate Change Conference, signed by 100 countries, is "halting and reversing" deforestation and forest degradation by 2030. These policies bring into sharp relief a need for clear definition of the term 'forest degradation'. Without clear and ecologically defensible nomenclature and methods, assessments of forest degradation could be subverted to suit political and economic agendas. Here, we argue that long-term, landscape-scale quantification of forest degradation is essential to achieve the intended positive impacts of such policies on biodiversity and carbon.

Forest degradation is broadly considered to involve human-induced changes to forest structure, composition and function in ways that do not involve permanent conversion to non-forest uses (this is forest loss, or deforestation[2]). Forests house 80% of the world's biodiversity and nearly half (47%) of the world's 4 billion hectares of forests are managed for timber production[3]. The total global area of degradation likely exceeds the area of forest loss[3,4] (Supplementary Fig 1a). The footprint of managed forests affected by EU imports alone, worth \$37 x 10^9 USD annually[5], includes most of the world's major wood producing countries. Unsustainable forestry is a key driver of biodiversity and carbon storage loss[6,7], so the inclusion of forest degradation in the EUDR and COP28 agreement has the potential to be a substantial step toward ameliorating the dual climate and biodiversity crises.

Forest Degradation Defined

The term "forest degradation" is variably defined in the scientific and policy literature[8]. It is generally agreed that degradation involves decline in some attribute, function or ecosystem service in response to human-caused disturbance[8]; disagreement stems from the attributes considered, and the magnitude of change necessary to qualify as degradation. Attributes considered under the umbrella of forest degradation include changes to tree species mixes, carbon loss, biodiversity loss through habitat loss or hunting, forest fragmentation, invasive species, declines in water quality and changes in a host of other ecosystem services.

Forests are naturally dynamic in both space and time, which means that disturbance – at tree, stand, and landscape scales – is typical of forest systems worldwide. Unlike deforestation, which is the relatively unambiguous conversion of forests to non-forest land uses (such as agriculture, or urban areas), understanding degradation requires considering the capacity of a system to reorganize and recover following disturbance. For instance, even light timber harvests involve removing wood biomass, thereby reducing carbon storage and habitat for some old-forest species. The key questions are whether this local(stand)-scale impact endures for longer than would have happened under a natural disturbance regime[9], and whether stand-scale loss is compensated for by regrowth elsewhere in the landscape, resulting in no net landscape-scale loss of biodiversity or carbon. Degradation can thus be framed as a continuous recovery function that is a product of both the severity of disturbance and the rate of recovery at landscape scales[8]. Ghazoul et al. (2015)[8] conceptualized forest degradation using resilience theory; if disturbances are too large or frequent, the system can shift to an alternative state from which it is difficult to return (Fig. 1a). This is a useful construct as it allows both for the occurrence of natural disturbance, and for sustainable forestry in which key ecosystem processes may decline briefly in parts of the landscape but are compensated for by emergence of these attributes elsewhere (a shifting forest mosaic).

EU Degradation Policy

To date, no guidance on how to define forest degradation has been provided in the COP28 commitment, but the EUDR has already outlined how degradation will be defined. In this policy, degradation is defined as: "structural changes to forest cover taking the form of the conversion of (a) primary forests or naturally regenerating forests into plantation forests or into other wooded land; or (b) primary forests into planted forests". Here, "other wooded land" is defined as forests with low canopy cover (5-10%), as opposed to "forest" (greater than 10% canopy)[1]. The benchmark year for the policy is 2020, so wood resulting from any conversion to plantation or other wooded land occurring before this period may still be imported to the EU. This benchmark date may have been intended to prevent countries from rushing to convert primary forest to plantations in the period before full policy implementation. Importantly, the policy requires precise geolocation of the origin of wood products, to enable determination of whether degradation has occurred at very local scales.

The current EUDR may lead to substantial reduction in the conversion of primary forest to intensively managed plantations in exporting countries. Given high amounts of biodiversity and carbon in primary forest, this could have a joint benefit for biodiversity and carbon storage. Plantations have expanded substantially in recent decades from 4% of global forest area in 1990 to 7% in 2020[2], and the EUDR could slow this expansion into primary forest. However, the policy suffers from two major stumbling blocks. First, to our knowledge, there exist no reliable global spatial data that enable monitoring of primary forest, naturally regenerating forest, or plantations at fine scales annually. New remote sensing sensors and products[10,11] offer some promise that this issue can be ameliorated in the future, but until then, reliable monitoring of degradation will be impossible.

Second, and more importantly, the majority of wood harvest worldwide occurs in forests that are not subsequently converted to plantations[3] yet we argue that this harvest has the potential to result in forest degradation. Plantations account for less than 10% of forest area in four top wood-producing countries[2] (Russian Federation, USA, Canada, Brazil; Supplementary Fig. 1b). This does not mean that non-plantation forests in these countries are free of degradation; indeed, many forests are harvested using short-rotation clearcut methods despite being allowed to naturally regenerate[6]. This results in arrested forest development and the emergence of an alternative stable state, ultimately precluding succession into the older forest composition and structure that was initially harvested (Fig. 1a, b). For example, in eastern Canada, mature, diverse forests are often clearcut and regenerate naturally into a different tree species mix: a conversion from shade-tolerant, long-lived tree species (such as, *Acer saccharum, Betula alleghaniensis* and *Picea rubra*) into shade-intolerant, short-lived trees (such as *Betula papyrifera* and *Populus tremuloides*) (Fig. 1b, d-f). This "age class truncation" has been shown to drive long-term declines in old forest biodiversity[6], and reductions in above-ground carbon in these forests[12]. Many regions globally – including southeastern US, northwestern US, eastern Canada, and Scandinavia exhibit patterns of rapid forest cover loss followed by regeneration that could be symptomatic of these practices (Supplementary Fig. 1a). Age-class truncation in naturally regenerated forests would therefore directly contradict EUDR goals of protecting biomass storage and biodiversity but would currently not result in exclusion from the EU market.

EUDR could also incentivize low-yield forestry that relies on natural regeneration rather than higher-yield plantations. Given expected increases in global wood demand, this might unintentionally result in expansion of harvesting into primary forests, resulting in a greater global footprint of degraded area[13]. Such consequences would likewise contradict stated EUDR goals related to halting biodiversity and carbon loss.

Ways forward for degradation policies

The difficulties in precisely defining and mapping the stand-scale degradation metrics suggested in the EUDR represent a substantial barrier to the policy's consistent implementation. Furthermore, we argue that a focus on short-term, stand-level forest practices can obfuscate broader-scale trends in carbon and biodiversity.

Two changes in the quantification of forest degradation would address the EUDR's global carbon and habitat goals more directly. First, rather than basing a policy on particular forest practices (such as plantations, natural regeneration), we suggest that the outcomes of these practices should be quantified, as they relate to core goals of the degradation policies. A series of remotely sensed indicators of ecological integrity and biodiversity have recently been proposed[14] which could be readily tracked to quantify degradation (Fig. 1c). Advances in remote sensing, greater availability of biodiversity data and species distribution models now enable tracking of carbon[15] as well as habitat mapping for thousands of species[16] over the long term, annually. Umbrella species (indicators of degradation) could be proposed for particular regions, the selections peer reviewed, and their habitat distributions mapped alongside above-ground carbon over time to discern systematic trends in forest degradation [6].

Second, we suggest that forest degradation monitoring is best conducted at landscape or regional scales and over the long term. Degradation would be audited for whole landscapes (for example, polygons of 10^3 – 10^6 hectares) rather than individual georeferenced properties. The complexity of dynamic forest mosaics makes it impossible to measure systematic degradation using stand-level measures. Although landscape-scale monitoring may be challenging for landowners with small, fragmented forests, precedent exists in the forest certification field for group auditing for spatial clusters of small landownerships across whole landscapes. The year 2020 could be retained as a benchmark date in EUDR, but we suggest that trends in biodiversity and carbon over the recent (2020-2024) period should be placed in the context of longer-term trajectories, such as since the origin of Landsat in 1985 (Fig. 1c). EUDR already proposes ranking countries as “high”, “standard” and “low” risk of degrading (with reduced requirements for reporting in each step along this gradient). These risk levels could be determined by examining longer-term trends in degradation at the country level (Fig. 1c).

Of course, any single global policy focused on forests is bound to be marred by exceptions and challenges. For instance, a goal of increasing carbon may exceed the natural range of variation in some forest landscapes, and result in fuel build up as well as biodiversity declines. Many proposed elements of forest degradation, including defaunation due to hunting, individual tree highgrading or spread of invasive species in the understory, fall far below the minimum resolution of air- or space-borne sensors. But as new technologies for monitoring biodiversity emerge, future iterations of degradation policies could include new criteria and methods for measuring them.

Given the immense biodiversity and carbon housed in forests globally, combined with the footprint of wood extraction, now is a critical time for global policies focused on halting forest degradation. Refocusing degradation metrics on habitat and carbon results, along with measures to account more comprehensively for forest dynamics at broader temporal and spatial scales, will better align new import policies with modern landscape ecology and current remote sensing capabilities.

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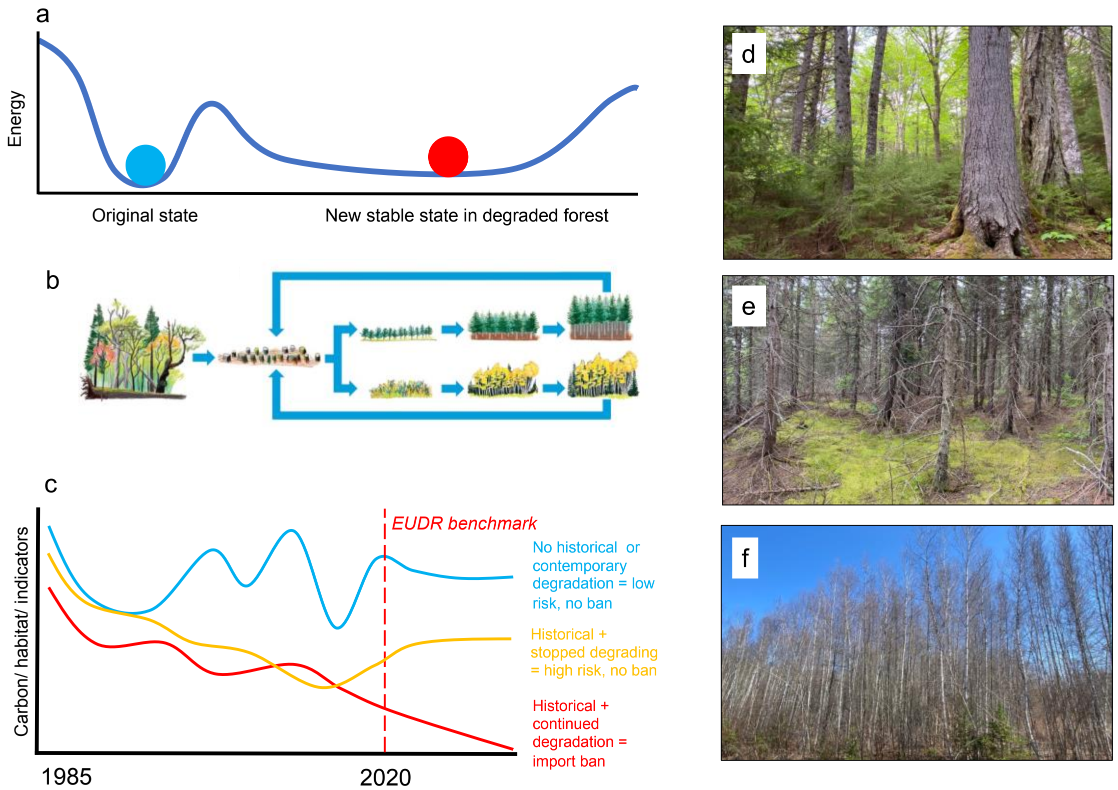

Fig. 1 Forest degradation as an alternative stable state. a, Forest degradation can be conceptualized using resilience theory: if disturbances are too large or frequent, the system can shift to an alternative state (a move to the red circle from blue circle) from which it is difficult to return (figure adapted from ref 7). b, Such state shifts are exemplified by short-rotation forestry, with either plantations (top row) or natural regeneration (bottom row), in which stands are perpetually cut before they return to their original mature state. c, Three scenarios for indicators of degradation such as mapped above-ground carbon or habitat. Blue line: natural fluctuations of indicators with no degradation and therefore low risk and no ban on imports under the current EUDR; yellow line: historical degradation followed by cessation of those practices after 2020 which support no EUDR ban, but careful monitoring; red line: long-term and contemporary degradation which would result in a ban under the EUDR. Fig. 1d-f show mature mixed Acadian (Wabanaki) forest, white-spruce plantation, and white birch natural regeneration following clearcutting.

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Supplementary Materials:

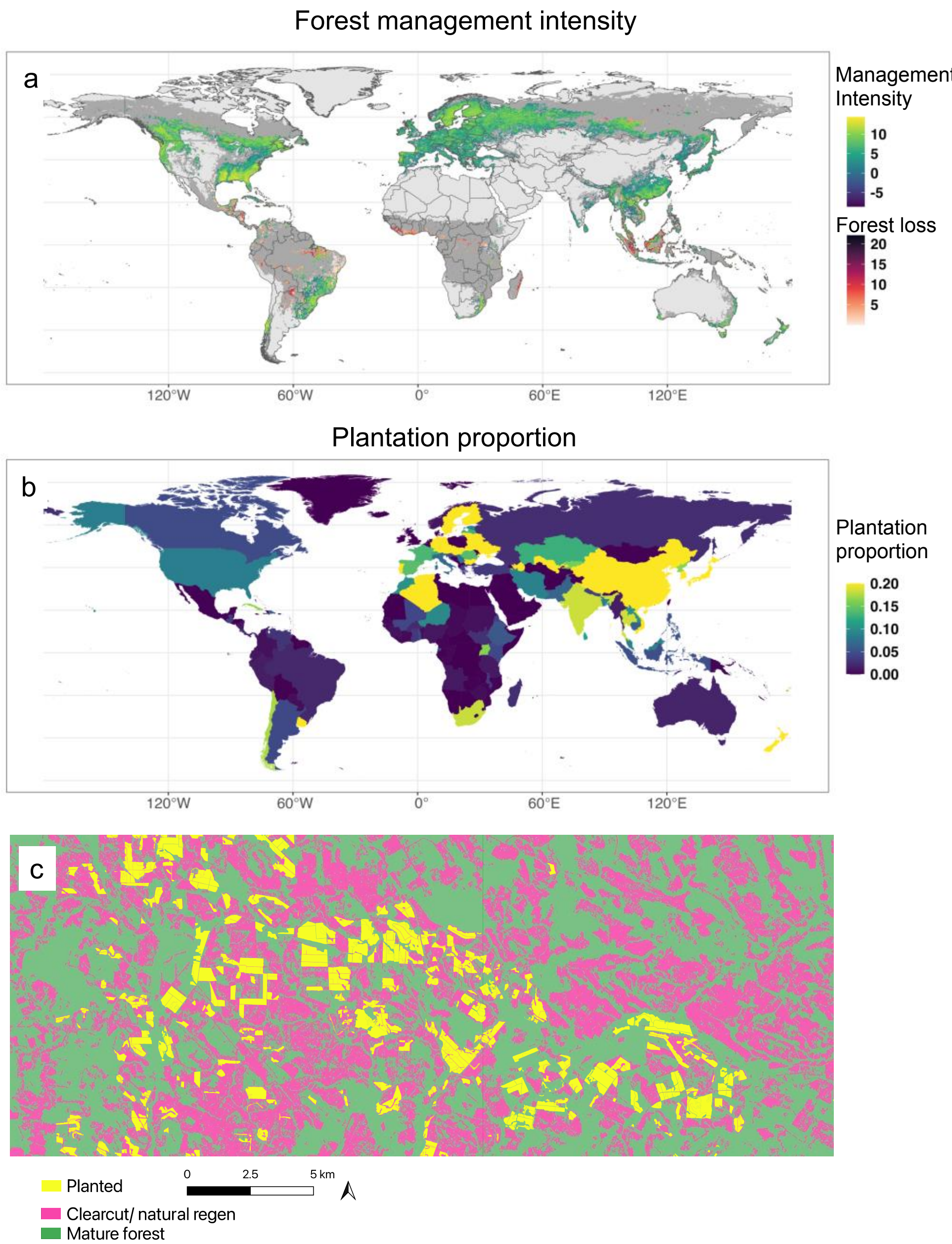

Fig. 1 The Global footprint of managed forests and tree plantations. a, Global footprint of managed forests as measured via Landsat. Bright yellow indicates locations with the greatest spatial variation in canopy removal and gain (a signature of intensive management; total loss x total gain at 15 km resolution from 2000-2020; values in 1000s ha, log scale, see supporting methods). Red color scale indicates forest loss with no or slow regeneration (1000s of ha, 15 km resolution). **b,** The proportion of forest land area attributed to plantation according to the FAO[2]. Most timber harvest globally relies on natural regeneration (only 7% of forests are plantations), but this does not preclude forest degradation in these areas. **c**, A 25 km^2 landscape in eastern Canada with clearcut forestry (1985-2020) and natural regeneration (pink) and plantations (yellow). Systematic decline in mature forest across the landscape (replacement of green by pink + yellow) degrades the forest in this region from a biodiversity and carbon.

Appendix A. Methods for creation of Supplementary Fig. 1a

To generate Fig. 1 a, Global map of production forest landscapes, we used Google Earth Engine to multiply the amount of forest loss (2000-2020) by the amount of forest gain (2000-2012) at a 15 km resolution for the entire globe. Forest loss and gain were derived from Global Forest Watch (GFW) data (https://www.globalforestwatch.org). We then divided by 1000 ha, and log-transformed these values for ease of visualization. This approach provides a measure of landscape dynamics; landscapes with very low or zero forest gain (i.e., primarily forest conversion to other land uses) will exhibit low scores. Similarly, landscapes with low rates of timber harvest (minimal loss and regeneration) will show low scores (e.g., much of western Europe).

Second, we used data from Curtis et al. (2018)[1] mask out areas that are classified as permanent loss. We then added a layer showing permanent forest loss from GFW (2000-2020) to show areas without regrowth (e.g., fire and permanent deforestation). Values used for this map are also in 1000s hectares for at a 15 km spatial resolution. Only cells with >10% forest cover in year 2000 are reported. Forest cover outside of managed forest areas or areas of high forest loss are shown in gray.

1 Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A. & Hansen, M. C. Classifying drivers of global forest loss. *Science* **361**, 1108–1111 (2018).