# Assessing the Forest Transition Hypothesis: Are Deforestation Dynamics Different Across Continents?

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## Abstract

Forest transition describes a land use change process where an initial period of forest cover loss is followed by a phase of recovery. Previous studies on forest transition, often limited by geographic or temporal constraints, have yielded mixed results about the plausibility of this hypothesis. This research analyzes the relationship between the Human Development Index (HDI) and deforestation rates using quantile regression method. The study encompasses 165 countries across four continents over the period 1990-2021. Our findings demonstrate that forest transition provides a plausible framework for understanding land use dynamics, with significant regional variations that elucidate current trends in forest cover changes. These results underscore the importance of considering regional contexts in forest conservation and development policies.

## 1. Introduction

Forest transition is a process of land use change in which a country or region initially experiences forest cover loss over a long period. However, at a later stage, the dynamics of land use are reversed, leading to the recovery of a fraction of the initially lost forest area. The overall behavior of the forest cover follows a "*U*" shape pattern over time (Rudel, Schneider, and Uriarte 2010; Barbier, Delacote, and Wolfersberger 2017). The concept of forest transition was introduced by the geographer Alexander Mather in the 1990s, after observing and documenting this behavior in developed countries (Mather 1992).

Forest transition can be divided into four phases: pre-transition, early transition, late transition, and post-transition. During the pre-transition phase, forest cover is high and stable. In the early transition phase, forest cover decreases rapidly. In the late transition phase, forest cover continues to decline but at a slower pace. Finally, during the post-transition phase, forest cover expands until it stabilizes again (Hosonuma et al. 2012). Thus, the hypothesis of forest transition suggests that the deforestation rate is close to zero during the pre-transition stage, accelerates during the early transition, slows down during the late transition, and reverses to become positive in the post-transition, reaching zero again upon completion.

When considering that countries and regions develop over time, forest transition can be studied as a consequence of social and/or economic development (Caravaggio 2020). Moreover, the hypothesis indicates that the deforestation rate, in terms of development level, should follow an inverse tilde (~) shape or, in mathematical terms, a cubic relationship with development.

Previous studies linking development and deforestation have found mixed or partial results regarding forest transition (a detailed discussion can be found in (Barbier, Delacote, and Wolfersberger 2017; Caravaggio 2020)). For example, using FAO data for the period 1971-1994 and including 43 developing countries, Culas (2012) identified a quadratic deforestation pattern in terms of GDP per capita for Latin America and Africa, but this pattern was rejected for Asia. Similarly, distinguishing between OECD and non-OECD countries for the period 1990-2007 and considering clusters of countries in Africa, Asia, and Latin America, Joshi and Beck (2016) identified a quadratic pattern only in Africa. This last results is similar to the one found by Ajanaku and Collins (Ajanaku and Collins 2021), in which support for a quadratic pattern is found in Africa. Likewise, for a sample of 95 countries from 1999-2015 using satellite data, Andrée et al. (2019) identified a quadratic relationship between income per capita and deforestation. It must be noted that quadratic patterns represent a partial picture of forest transition, corresponding to the early to late transition stages. Therefore, to empirically test the forest transition hypothesis, a cubic relation between development level and deforestation rate is required (Caravaggio 2020).

Other related work has focused on identifying factors that influence forest transition. For instance, high GDP and low remaining forest cover promote forest cover expansion (Rudel et al. 2005). Additionally, economic development has been found to shorten the deforestation period without increasing its intensity (Wolfersberger, Delacote, and Garcia 2015).

In the literature on forest transition, GDP per capita is a common indicator of development level. However, deviations from this approach exist. For example, Redo et al. (2012), using satellite images for the period 2001-2010 in Central America, identified that countries with a low Human Development Index (HDI) experienced the highest deforestation rates, while those with higher HDI exhibited increasing or stable forest cover. In this study, a similar approach was followed, using HDI as a development indicator, as a stronger relationship was found using this measure instead of GDP per capita.

Previous literature is often geographically limited (e.g., a narrow number of countries included) and/or temporally restricted (e.g., time spans of less than 25 years). Consequently, the spectrum of development is confined to the specific locations and periods studied, making it difficult to examine land use dynamics on the right tail of forest transition. This study aims to address this knowledge gap. Specifically, by analyzing a broader set of countries at different development stages with diverse locations over a longer time span, we aim to achieve two main objectives: first, to determine whether forest transition provides a plausible explanation of land use dynamics at a continental level; and second, to estimate the development level required to initiate each phase of forest transition, with particular emphasis on the second turning point —the development level needed to shift from deforestation to reforestation.

The results indicate that forest transition does indeed offer a plausible explanation of land use dynamics, with significant regional variations that help explain current trends.

To detail the findings, the rest of the paper is structured as follows: Section Two presents the data sources and modeling strategy. Section Three analyzes the fitted relationship between development and deforestation rate for each continent. In Section Four, the findings are discussed in a broader context. The manuscript concludes with some final remarks.

## 2. Methods

To begin with, relevant statistical data was collected and cleaned. Once data was collected, an exploratory analysis was performed. Based on exploratory analysis, statistical methods and models were chosen. The selected models were useful to identify forest transition stages, which were the basis to obtain the results of our analysis. The mentioned steps are further described in the following sections.

### 2.1. Data Sources

In order to analyze land use change patterns worldwide and its link to development, forest cover and Human Development Index (HDI) statistics were consulted. The former was obtained from FAO (Food and Agriculture Organization) statistics ("FAOSTAT" 2023) and the latter from UNDP (United Nations Development Programme) data center (PNUD 2023). During the time in which this research was prepared, statistical figures were available for 178 countries in the five continents during the period 1990-2021.

| Variable name | Type of variable | Units or categories | Transformation | Source |
|---|---|---|---|---|
| Deforestation rate (dr) | numerical continous | Percentage | $\%\Delta f_{t-1} = \frac{f_t - f_{t-1}}{f_{t-1}}$ | Own calculations based on FAOstat data. |
| Human Development Index (hdi) | Numerical | Index | NA | UNDP |
| Continent (con) | Categorical | Africa<br>Americas<br>Asia<br>Europe | Countrycode function | Own calculations based on FAOstat data. |

**Table 1.** Variables used in the analysis and its statistical properties.

The statistical information was imported to R software (2023). Subsequently, data was cleaned and transformed (when required), using dplyr package (Wickham et al. 2023). Specifically, csv files were downloaded from the sources indicated in Table 1, processed, and joined to obtain a data frame with forest cover and HDI per country in the period of time mentioned earlier. After that, deforestation rate was calculated as the annual relative change of forest cover (see Table 1). Therefore, a negative value indicates that forest cover decreased in a specific country and year. Likewise, a positive value means that forest covered increased. As a result of this data transformation, one observation per country was lost. Hence, deforestation rate is available for the period 1991-2021.

The continent where each country is located was added using the countrycode package (Arel-Bundock, Enevoldsen, and Yetman 2018). To achieve it, country name (in English) was provided and the function generated the continent where the country is located as the output. Continent, as will be shown later, was an important part of the analysis due to the presence of regional patterns. Finally, it must be highlighted that countries in Oceania were excluded from the analysis. This choice responds to diverse country specific trajectories and, consequently, lack of a regional pattern. As a result, the number of countries included in the analysis was reduced to 165 (Africa: 50; the Americas: 34; Asia: 42; Europe: 39).

## 2.2. Exploratory Data Analysis

Figure 1 displays the relationship between development level and deforestation rate for each continent considered in the analysis (*i.e.* Africa, the Americas, Asia and Europe). As the figure shows, the relationship between development and deforestation rate is characterized by the presence of outliers. However, a general pattern can be observed: low development level is associated with forest cover contraction or deforestation process (i.e. negative rates). In contrast, high development level is associated with forest cover expansion or reforestation/afforestation process (i.e. positive rates). In addition, it can be noticed that the development level in which deforestation process starts and the transition from deforestation to reforestation/afforestation is different in each continent. For example, in Africa deforestation process starts early, with low development level (e.g. HDI < 0.4). However, in Asia, a higher development level (e.g. HDI > 0.4) is required to trigger deforestation. Likewise, while in Europe, the reversal of deforestation process is achieved with a HDI level of around 0.6, the rest of continents - and specially Africa and Americas – still experience an important degree of deforestation around the mentioned development level. This suggests that forest transition might exhibit regional variations.

As it is shown in the following sections, the previous insights were useful to inform the specification of the statistical model along with regression method.

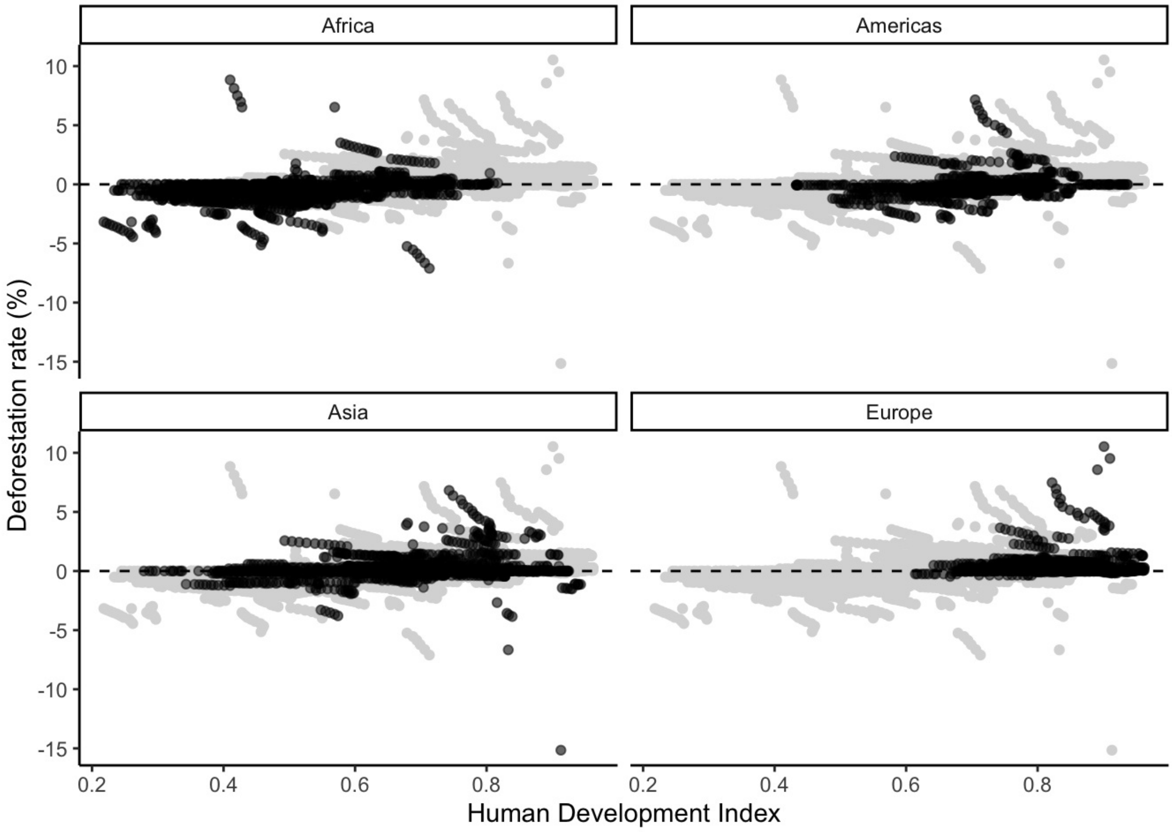


**Figure 1.** Deforestation rate vs HDI per continent in the period 1991-2021.

## 2.3. Regression Model

From a mathematical point of view, forest transition indicates that the relationship between development and deforestation rate follows a cubic equation. Therefore, different model specifications using linear, quadratic and cubic specifications were tested. The mentioned models were fitted using quantile regression, a method robust to outliers, using the software R (2023) and the package quantreg (Koenker 2023). Model performance evaluation and selection was based on mean absolute error (mae), an appropriate metric in the presence of outliers. The resulting figures are shown in Table 2.

| model | mae |
|---|---|
| 0.5 | |
| dr ~ hdi*continent + I(hdi^2) + I(hdi^3) | 0.5390 |
| dr ~ hdi + I(hdi^2)*continent + I(hdi^3) | 0.5394 |
| dr ~ hdi * continent + I(hdi^2) | 0.5395 |
| dr ~ hdi * continent | 0.5395 |
| dr ~ hdi + I(hdi^2) * continent | 0.5397 |
| dr ~ hdi + I(hdi^2) + I(hdi^3)*continent | 0.5398 |
| dr ~ hdi + I(hdi^2) + I(hdi^3) + continent | 0.5461 |
| dr ~ hdi + I(hdi^2) + continent | 0.5481 |
| dr ~ hdi + continent | 0.5514 |
| dr ~ hdi + I(hdi^2) + I(hdi^3) | 0.5595 |
| dr ~ hdi + I(hdi^2) | 0.5603 |
| dr ~ hdi | 0.5648 |
| 0.25 | |
| dr ~ hdi*continent + I(hdi^2) + I(hdi^3) | 0.6167 |
| dr ~ hdi + I(hdi^2)*continent + I(hdi^3) | 0.6172 |
| dr ~ hdi + I(hdi^2) + I(hdi^3)*continent | 0.6173 |
| dr ~ hdi * continent | 0.6209 |
| dr ~ hdi + I(hdi^2) * continent | 0.6215 |
| dr ~ hdi * continent + I(hdi^2) | 0.6226 |
| dr ~ hdi + continent | 0.6360 |
| dr ~ hdi + I(hdi^2) + continent | 0.6374 |
| dr ~ hdi + I(hdi^2) + I(hdi^3) + continent | 0.6410 |
| dr ~ hdi + I(hdi^2) + I(hdi^3) | 0.6549 |
| dr ~ hdi + I(hdi^2) | 0.6606 |
| dr ~ hdi | 0.6702 |
| 0.75 | |
| dr ~ hdi + I(hdi^2) + I(hdi^3) + continent | 0.6319 |
| dr ~ hdi + I(hdi^2) * continent | 0.6329 |
| dr ~ hdi + I(hdi^2) + continent | 0.6332 |
| dr ~ hdi + I(hdi^2) + I(hdi^3)*continent | 0.6342 |
| dr ~ hdi*continent + I(hdi^2) + I(hdi^3) | 0.6349 |
| dr ~ hdi + I(hdi^2)*continent + I(hdi^3) | 0.6350 |
| dr ~ hdi * continent + I(hdi^2) | 0.6396 |
| dr ~ hdi * continent | 0.6424 |
| dr ~ hdi + continent | 0.6427 |
| dr ~ hdi | 0.6641 |
| dr ~ hdi + I(hdi^2) + I(hdi^3) | 0.6643 |
| dr ~ hdi + I(hdi^2) | 0.6646 |

**Table 2.** Model Specification and performance metric (mae) per quartile (q1 = 0.25, q2 = 0.5, q3 = 0.75).

Quantile regression is an statistical method in which -instead of estimating the conditional mean, as in OLS- the conditional quantile of choice is estimated, through the specification of parameter tau ($\tau$) (Koenker 2023). For instance, to estimate the conditional median, tau must be equal to 0.5. Quantile regression is robust to outliers and it allows to explore the behavior of the distribution in the lower and upper range of the distribution by estimating a different quantile (e.g. $\tau = 0.25$ for the first quartile or $\tau = 0.75$ for the third quartile).

In order to evaluate forest transition as a possible explanation of observed deforestation, different model specifications were fitted and evaluated for the first, second and third quartile (i.e. $\tau = 0.25$, $\tau = 0.5$, $\tau = 0.75$). In this case the first quartile approximates the behavior of countries that experiment a higher than typical deforestation rate. Likewise, the second quantile, approximates the behavior of countries that exhibit a typical deforestation rate. Third quantile, thus, approximates the behavior of countries that experiment a lower than typical deforestation rate.

As it can be observed in Table 2 regardless of quartile, the best performing model is consistent with forest transition. In other words, the model follows a cubic equation. In the case of the first and second quantile, the best performing model has the same specification: a cubic equation in which the intercept and linear term depend on the continent. In the case of the third quartile, only the intercept changes in terms of continent and the cubic, quadratic and liner term of the equation are the same for all continents.

### 2.4. Forest transition stages

Once the best model for each quartile was identified, multiple runs (n = 1000) using bootstrap methods were fitted with the aim of pinpointing forest transition stages for each run. The bootstrap replicates were created using the package rsample (2023). Figure 2 shows the identification strategy: the roots of the estimated cubic function and its minimum were calculated. The lowest root correspond to the beginning of the early transition. The minimum shows the starting point of the late transition. The middle root shows the beginning of the post transition. And the highest root indicates the conclusion of the forest transition.

This method allowed to identify the length (i.e. difference between early and late transition in terms of HDI) and severity (i.e. deforestation rate in beginning of late transition) of deforestation process in each continent.

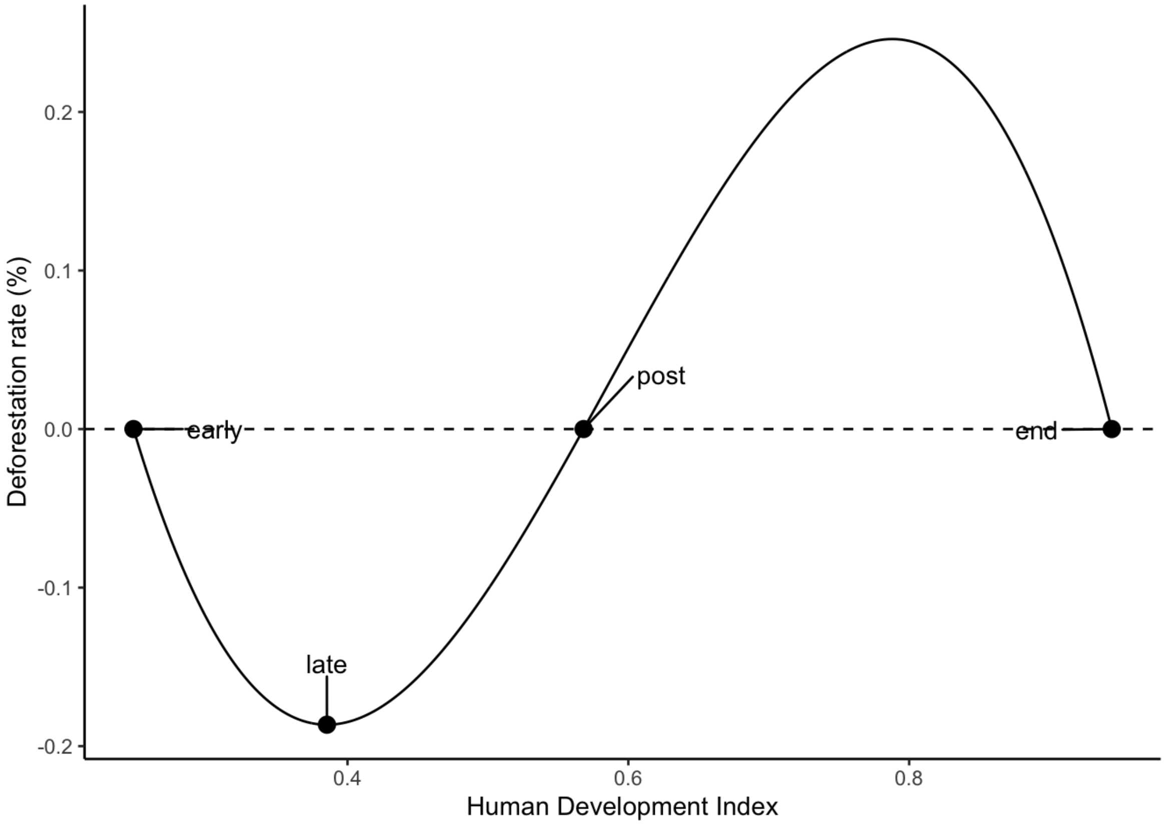


**Figure 2.** Identification of Forest transition phases based on a possible model fit.

## 3. Results

In the following sections the length and severity of forest transition in each continent and quantile is analyzed with the aim of identifying these characteristics of forest transition on a regional basis.

### 3.1. Deforestation length

Deforestation length (*dl*) can be understood as the time during which deforestation process takes place. In terms of forest transition stages, it can be seen as the difference in development level between early transition and post-transition, which corresponds to the first and second roots, respectively. The third root of the fitted models represents the conclusion of forest transition process. Figure 3 displays the distribution of the roots for each continent and quartile. It must be considered that in some cases not real roots were calculated. In addition, some real roots were outside the HDI range (*i.e.* 0-1). The roots with those characteristics were filtered out of the analysis. In addition, the graph shows the median deforestation length and the interquartile range of the HDI for the most recent year in the data, as a shaded area.

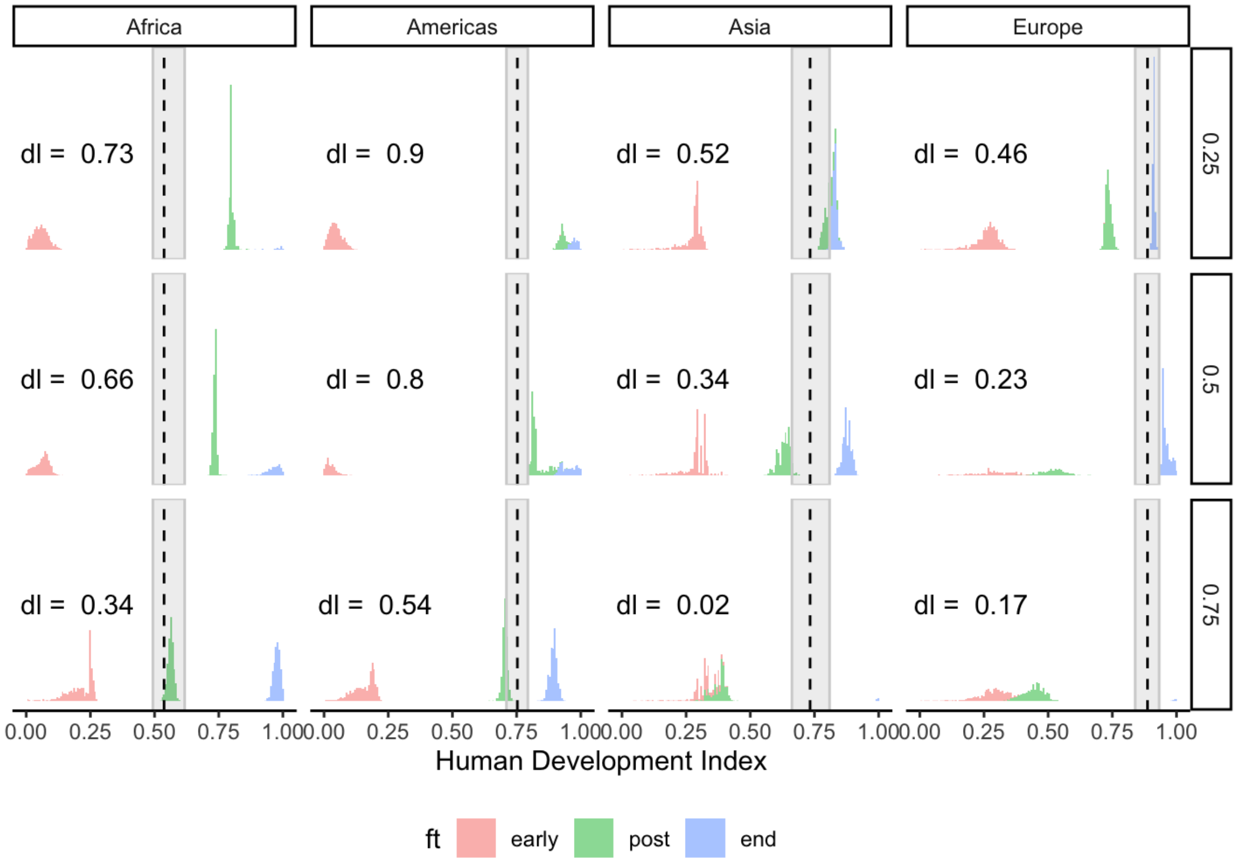


**Figure 3.** Length of forest transition per continent and quantile.

As it can be observed in Figure 3, regardless of quartile, the longest forest transitions correspond to the Americas and Africa, respectively. For instance, in the second quartile, the median length of deforestation process is 0.8 in the Americas and 0.66 in Africa, while in Europe and Asia the same figure is 0.34 and 0.23, respectively. For the first and third quartile, a similar pattern is observed.

In addition, it can be seen that current development level indicates that Europe and Asia are characterized by an expanding forest cover dynamic, while Africa and the Americas are in the opposite situation. In the case of Europe, regardless of the quartile, the development level is located beyond the estimated post transition distribution. This indicates that European countries are characterized by an expanding forest cover and even near to the conclusion of the transition in terms of development. A similar pattern is observed for Asia, except that in the first quartile, the median is slightly below the post transition threshold.

For Africa and the Americas a different pattern is observed. For the first and second quartile, development level is consistent with deforestation dynamic. In other words, development level is between early a post transition distributions. However, for the third quartile, development level surpasses post transition distribution in the case of the Americas and overlaps with post transition distribution in the case of Africa. This means that countries in these continents, characterized by a low level of deforestation are close to stable forest cover or already on a forest cover expansion dynamic.

In sum, accorind to the findings, the Americas and Africa are characterized by a contracting forest cover, while Asia and

Europe are characterized by the opposite situation.

## 3.2. Deforestation severity

The severity of deforestation during forest transition can be represented by the highest estimated deforestation rate, which in terms of forest transition corresponds to the beginning of late transition stage (see Figure 2). Figure 4 shows the mentioned point for each bootstrap repetition. It must be clarified that, as unusual minima were found, these were filtered out using interquartile rage method (Kassambara 2023). Likewise, positive minima, which imply reforestation/afforestation, were filtered out too.

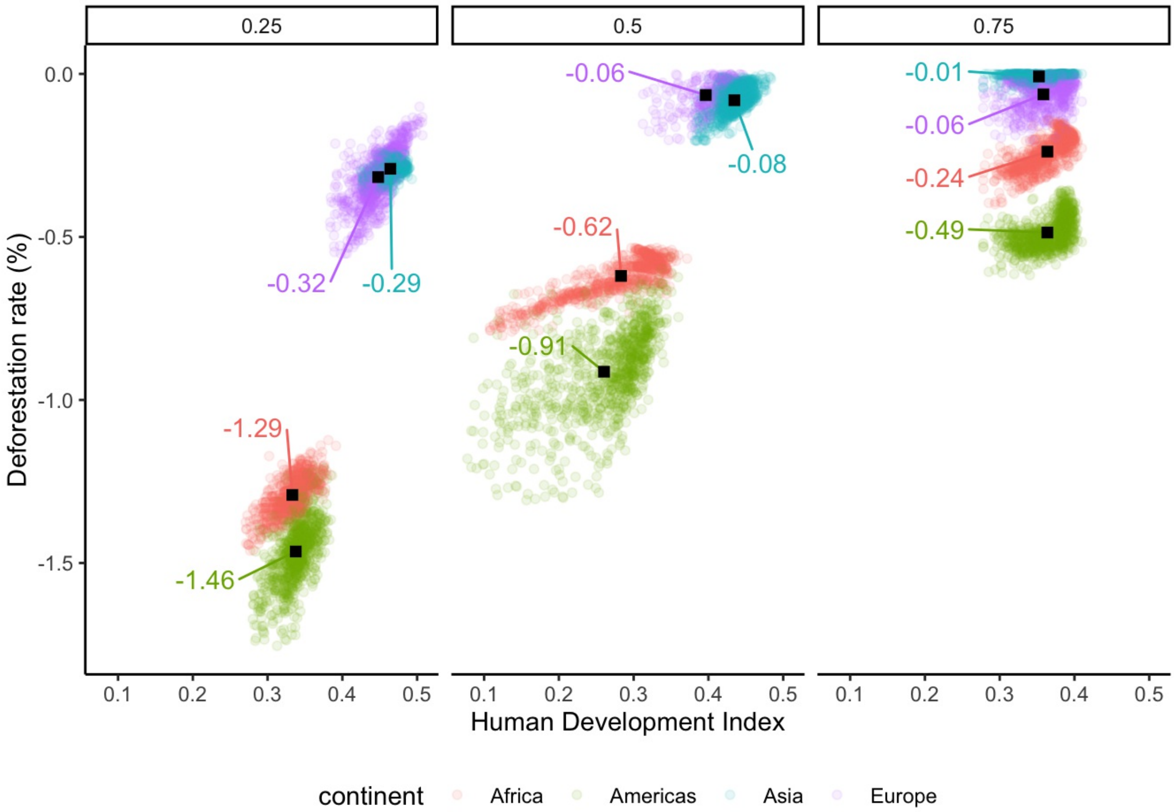


**Figure 4.** Severity of forest transition per quartile.

As it can be observed, regardless of quartile, the highest (and second highest) deforestation rates were estimated in the Americas and Africa. In the first quartile, for instance, the mean of the highest deforestation rate in the Americas is -0.6196492, while in Africa this figure is -1.2913411. The same figures in Asia and Europe are -0.2383979 and -1.464738, respectively. This indicates an important difference in highest deforestation rate among the studied continents.

For the second quartile and third quartile, a similar pattern is observed. This is, the average of the highest deforestation rates is the greatest in America, followed by Africa.

These results suggest that deforestation is more severe in the Americas and Africa. However, the gap among continents is closed as we move across the distribution. In other words, the gap is the highest in the first quartile (*i.e.* countries with a higher than usual deforestation rate) and the lowest in the third quartile (*i.e.* countries with lower than usual deforestation rate).

## 4. Discussion

The findings of this study indicate that deforestation processes in the Americas and Africa are not only prolonged but also more severe compared to Asia and Europe. Moreover, current development (in terms of HDI) levels suggest that these continents are still experiencing deforestation, aligning with Culas (2012), who found that while Asia has surpassed its deforestation threshold in terms of income, Latin America and Africa have not. This is further supported by the FAO (2022) report, which indicates that these continents currently exhibit the highest deforestation rates. However, the same report notes that Asia faces deforestation primarily driven by cropland expansion, a pattern our study did not capture. This discrepancy might be attributed to the level of data aggregation used in our analysis, suggesting that a more granular assessment (e.g., considering sub-regions within a continent) could reveal such region-specific drivers.

Our findings highlight the need to explore the factors determining the characteristics of forest transition and, in particular, the deforestation process. It has been recognized that development plays a crucial role in determining forest cover behavior in the long run (Rudel et al. 2005; Culas 2012; Andrée et al. 2019; Ajanaku and Collins 2021). However, given the significant differences detected here in terms of length and severity, it is essential to further investigate additional influencing factors. Forest scarcity, for instance, may be a critical factor in reversing deforestation trends (Ewers 2006). Additionally, the role of governance and institutions in forest management and policy implementation is vital (Barbier and Tesfaw 2015)but requires further investigation to better understand their specific impacts. For instance, the role of institutions in shortening the length (e.g. effect on turning point) or deceasing the severity of deforestation (e.g. effect on maximum deforestation rate).

One important implication for policy-making is the recognition that achieving a global forest transition may prove more challenging than local or regional transitions (Pendrill et al. 2019). Some studies suggest that agricultural displacement is a significant factor in countries that have reached post-transition stages, where reforestation or afforestation is feasible because deforestation activities have been outsourced abroad (Pendrill et al. 2019; Oliveira et al. 2023). Policies focusing solely on local or regional deforestation may easily overlook this critical aspect of global land-use dynamics.

Additionally, the ecosystem services provided by mature forests differ significantly from those of young forests. Mature forests offer superior carbon sequestration and biodiversity benefits (Luyssaert et al. 2008; Watson et al. 2018). Therefore, the quality of forest transitions must be assessed, considering the ecosystem services provided (MacDonald and McKenney 2020). Development-based studies, such as this, do not capture the mentioned dimension, highlighting the need for complementary studies to provide a more comprehensive understanding of forest transitions that goes beyond mere forest cover expansion.

In sum, our findings underscore the need for targeted development initiatives in the Americas and Africa to address deforestation effectively. These initiatives, nonetheless, should ideally consider a holistic approach, which takes into account both local and global dynamics, as well as the quality of forest ecosystems. Future research should focus on the specific factors influencing forest transitions and the implications of global land-use changes to develop more effective and comprehensive conservation and reforestation strategies.

## 5. Conclusions

This study analyzed forest transitions at a continental level, examining the relationship between the Human Development Index (HDI) and deforestation rates from 1991 to 2021. The analysis included 165 countries from four continents: Africa, the Americas, Asia, and Europe.

The findings demonstrate that the forest transition model provides a plausible explanation for land use dynamics. Statistical models incorporating cubic specifications showed the best performance in the regression analyses, supporting the forest transition hypothesis.

Crucially, the results reveal significant regional differences. The Americas and Africa experience longer and more severe deforestation processes compared to Asia and Europe. Current development levels indicate that Europe and Asia have largely moved beyond deforestation and are now experiencing forest cover expansion. In contrast, the Americas and Africa continue to face deforestation, reflecting ongoing challenges in achieving forest cover recovery.

Further research is necessary to uncover the underlying factors driving the more severe deforestation processes in the Americas and Africa. Understanding these factors is critical for developing effective regional strategies to mitigate deforestation and promote sustainable land use.

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