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Spatiotemporal pattern of global forest change over the past 60 years and the forest transition theory

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Supplementary material for this article is available online

Abstract

Forest ecosystems play an indispensable role in addressing various pressing sustainability and social-ecological challenges such as climate change and biodiversity loss. However, global forest loss has been, and still is today, an important issue. Here, based on spatially explicit data, we show that over the past 60 years (1960–2019), the global forest area has declined by 81.7 million ha (i.e. 10% more than the size of the entire Borneo island), with forest loss (437.3 million ha) outweighing forest gain (355.6 million ha). With this forest decline and the population increase (4.68 billion) over the period, the global forest per capita has decreased by over 60%, from 1.4 ha in 1960 to 0.5 ha in 2019. The spatiotemporal pattern of forest change supports the forest transition theory, with forest losses occurring primarily in the lower income countries in the tropics and forest gains in the higher income countries in the extratropics. Furthermore, economic growth has a stronger association with net forest gain than with net forest loss. Our results highlight the need to strengthen the support given to lower income countries, especially in the tropics, to help improve their capacity to minimize or end their forest losses. To help address the displacement of forest losses to the lower income countries in the tropics, higher income nations need to reduce their dependence on imported tropical forest products.

1. Introduction

Forest ecosystems play important roles in the conservation of global biodiversity [1–5] and offer a plethora of valuable ecosystem services, including climate regulation [6–9], provisioning of basic materials for sustenance [4, 8, 10] and reduction of the impacts of natural hazards [8, 11, 12]. However, nearly half of the world's forest has been lost over the past 8000 years due primarily to human activities [13]. Data from the most recent global Forest Resources Assessment (FRA) [14] and other studies [15, 16] show that the world's forests continue to decline. The continuous loss and degradation of forests affects the integrity of forest ecosystems, reducing their ability to generate and provide essential services [17–19] and sustain biodiversity [3, 20, 21]. It also impacts the lives of at least 1.6 billion people worldwide, predominantly in developing countries, who depend on forests for various purposes [22–24].

Today, monitoring of the world's forests is an integral part of various global environmental and social initiatives, including the Sustainable Development Goals (SDGs), the Paris Climate Agreement and the post-2020 global biodiversity framework [4, 5, 9, 24]. To help achieve the goals of these initiatives, there is a profound need to reverse, or at least flatten, the global net forest loss curve by conserving the world's remaining forests and restoring and rehabilitating degraded forest landscapes [17, 25, 26].

In the early 1990s, geographer Alexander Mather proposed the forest transition theory (FTT) [27, 28] based on the positive correlation he observed between forest expansion and economic growth. In particular, FTT hypothesizes that forest cover change is a function of social and economic development, and that forest cover generally declines as countries develop economically, but this trend eventually reverses with further economic development and industrialization, resulting in a U-shaped curve [27–29]. In a nutshell, forest transitions occur within countries or regions when net forest gain replaces net forest loss [30]. Among the direct causes that lead to forest transition are agricultural land abandonment [31–33] and forest restoration and rehabilitation [27, 32]. Essentially, FTT suggests that if new policies that can accelerate forest transitions could be identified, then the corresponding forest gains and carbon sequestration might slow climate change, avert biodiversity losses, and prevent a further deterioration in ecosystem services [30]. For forest plantations, however, although they can also provide certain ecosystem services, their capacity to protect biodiversity and/or increase carbon sequestration is much less (especially non-native and/or monoculture plantations) when compared with natural forest ecosystems [34–36].

There are two main non-exclusive pathways that explain forest transitions, namely, the economic development pathway and the forest scarcity pathway. The economic development pathway underpins an initial period of industrialization and economic growth leading to fast deforestation, and then resurgence of forest under higher income and rural-to-urban migration [30, 37]. The forest scarcity pathway, on the other hand, is driven by higher timber prices and demand for forest ecosystem services (including protection from natural hazards), highlighting the need for forest plantations and forest restorations [30, 37]. Although there have been a number of studies that fit into one or the other category [33, 38–43], a quantitative assessment of evidence for the FTT based on global and spatially explicit data with extensive temporal coverage is lacking.

Advances in Earth observation technology have been gradually transforming global forest monitoring, from forest inventory and area estimation to wall-to-wall mapping and change detection with satellite data [15, 44] (see also www.globalforestwatch.org). In particular, the increasing availability of Earth observation data at various spatial and temporal scales [16, 45] is now aiding many forest-related studies [5, 9, 46–48]. Advances in related fields (e.g. geospatial science, data science, and computer science) have also enabled the reconstruction and modeling of past global land use/cover (LUC) extending from decades to centuries back in time [49, 50]. These long-term historical LUC estimates also now play an important role in global environmental change monitoring [16, 51]. Such advances in Earth observation technology and data availability now make it possible to study FTT at a global scale and wide temporal coverage.

Here, we tracked the extent of global forest change over the past 60 years using HIstoric Land Dynamics Assessment + (HILDA+), which is one of the most recently published spatially explicit and temporally, spatially and thematically consistent LUC datasets [16, 50] (see section 2) to answer two critical questions. First, how has the extent of global forest change varied over space and time? Second, how do the detected trends in global forest change relate to FTT? To clarify these questions, we quantified both forest losses and gains at the global, regional and national levels across decades from 1960 to 2019. We evaluated whether there is evidence to show that the extent of forest change was related to the socioeconomic status of countries and regions and if the evidence supports FTT. Finally, we explored the implications of the findings in the context of global sustainability.

2. Methods

2.1. LUC dataset

In the selection of a LUC dataset to be used, aside from being spatially explicit, we also considered a number of other desirable features: global and wide temporal coverage (i.e. to have a better grasp of the spatiotemporal pattern of forest change); consistency in terms of spatial, temporal and thematic resolution; and availability of documentation including accuracy assessment, quality assurance, or both.

We initially considered a number of datasets, including the Global Land Surface Satellite-land cover (GLASS-LC) dataset [52], with annual temporal resolution from 1982 to 2015 and a spatial resolution of 5 km; the Moderate Resolution Imaging Spectroradiometer (MODIS)-LC dataset [53], with annual temporal resolution from 2001 to 2019 and a spatial resolution of 500 m; and the Climate Change Initiative (CCI)-LC dataset [54], with annual temporal resolution from 1992 to 2018 and a spatial resolution of 300 m. Because of its long temporal record and quantification of annual uncertainty, and considering the above-mentioned desirable features, we decided to use the HILDA+ dataset [16, 50], which is further described below. Nevertheless, all the above-mentioned datasets were also used for comparison (see section 2.7).

We sourced the HILDA+ dataset (in GeoTIFF format) from a recent study [16]. This dataset is publicly available at https://doi.org/10.1594/PANGAEA.921846 [50]. The entire dataset (vGLOB 1.0) consists of an annual LUC layer from 1960 to 2019, wherein each layer contains eight classes, namely, forest, cropland, pasture/rangeland, unmanaged grass-/shrubland, sparse/no vegetation, urban, ocean and water (supplementary table 1). The downloaded dataset is projected to Eckert IV, which is an equal-area pseudocylindrical map projection, and has a spatial resolution of 1 km. In our analysis, we used seven LUC layers at 10 years intervals (i.e. 1960, 1970, 1980, 1990, 2000, 2010 and 2019) (supplementary figure 1).

The HILDA+ dataset was produced via a complex reconstruction procedure that evolved from the approach developed for Europe's HILDA [55]. The procedure utilized the 'reported Food and Agriculture Organization (FAO) land use trends and remote sensing-based class probability maps for change allocation (harmonisation of multiple Earth observation-based land cover products)' [50]. It employed a base map at year 2015 as a starting point for change allocation backward to 1960 and forward to 2019 [16]. A more detailed documentation of this dataset and the reconstruction procedure employed has been published [16, 50].

2.2. Other datasets

The other datasets used in our analysis included a country boundary dataset in geographic information system (GIS) vector format from the Database of Global Administrative Areas (version 3.6, https://gadm.org), a regional classification of countries from the World Bank (WB) based on income level [56] (supplementary figure 2(a)), and a global dataset of country-level population [57] and gross domestic product (GDP) [58]. To facilitate the analysis, these datasets were harmonized following the harmonization procedure implemented in a recent study [59]. The harmonization procedure resulted in a total of 197 countries with a GIS polygon boundary, population data and WB country classification. These countries were used as the basis for regional synthesis. Here, a 'region' refers to a group of countries that belong to the same level of income and human development, meaning a region is not necessarily conterminous and can be composed of countries from multiple continents.

2.3. Forest change detection

We first reclassified the classes of the HILDA+ LUC maps into forest and non-forest categories (supplementary table 1). After reclassification, we performed an inter-decadal comparison by 'combining' or 'cross-tabulating' all the reclassified forest/non-forest maps to detect and map forest changes (loss and gain) at each decadal interval. From this analysis, we generated a multi-decadal forest change map with the following classes: 'persistent forest', 'persistent non-forest', 'persistent forest loss', 'persistent forest gain', 'non-persistent forest', 'non-persistent non-forest', 'non-persistent forest loss', and 'non-persistent forest gain'.

Persistent forest and persistent non-forest refer to areas that remained forest and non-forest, respectively, across decadal time intervals. Persistent forest loss and gain refer to areas that transitioned from forest to non-forest and non-forest to forest during 1960–1970 and remained as loss (non-forest) and gain (forest), respectively, across decadal time intervals. Non-persistent forest and non-persistent non-forest refer to areas that were forest and non-forest in 1960 and remained forest and non-forest, respectively, in 2019, but experienced change between 1960 and 2019. Non-persistent forest loss and gain refer to areas that were forest and non-forest in 1960 and transitioned to non-forest and forest, respectively, in 2019, but also experienced change in between; they include forest losses and gains, respectively, that occurred only in recent decade (2010–2019).

The total forest loss between 1960 and 2019 is the sum of persistent forest loss and non-persistent forest loss, whereas the total forest gain is the sum of persistent forest gain and non-persistent forest gain. The overall net change is the difference between total forest loss and total forest gain.

In addition to the combined raster layer involving multiple time points, we also produced a combined raster layer for the entire period (1960–2019). The goal was to countercheck the total forest loss and total forest gain detected from the combined raster layer involving multiple time points. This also helped facilitate a straightforward detection of forest gains and forest losses over the entire period.

2.4. Country and regional-level analysis

First, to quantify forest extents and changes (losses and gains) in each country, we performed a zonal analysis. We used the harmonized GIS country boundary dataset as input in which countries were used as individual zones and the reclassified forest/non-forest maps and the combined raster map (1960–2019) as the input raster data.

Second, using the resulting table from the zonal analysis of the combined raster map (1960–2019), we combined the countries that belonged to a particular region, i.e. a group of countries as per the WB country classification based on income level [56] (supplementary figure 2(a)) and determined the share of each region to the total forest loss and gain between 1960 and 2019. We also expressed the detected forest loss and gain relative to the land area of each country and summarized the results at the regional level.

Third, using the resulting tables from the zonal analysis of the reclassified forest/non-forest maps, we determined the rate of change, i.e. the rate of net forest change, in each country for each decade (equation (1)):

$$\text{Rate of change}\,(\%) = \left(\frac{F_{t2}}{F_{t1}} - 1\right) \times 100, \quad (1)$$

where F_{t1} and F_{t2} refer to the area of forest at time $t1$ and $t2$, respectively (e.g. for the 1960–1970 decadal interval, $t1$ refers to 1960 and $t2$ refers to 1970; for the 1970–1980 decadal interval, $t1$ refers to 1970 and $t2$ refers to 1980; and so on).

We also summarized the results at the regional level by determining the proportion of countries in each region with a net forest loss and a net forest gain. We also determined the countries that were consistently net forest-losing and net forest-gaining across decades and summarized the results at the regional level. Additionally, we compared the WB regions in terms of the proportion of forest that each country had at the starting time of the analysis (1960).

Fourth, we summarized the extent of forest at decadal intervals from 1960 to 2019 and determined forest per capita by dividing forest area by population at each time point. Along with GDP per capita, forest area and forest per capita were plotted simultaneously. We produced one plot at the global level and one plot for each WB region. At the global level, we determined the proportion of the world's forest at each decadal time point based on the 2019 global land area estimate (13 030.1 Mha) [60]. We also calculated the annual net forest change during each decade. Additionally, we determined the correlation between change in GDP and net forest gain and net forest loss using data at the country level.

We examined and interpreted the results of all these steps to clarify whether there is evidence to show that the extent of forest changes (loss and gain) was related to the socioeconomic status of countries and regions and to support FTT in general. We discussed the implications of the findings in the context of global sustainability.

2.5. Statistical analysis and geoprocessing

We used Pearson's r to determine correlation coefficients. We performed Student's t-test (two-tailed) to determine the statistical significance of the correlation coefficients. To help facilitate the analysis, visualize the distribution of data points and compare regions, we used charts/graphs, including boxplots (inclusive median). All the geoprocessing procedures were performed in ArcMap 10.8 (tools: 'reclassify' for reclassifying raster maps; 'combine' for combining or cross-tabulating raster maps; 'tabulate area' for zonal analysis).

2.6. Dealing with 'no data'

As mentioned above, we used the 197 countries resulting from the harmonization procedure for regional synthesis. However, some countries had no GDP data at some time points. To address this, for regional synthesis that involved the use of GDP, countries without data at a particular time point or period were excluded for that specific time point or period.

2.7. Uncertainty and sensitivity analysis

According to the data source, in the production of the HILDA+, uncertainty analysis was performed to examine the agreement of the used input datasets and the area fraction for each LUC class [16]. Such analysis revealed highest agreements in forests and areas with sparse/no vegetation; disagreement was larger in agriculture-dominated areas, such as cropland and pasture/rangeland [16].

For sensitivity analysis, we used another country groupings, i.e. based on the United Nations (UN) level of human development [56] (supplementary figure 2(b)). We also compared the forest extent estimates and trajectories of forest change detected from the HILDA+ with those from other available Earth observation-derived LUC datasets, including the CCI-LC [54], GLASS-LC [52] and MODIS-LC [53]. The statistics reported by FAO in its most recent FRA [14] were also included in the comparison. Supplementary table 2 presents the details of these datasets and the forest reclassification procedure used for the CCI-LC and MODIS-LC datasets.

3. Results

3.1. Global forest change over the past 60 years

Between 1960 and 2019, the world lost 437.3 million ha (Mha) (−10.4%) and gained 355.6 Mha (+8.5%) of forest (figure 1; see also supplementary figure 3). In terms of share to the world's total forest loss by the WB regions (based on income level), the upper middle income region had the highest (30%), followed by the lower middle income region (27%) (figure 2(a)). Among the UN regions (based on level of human development), the second most developed (high) region had the highest share (33%), followed by the least developed region (27%) (figure 2(b)). By contrast, in terms of share to the world's total forest gain, about 59% and 43% were contributed by the high income region (figure 2(a)) and the most developed (very high) region (figure 2(b)), respectively.

The proportion of forest loss and gain relative to each country's land area varied considerably across income and human development levels (figures 2(c) and (d)). Despite the observed variability, however, the results reveal a clear pattern: on average, the lower income countries and countries with lower levels of human development had higher proportions of forest loss, while the higher income countries and countries

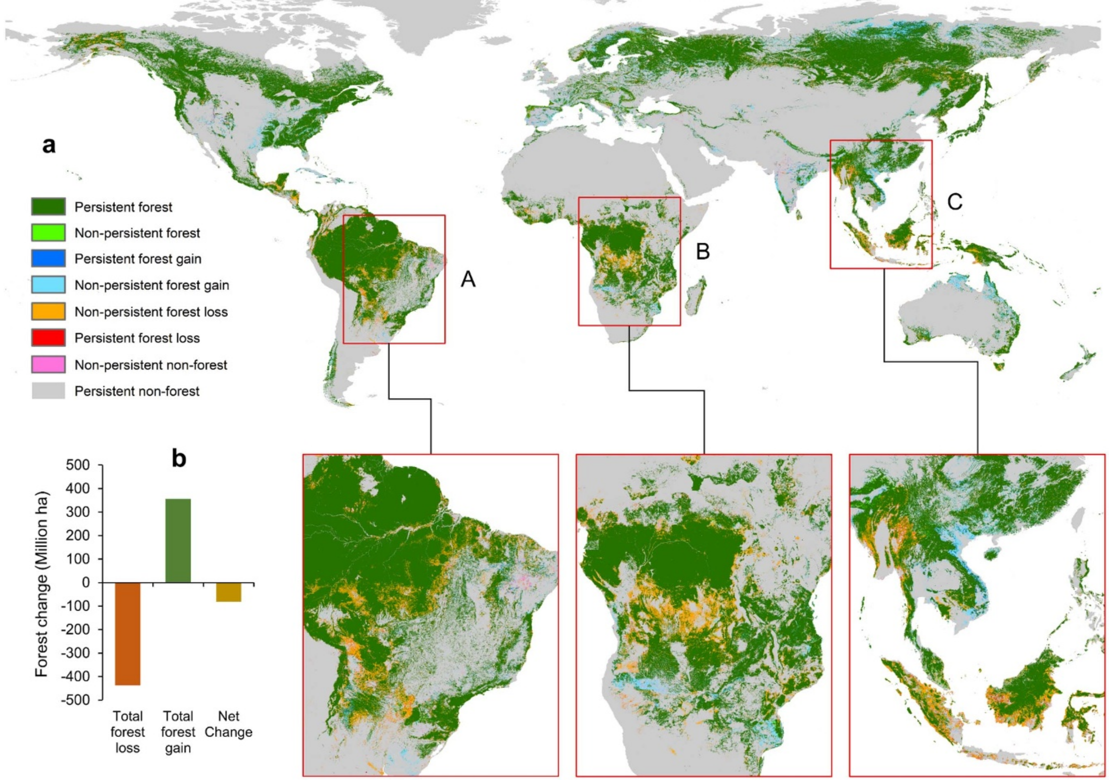

Figure 1. Global forest loss and gain across decades from 1960 to 2019. (a) Map showing the spatial distribution of forest loss and gain, with insets A, B and C showing parts of South America, Africa and Southeast Asia, respectively (for the descriptions of the map legend, see section 2). (b) Extent of total forest loss, gain and net change between 1960 and 2019. Total forest loss includes both persistent forest loss and non-persistent forest loss; total forest gain includes both persistent forest gain and non-persistent forest gain.

with higher levels of human development had higher proportions of forest gain (figures 2(c) and (d)).

3.2. Net forest loss and gain across decades

Across decades, the majority of the countries with a negative rate of change (net loss) were in the global south in the tropics, whereas the majority of the countries with a positive rate of change (net gain) were in the global north in the extratropics (figure 3(a)). While there was fluctuation in the number of countries with net forest loss across decades, an overall increase was observed, i.e. from 32% (64 countries) in 1960–1970 to 40% (78 countries) in 2010–2019 (figure 3(b)-upper panel, see 'Combined'). While there was also fluctuation in the number of countries with net forest gain, an overall decrease was observed, i.e. from 50% (98 countries) in 1960–1970 to 42% (82 countries) in 2010–2019. The top 10 countries in terms of area and rate of net forest loss and net forest gain between 1960 and 2019 are given in supplementary tables 4 and 5, respectively.

At the regional level, the low income region had the highest proportion of countries with net forest loss, consistent across all decades (figure 3(b)-upper panel); this was also the only region with a consistently increasing proportion of countries with net forest loss. In contrast, despite fluctuations, the high income region consistently had the highest proportion of countries with net forest gains. The high income region was also the only region with a consistent positive net change (net forest gain) across all decades, rising from 14.1 Mha during 1960–1970 to 26.6 Mha during 1980–1990 before declining to 9.0 Mha during 2010–2019 (figure 3(b)-lower panel). At the global level (Combined), the trend of forest change was a net forest loss across all decades, except during 1960–1970, when gross forest gain outweighed gross forest loss (see also supplementary figure 3). Global net forest loss also accelerated rapidly in recent decades, with 14.8 Mha in 1990–2000, 25.3 Mha in 2000–2010 and 35.5 Mha in 2010–2019 (figure 3(b)-lower panel, see 'Combined'; supplementary figure 3).

In total, there were 45 (23%) consistently net forest-gaining and 40 (20%) consistently net forest-losing countries across all decades since 1960 (figure 4(a)). The proportion of consistently net forest-gaining countries increased with income level, and vice versa (figure 4(b)). On the other hand, while the proportion of forest in 1960 varied across the consistently net forest-gaining countries within each region, there was a clear trend: the proportions of forest were generally lower in the low and lower middle income countries than in the upper middle

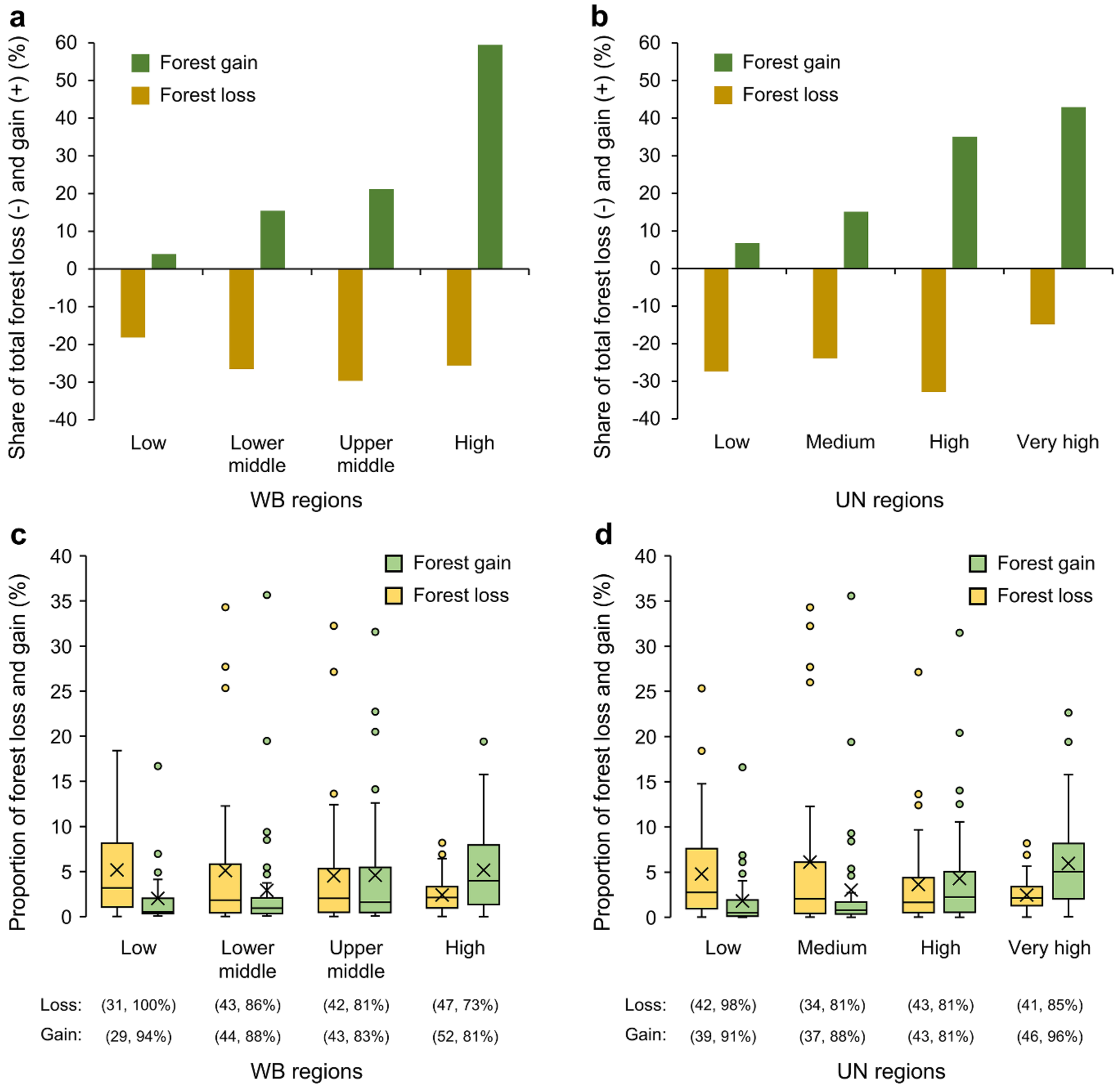

Figure 2. Regional characteristics of forest loss and gain between 1960 and 2019. (a) and (b) Percentage share of each WB region (based on income level) and UN region (based on level of human development), respectively, to the world's total forest loss and gain. (c) and (d) Percentage of forest loss and gain relative to the respective land areas of the countries across WB regions and UN regions, respectively. For (c) and (d), the numbers at the bottom refer to the number of countries that recorded gross forest loss and gain in each region, respectively, with their corresponding percentages (%) relative to the total number of countries in each region. The central rectangle of each box plot spans from the first quartile Q1 (lower end of the box) to the third quartile Q3 (upper end of the box), which is the interquartile range (IQR = Q3 − Q1). The horizontal line inside each box is the median. In cases where the values are higher than the upper fence for outliers (Q3 + 1.5 × IQR), the upper whisker (the end of the line that is above each box) is the highest value below the upper fence; otherwise, the upper whisker is equal to the highest value. The symbol '×' on the boxplots indicates the mean value.

income countries, and especially in the high income countries (figure 4(c)).

3.3. Global forest change and socioeconomic status

At the global level, while there was a net forest gain between 1960 and 1970, the world's forest has been continuously decreasing decade by decade since 1970, i.e. from 4 195.6 Mha (32.2%) in 1970 to 4 105.9 Mha (31.5%) in 2019 (figure 5(a)). While the inter-decadal rate of net forest loss slowed to about a half Mha per year during the 1980–1990 period, it continuously accelerated during the past three decades, reaching almost 4 Mha per year in the most recent decade (2010–2019) (figure 5(a); see also figure 4(b)-lower panel and supplementary figure 3). With the increase in the world's population from 3.03 billion in 1960 to 7.71 billion in 2019, forest per capita decreased from 1.4 ha in 1960 to 0.5 ha in 2019 (figure 5(a)).

A similar trend of a decreasing forest area was observed in the low, lower middle and upper middle income regions (figure 5(b)) and in the less developed regions (supplementary figure 4). By contrast, increasing forest area along with increasing GDP per capita was observed in the high income and most developed regions. The low income and least developed regions had the largest drop in forest per capita, with −2.3 ha and −1.8 ha, respectively, over the past six decades, in contrast with their lowest rise in GDP per capita. The higher income and the more

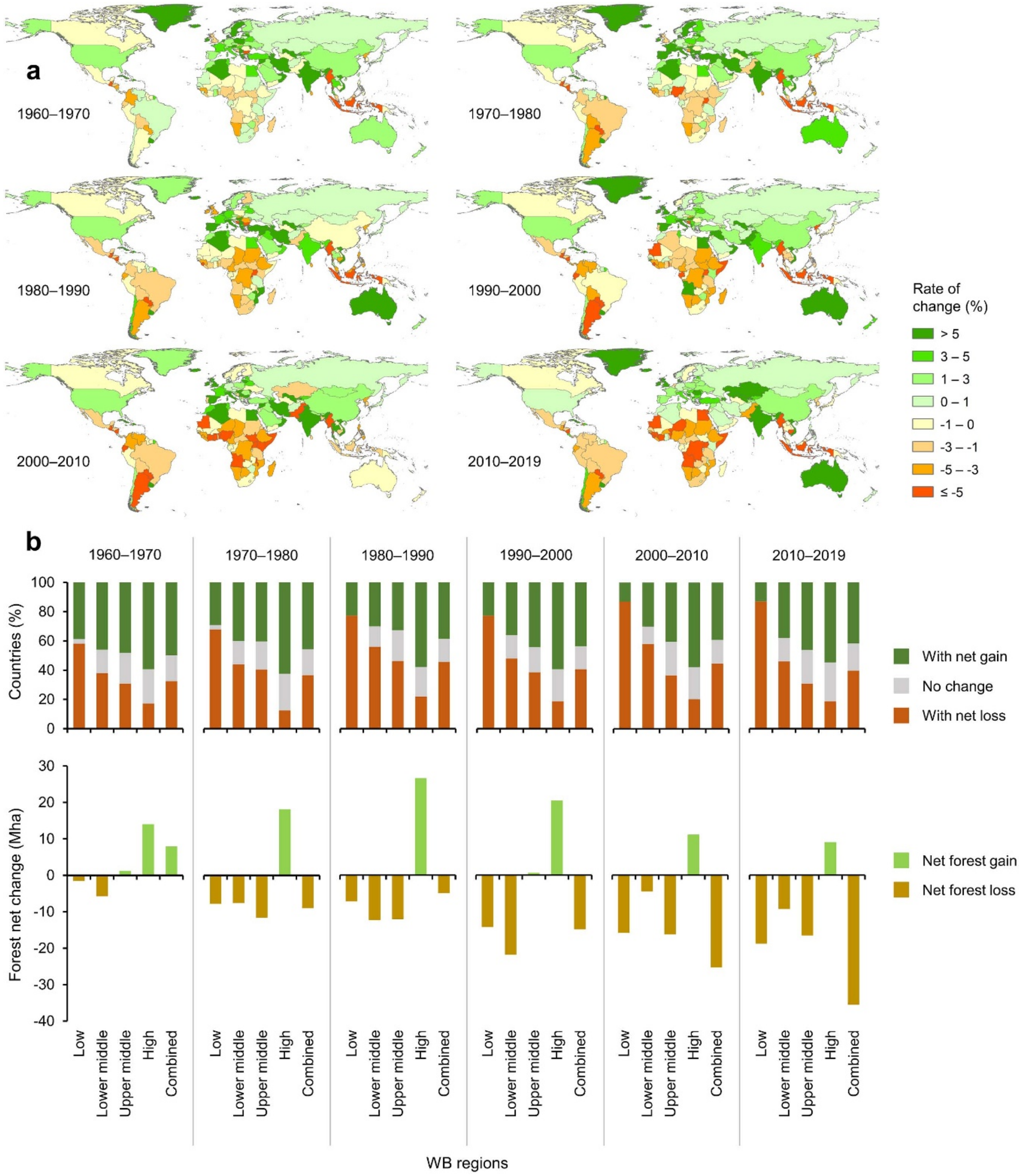

Figure 3. Regional characteristics of net forest change across decades over the past 60 years. (a) Country level rate of change (negative for net forest loss and positive for net forest gain) relative to the area of forest at the start of each decade. (b) Upper panel: percentage of countries with a net forest loss and net forest gain relative to the total number of countries in each WB region (based on income level). Lower panel: regional level extent (area) of net forest loss and gain. 'Combined' refers to the total of all regions.

developed regions had accelerating GDP rise per capita (especially the richest and most developed regions) accompanied by a relatively more stable (for the upper middle income and highly developed regions), or an increasing (for the richest and most developed regions), forest extent.

Net forest gain and change in GDP were positively correlated across all six decades (figure 6(a)). All the correlation coefficients (i.e. $r = 0.32$–0.79) were statistically significant ($p < 0.005$). In contrast, net forest loss and change in GDP were positively and significantly correlated in only two decades (1970–1980 and 2000–2010) (figure 6(b)).

4. Discussion

4.1. Challenges and implications of the findings

The challenge of global forest conservation remains and has become more urgent, as forest loss has continuously outpaced forest gain, globally and decade by decade since 1970 (figure 5(a); supplementary figure 3). The rate of global net forest loss has also accelerated in recent decades (figure 3(b)-lower panel, see 'Combined'; figure 5(a)), with the slight increase in gross forest loss and the slight decrease in gross forest gain between the 1990–2000 and 2000–2010 periods and the higher decrease in

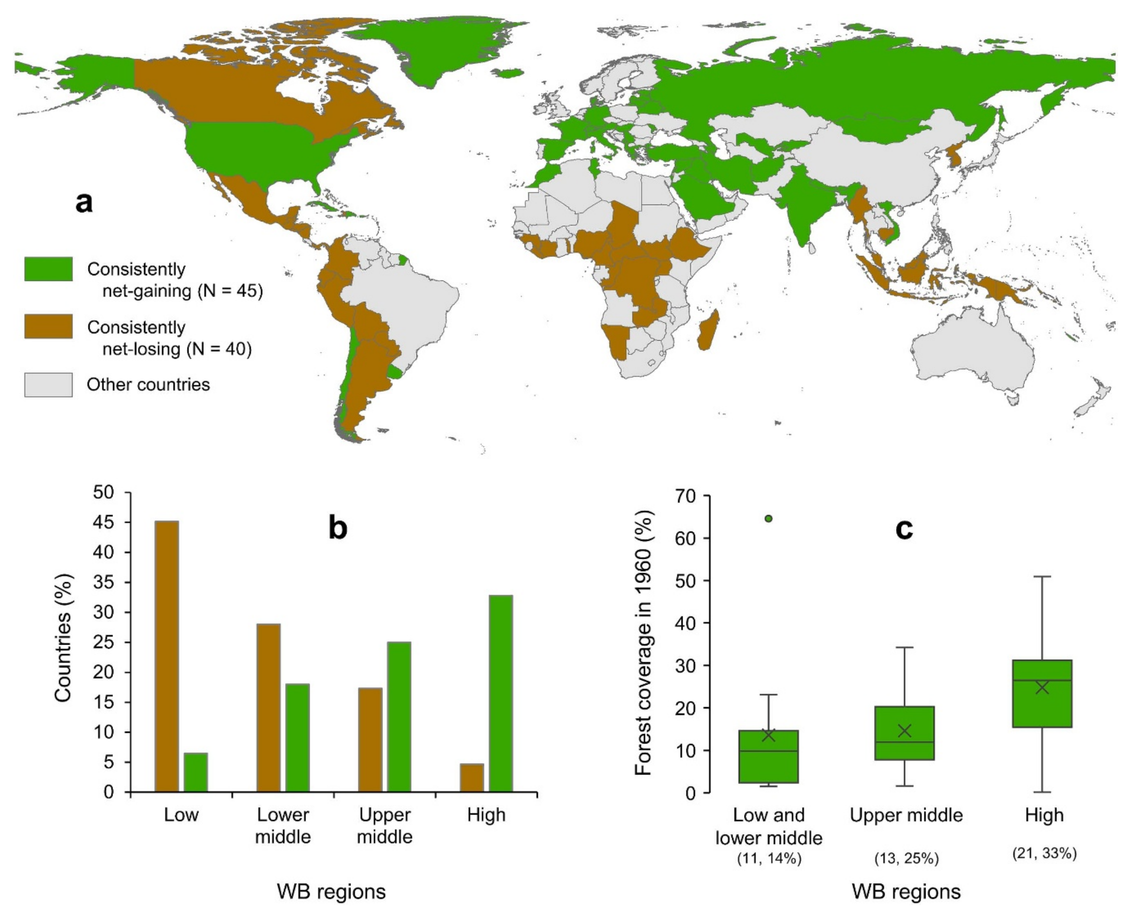

Figure 4. Consistently net forest-gaining and net forest-losing countries across decades from 1960 to 2019. (a) Spatial distribution of consistently net forest-gaining and net forest-losing countries. 'Other countries' refers to those that were neither consistently net forest-gaining nor consistently net forest-losing across all decades. Brazil, for example, is included in this category because it had a net gain during 1960–1970 but had a net loss in all subsequent decades. (b) Percentage of consistently net forest-gaining and net forest-losing countries in each WB region (based on income level). (c) Percentage of forest in 1960 in consistently net forest-gaining countries relative to the respective land areas of the countries across regions. For (c), the numbers at the bottom refer to the number of consistently net forest-gaining countries in each region, with their corresponding percentages (%) relative to the total number of countries in each region. In (c), there were only two low income countries; hence, they were combined with lower middle income countries. See captions of figure 2 for the interpretation of the boxplots in (c).

gross forest gain outweighing the decrease in gross forest loss between the 2000–2010 and 2010–2019 periods (supplementary figure 3). Furthermore, despite some fluctuations, the number of countries with net forest loss has been increasing, whereas the number of countries with net forest gain has been decreasing (figures 3 and 6), contrary to what is expected of the various global environmental initiatives established earlier, such as Agenda 21 (1992) and the UN-REDD Programme (2008) (see also supplementary figure 3 for some other relevant global initiatives and advances in scientific knowledge related to forest conservation and sustainability in general).

In the context of global sustainability [4, 13, 24], climate change [7–9] and biodiversity conservation [1–3], there is a need to strengthen current global efforts both in reducing deforestation and forest degradation and in enhancing forest restoration and conservation (e.g. SDG 15) to at least flatten the world's forest loss curve (figure 5). In particular, international forest policy programs need to revisit and redesign global forest trade from lower income countries. For instance, between 1972 and 2009, low income countries harvested more than 170 Mha of forest products for export, while higher income countries were the only net importers [61]. Global partnerships (e.g. SDG 17), forest certification programs and other incentive mechanisms (e.g. UN-REDD Programme) need to be fully operationalized to help the less developed and lower income countries restore their lost forests and conserve or enhance their remaining forests.

In 1960, the proportion of forest in the consistently net forest-gaining countries was higher in the higher income regions (figure 4(c)). The data, however, could not reveal when and at which proportion of forest or level of forest scarcity these consistently net forest-gaining countries started to experience forest transition. The data indicate that forest transition in these countries started before 1960, the beginning year of the dataset that we used. Nevertheless, such observation (figure 4(c)) is indicative of the more developed and higher income countries being

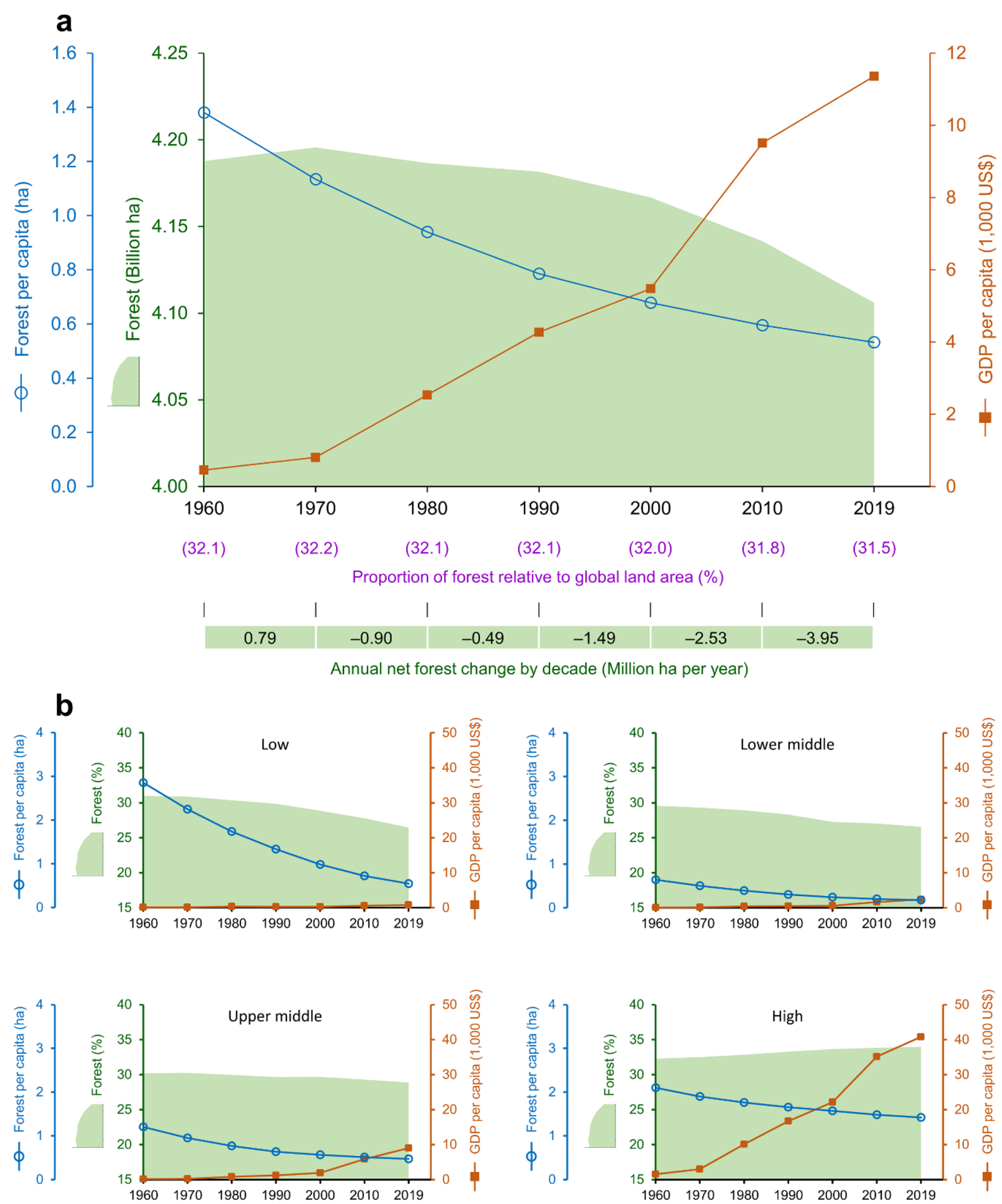

Figure 5. Forest extent, forest per capita and GDP per capita and their changes from 1960 to 2019. (a) Global data. The figure also lists the decadal percentage of global forest (purple) and annual net change by decade (green bar at the bottom). (b) Data for the WB regions (based on income level) (see also supplementary figure 4 for the UN regions). In (a), forest extent is measured in area, whereas in (b), it is measured as percentage of the total land area of countries in each region. Supplementary table 3 provides the country-level dataset.

more proactive and financially capable of forest restoration and conservation.

The more developed and higher income countries had a better forest change trajectory, i.e. had a lower forest area decline and/or a higher forest area increase (figure 5(b); supplementary figure 4). This indicates that for the less developed and lower income countries, unless they receive essential assistance in a timely manner, they should first strive to attain economic progress and stability to increase their capability to flatten their own respective forest loss curves. The correlation between economic growth and net forest gain is stronger than between economic growth and net forest loss (figure 6). Our hypothesis why this has been the case is that the more developed and higher income countries have relatively more resources (e.g. financial, infrastructure) to conserve and enhance their forests than the less developed and lower income countries. The more developed and higher income countries also did not fully rely on their own forest resources to satisfy domestic needs, but rather on forest resources imported from other

a

	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010	2010–2019	**1960–2019**
Pearson's r	0.533	0.397	0.429	0.321	0.791	0.565	**0.617**
$p <$	0.0001	0.005	0.001	0.005	0.0001	0.0001	**0.0001**
n	52	54	49	73	73	80	**40**
N	98	90	76	86	77	82	**86**

0.6–0.8
0.4–0.6
0.2–0.4
0.0–0.2

b

	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010	2010–2019	**1960–2019**
Pearson's r	-0.003	0.266	0.110	-0.005	0.591	-0.119	**0.381**
p	= 0.986	< 0.05	= 0.350	= 0.966	< 0.0001	= 0.312	**< 0.005**
n	36	53	73	70	85	73	**52**
N	64	72	90	80	88	78	**86**

(+ or –)
0.4–0.6
0.2–0.4
0.0–0.2

Figure 6. Correlation coefficients across six decades (1960–2019). Correlation between (a) change in GDP and net forest gain, and (b) change in GDP and net forest loss. For net forest loss, absolute values were used in the correlation analysis. '*N*' refers to the number of countries with a net forest gain or loss during each time period and '*n*' is a subset of '*N*' that refers to the number of countries that have GDP data at each time period and were used in the correlation analysis. Bold values to the right are for the entire 1960–2019 period.

countries through international trade, especially from developing countries in the tropics, as has been shown in other studies [43, 61–63].

Our results also confirm earlier observations [39–41] that forest transition is not exclusive to the most developed and wealthiest countries (see, for example, Vietnam, India, China and Uruguay). However, with forest transition happening in the more developed and higher income countries (i.e. not exclusively the richest and most developed nations), forest loss is displaced to the less developed and lower income countries through international trade [43, 62, 63]. This trend is consistent with FTT and the global displacement of land use which is a consequent of forest transition [37, 39, 43, 62]. A recent study that used data for 2001–2015 concluded that while many developed countries (including some developing countries such as China and India) have obtained net forest gains domestically (see also figures 1, 3(a) and 4(a)), they have also increased the deforestation embodied in their imports [63]; this study also concluded that tropical forests are the most threatened biome [63] (see also figures 1 and 3). This threat is alarming, considering the critical roles that tropical forests play in the context of climate change (mitigation and adaptation) [7–9, 64] and biodiversity conservation [1, 2, 65, 66]. Habitat losses in the tropics cannot be directly compensated by forest habitat gains in temperate regions [1]. Hence, the more developed and higher income countries should adhere to responsible use of forest resources so that they can reduce their dependence on imported forest-related products from the less developed and lower income countries, especially those in the tropics. The draft outline of the post-2020 biodiversity framework recognizes this and urges member states to reduce unauthorized timber exports by 50% or more, particularly for countries with a significant history of illegal timber trade [67]. Strengthening the regulation of global timber trade through a forest certification program can be a way forward for less developed and lower income countries. Similarly, the European Commission has recently proposed a new regulation to promote the consumption of deforestation-free products, with the aim to reduce the European Union's contribution to global deforestation, forest degradation, greenhouse gas emissions and biodiversity loss [68].

4.2. Drivers of forest change

Socioeconomic conditions and international trade are important drivers of forest change (gain and loss), though there are others. Generally, drivers of forest loss can be classified into proximate causes (agricultural expansion, wood extraction, infrastructure extension and other factors including biophysical factors like fires and social trigger events like war) and underlying driving forces (demographic, economic, technological, policy and institutional and cultural factors) [69–71]. Proximate causes of forest transition and enhancement (i.e. the improvement of forest cover) include afforestation, reforestation, forest restoration and rehabilitation and natural regeneration [24]. Underlying driving forces of forest transition and enhancement also can be related to policy, institutional and cultural factors, including increased environmental awareness and commitment by countries to international agreements [32, 41, 48, 72, 73].

For the top net forest-losing countries in terms of area over the past 60 years (i.e. Indonesia, Brazil, DR Congo, Myanmar, Paraguay and Colombia; see supplementary table 4(a)), the dominant drivers of forest loss are unprecedented commercial logging, industrial-scale clearing for mining, expansion of oil palm plantations, decentralization of forest management and socio-political transitions, among others [74–76]. For instance, since the late 1990s, Indonesia has increased its production of wood-based panel and paper [77] and decentralized forest governance, which in turn authorized the provincial governments to fast-track forest clearance for mining and other industrial activities including oil palm plantations [78, 79]. Mining activities are also a leading factor behind the loss of primary forest in Brazil and Paraguay, and several protected areas were either encroached or officially earmarked for mineral exploration [74, 75]. Contrarily, selective logging and small-scale, non-mechanized forest clearing for agriculture resulted in the persistent loss of forest in DR Congo [74, 80]. Myanmar's drivers of forest loss are also similar to DR Congo's, but further characterized by socio-political transition, poverty and a logging ban in Thailand, which increased the demand for the country's (Myanmar) timber [81]. In Colombia, armed conflicts, cattle ranching and agriculture expansion are the proximate causes of forest loss and degradation [82].

For the top net forest-gaining countries in terms of area (i.e. Australia, India, USA, China, Russia and Vietnam; see supplementary table 4(b)), the dominant drivers of forest gain are proactive conservation policies, sustainable forest management, reforestation, and afforestation, among others [31, 32, 40, 73, 83]. In the USA, Australia and China, forest plantations have played a massive role in restoring lost forests, which has been further supported by agricultural land abandonment, alongside environmental initiatives [32, 73, 84]. In India, in contrast, forest transition closely followed the end of the colonial regime, which led to the adoption of robust and conservation-centric forest policies. Factors that led to forest recovery included agricultural intensification, proactive government policies, private forest production and community forestry [77, 83]. In fact, many researchers credit the existing community forest arrangement, *aka* Joint Forest Management, as the key to India's forest transition [83, 85]. Forest restoration in Vietnam was supported by conservation initiatives and policies including a national-scale reforestation program in the early 1990s and control of illegal trade of wood products [39, 86].

4.3. Comparisons and limitations

One potential source of uncertainty in our results is the primary dataset used (HILDA+) (supplementary figure 1), which was a product of a reconstruction and modeling procedure [16]. Such a procedure was necessary due to the lack of actual spatially explicit LUC data back to the 1960s [16], which could have also served as a reference for validation. Nevertheless, the dataset used is properly documented, peer-reviewed and freely available for scientific scrutiny.

Compared with other spatially explicit datasets covering a few decades back (see section 2 for details), the forest extent estimates from HILDA+ were generally lower than those of GLASS-LC, but higher than those of MODIS-LC; they were relatively closer to those of CCI-LC (supplementary figure 6). A previous study that compared forest estimates in the Philippines derived from various remotely sensed datasets found that CCI-LC had the least overall disagreement with the reference data used among the datasets of global coverage, including MODIS-LC [87]. Another study at the global scale found that CCI-LC and MODIS-LC had statistically the same overall thematic accuracy [88]. In terms of net change, HILDA+ showed a decreasing area of forest during the last 2–3 decades, consistent with those of the other datasets including the FRA reports by the FAO, but not with that of GLASS-LC (supplementary figure 5).

However, while HILDA+ and FAO's FRA reports both show a decreasing global forest extent in recent decades, they differ in the rates of net decrease. HILDA+ shows that the rates of net forest loss have accelerated in recent decades (c. 1990–2020) (figure 3(b)-lower panel, see 'Combined'; figure 5(a); supplementary figure 3), whereas FAO's FRA reports show the opposite [14, 89]. Such a discrepancy between the FRA reports and other datasets, including HILDA+, is not uncommon [24, 90, 91] and can be due to a number of reasons, from the definition of forest to the data used and methods employed for forest classification [24, 89, 92]. The lack of spatially explicit data that is supposed to back up the FRA reports made us unable to perform a detailed comparison with HILDA+.

Another source of uncertainty in our results comes from the country groupings used in our regional analysis, which was static at about the current time point (WB's fiscal year 2016) [56], owing to the lack of such country classifications in earlier years (e.g. 1960 and 1970). Nevertheless, the results based on income level (WB regions) are complemented by, and consistent with, the results based on level of human development (UN regions) (figures 2(b) and 5(b); supplementary figure 4). Economic growth may have resulted in changes in the classification of countries and thus in WB and UN country groupings over time. The direct use of correlation analysis relating change in GDP to net forest gain and net forest loss (figure 6), without having to rely on country groupings, was intended to capture the potential influence of economic growth that may have resulted in changes in country groupings. The results of the correlation analysis, therefore, strengthen our regional analysis.

Finally, our findings were based on forest change estimates at decadal interval as per the HILDA+ dataset at seven time points (see section 2.1 and supplementary figure 1). In our analysis, the propagation of uncertainty in the HILDA+ dataset to decadal estimates of forest loss or gain was not conducted. The uncertainty of annual change estimates had been considered in the production of HILDA+ [16].

4.4. Insights on FTT

Overall, FTT provides a platform for understanding the plausible factors that influence the spatiotemporal pattern of forest changes at different scales (from local to global). Our analysis focused on the global scale with extensive temporal coverage (60 years) to examine the relationship between forest change and socioeconomic conditions of countries and regions. As discussed above, availability of financial resources and relevant policies and initiatives towards forest conservation are important drivers of forest transition. However, the consequent displacement of forest loss to the lower income countries in the tropics is an urgent issue that must be addressed.

These factors influencing forest transition and the consequent displacement of forest losses have been established to be within the scope of FTT, but there are also other important issues that need to be considered. For example, the issue of forest quality and integrity is not yet well-considered in FTT [29]. We note that not all cases of forest cover increase are equally beneficial in the context of biodiversity conservation; for example, monocultures and industrial plantations are also known as 'green deserts' [24, 36] (see also section 1). There are also issues regarding the minimum tree canopy cover to be used for a land to be considered forest [93], as well as on the implications of tree canopy cover thresholding for forest monitoring [24, 94, 95]. All of these issues are related to how forest is defined and classified, which remains contentious [24, 93–95]. Some studies have also shown that drivers of forest expansion go beyond human interventions as natural regeneration and other biophysical factors such as climate change, nitrogen deposition and CO_2 fertilization also have effects [47, 96]. Hence, because FTT is not broad enough to address these issues and deal with the complexity of forest change, there is a need for a new theory or framework, or to at least reconsider or expand it.

5. Summary and conclusions

In this study, we examined how the extent of global forest change varied over space and time and how the detected trends in global forest change related to FTT using spatially explicit data of global and wide temporal coverage. We found that over the past 60 years (1960–2019), the global forest area has declined by 81.7 Mha (i.e. 10% more than the size of the entire Borneo island), equivalent to a net forest loss rate of 1.4 Mha per year. This loss is despite the sizeable forest gains over the period, higher numbers of consistently net forest-gaining countries across decades, increasing gross forest gain over the 1960–2000 period and decreasing gross forest loss in the most recent decade. Consequently, with this forest decline and the population increase over the period, the global forest per capita has decreased by over 60% (from 1.4 ha in 1960 to 0.5 ha in 2019).

The results also revealed that forest transition is not exclusive to the most developed and wealthiest nations. In general, however, there is evidence to show that forest change trajectory was related to socioeconomic conditions of countries: lower income and less developed countries were more associated with forest loss, whereas higher income and more developed countries were more associated with forest gain. There was also a positive relationship between proportion of forest and GDP in the high income and highly developed regions and a significant positive correlation between change in GDP and net forest gain. These findings support the FTT hypothesis (i.e. forest extent expands with socioeconomic growth). But since drivers of forest cover change are not limited to human interventions and socioeconomic factors as biophysical factors such as climate change also have effects, there is a need to at least reconsider or expand FTT.

Overall, our results highlight the need to strengthen the support given to lower income countries, especially in the tropics, to help improve their capacity to minimize or end their forest losses. To help address the displacement of forest loss to the lower income countries in the tropics, higher income nations need to reduce their dependence on imported tropical forest products. This is important considering the indispensable role that tropical forest ecosystems play in addressing various pressing sustainability and social-ecological challenges such as climate change and biodiversity loss.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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