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# Deforestation driven by urban population growth and agricultural trade in the twenty-first century

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**Reducing atmospheric carbon emissions from tropical deforestation is at present considered a cost-effective option for mitigating climate change. However, the forces associated with tropical forest loss are uncertain[1]. Here we use satellite-based estimates of forest loss for 2000 to 2005 (ref. 2) to assess economic, agricultural and demographic correlates across 41 countries in the humid tropics. Two methods of analysis—linear regression and regression tree—show that forest loss is positively correlated with urban population growth and exports of agricultural products for this time period. Rural population growth is not associated with forest loss, indicating the importance of urban-based and international demands for agricultural products as drivers of deforestation. The strong trend in movement of people to cities in the tropics is, counter-intuitively, likely to be associated with greater pressures for clearing tropical forests. We therefore suggest that policies to reduce deforestation among local, rural populations will not address the main cause of deforestation in the future. Rather, efforts need to focus on reducing deforestation for industrial-scale, export-oriented agricultural production, concomitant with efforts to increase yields in non-forested lands to satisfy demands for agricultural products.**

Maintaining carbon stocks in tropical forests is widely recognized as a relatively low-cost option for mitigating climate change[3,4] with ancillary benefits for biodiversity, regulating precipitation and a host of other ecosystem services[5]. The United Nations framework convention on climate change is considering whether reduced emissions from avoided deforestation and degradation (REDD) will be included as an allowable reduction strategy during the second, post-2012 commitment period. Voluntary carbon markets are also developing standards for incorporating REDD activities[6]. These initiatives will be effective in reducing deforestation only if they address the factors that promote forest loss. Yet demographic and economic factors associated with deforestation remain poorly understood, partly because these complex factors vary throughout the tropics and over time[7], and partly because consistent and reliable data have not been available for cross-country analyses[1].

Major demographic and economic shifts are sweeping across many places in the tropics (Fig. 1). Population growth rates are slowing overall, but urban growth is vastly outpacing rural growth[8]. In the next 20 years, 22 of the 41 countries included in this analysis are projected to have fewer rural inhabitants than they do today, whereas all of the countries have increasing urban populations. In nine of the countries, urban populations are projected to more than double in the next 20 years[9]. Many countries throughout the tropics are also on a trajectory of increasing agricultural exports. The question we address in this study is the likely impact of these changing demographic and economic factors on pressures to clear tropical forests.

Debates on whether these trends will reduce or increase pressure to clear more forests are unresolved. Some argue that depopulating rural landscapes will reduce pressures on forests[10]. Others argue that reducing demand for agricultural lands in rural areas coupled with increasing yields can result in land-sparing[11]. Others implicate industrial-scale, mechanized agriculture as the next wave of deforestation following the planned settlements and small-scale farmers in previous decades[12]. Reliable data on changes in forest area have not been available to quantify factors associated with past changes in forest area to resolve these debates.

We use a newly available, spatially explicit analysis of forest loss (not including regrowth) in the humid tropical forest biome based on extensive samples of high-resolution satellite observations (30 m) and regression estimators to extrapolate to lower resolution (500 m) data[2]. We assess demographic and economic factors associated with forest loss for 41 countries across the humid tropics (see Supplementary Table S1 for criteria and list of countries). These countries collectively cover 98% of all forest area in the humid tropical forest biome[13]. For each data set we apply two methods, multiple linear regression and regression trees[14], to identify relevant factors. The aim is to identify factors most strongly associated with forest loss, rather than to predict forest loss *per se*. We examined ten possible correlates: four demographic factors for 2000–2005 (urban, rural and total annual population growth and per cent of population that is urban), four factors related to agricultural production (net agricultural trade per capita, per cent of agricultural production that is exported, agricultural exports per unit production and per cent forest remaining in biome) and two economic factors (gross domestic product per capita and annual gross domestic product growth) (see Supplementary Table S2 for sources and the Methods section for selection of variables). All pairs of the variables used in the analysis have tolerance values greater than 0.5 (Supplementary Table S3) and variables were tested for multicollinearity (Supplementary Tables S4 and S5).

Both methods show a positive association of forest loss with urban growth and agricultural exports. The most highly significant factors associated with satellite-derived forest loss are urban growth rate ($p < 0.001$) and net agricultural trade per capita ($p < 0.001$) (Table 1 and Supplementary Table S2). Although these associations do not prove causality, the positive correlations do suggest that the traditional mode of clearing in frontier landscapes for small-scale production to support subsistence needs or local markets is no longer the dominant driver of deforestation in many places[15–17]. Rather, our analysis indicates that higher rates of forest loss for 2000–2005 are strongly associated with demands for agricultural products in distant urban and international locations.

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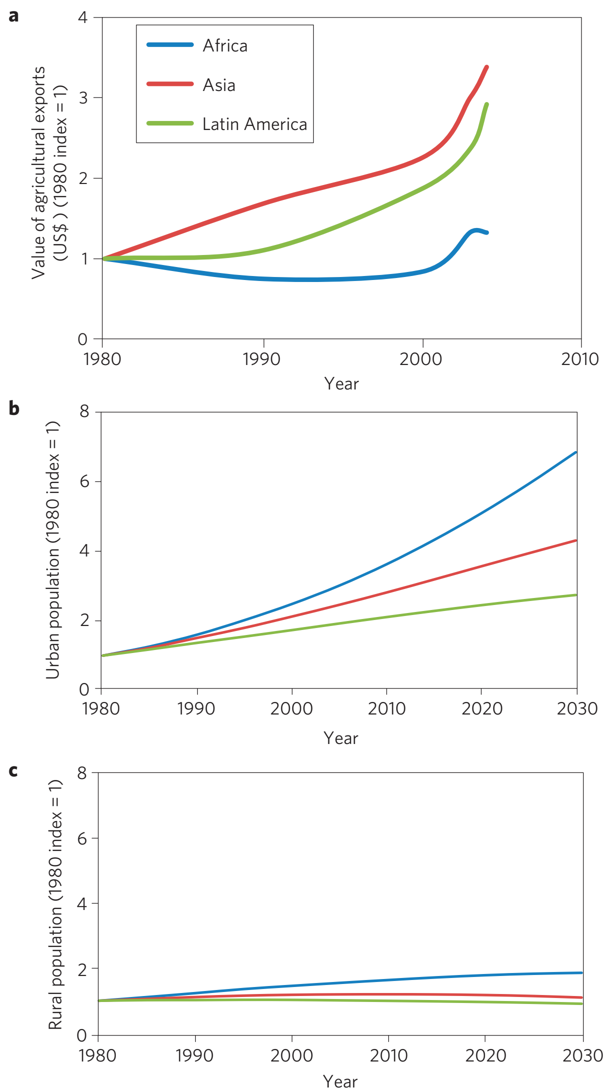


**Figure 1 | Trends in agricultural exports, urban population and rural population for the countries in this study. a–c**, Trends in agricultural exports (**a**), urban population (**b**) and rural population (**c**). The values are indexed to 1980 for 41 countries included in this study aggregated by continent. The per cent of the total population that is urban was 28, 21 and 64 in 1980 and is projected (medium variant) to be 59, 52 and 84 in 2030 in the African, Asian and Latin American countries included in the study respectively. Demographic data are from ref. 9 and export data are from ref. 30. See Supplementary Table S1 for list of countries.

Total population growth is mildly significant ($p < 0.01$), with a negative coefficient refuting the claim that increasing population causes deforestation. Rural population growth rates related to local demand are not significantly correlated.

The regression tree provides a complementary, non-parametric approach[14] and is used here to test the robustness of results from the linear regression. The regression tree confirms the significance of agricultural exports and urban growth as national-scale drivers of forest loss in 2000–2005 (Fig. 2). The same variables significant in the linear regression were selected by the regression tree. As with the linear regression, the variables associated with high forest loss are associated with demands for agriculture in urban and international markets rather than rural population dynamics.

Net agricultural trade is the first split in the regression tree, meaning that it is the most powerful discriminator between countries with relatively high and low forest loss. The highest forest loss occurs in those countries with relatively high agricultural trade and high urban growth (right-most node in the tree), although these countries comprise only 2% of the remaining forest area (see Supplementary Table S6). Almost 60% of the remaining forest area occurs where net agricultural trade, per cent of agricultural products exported and urban growth are all relatively low (the three left-most nodes in the tree). As demands for agricultural products grow in these countries, this large remaining forest area is likely to experience increasing pressures.

**Table 1 | Results of ordinary least-squares regression for annual forest loss for 2000–2005 (ref. 2).**

| Variable | Coefficient |
|---|---|
| Intercept | 0.031 (0.003)* |
| Annual urban growth rate (2000–2005) | 0.016 (0.004)* |
| Total annual growth rate (2000–2005) | –0.010 (0.004)† |
| Net agricultural trade per capita (2003–2004) | 0.008 (0.003)* |
| % of agricultural production exported | 0.007 (0.004)‡ |
| $R^2$ | 0.52 |
| Adjusted $R^2$ | 0.47* |

Values are standardized coefficients with standard error in parentheses. Arcsine transformation was carried out on the dependent variable. See Supplementary Table S2 for results with all variables used in the analysis, and data sources, and see Supplementary Tables S3, S4 and S5 for multicollinearity diagnostics. $n = 41$.

* $p < 0.001$
† $p < 0.01$
‡ $p < 0.10$

Variables associated with forest loss vary within and between regions[7]. Urban population growth, the most significant variable in our analysis, is positively associated with forest loss in all three regions of Africa, Asia and Latin America (Fig. 3) although to varying degrees. In African countries in which forest loss is relatively low, the association with urban growth is less pronounced (lower slope) than in Latin American and Asian countries. Agricultural trade is not significantly associated with forest loss for African or Latin American countries, whereas it is significant ($p < 0.02$) for Asian countries. These differences suggest varying pressures operating unevenly across the regions.

The results build on previous cross-national studies by incorporating satellite-based data from the current decade. Previous studies have been plagued by poor data quality[1,18] and have generally relied on country-level data of net change in forest area[19]. This analysis indicates the value of satellite-derived data on gross forest loss (Supplementary Fig. S1). Country-level data of net change yielded no significant correlations with the economic and demographic variables used in this study.

Comparison of these results with previous studies indicates a transition towards increasing influence of urbanization and international trade as pressures on tropical forests. Most previous studies do not consider distal demands for agricultural products as drivers of deforestation. Those analyses that distinguish between urban and rural population growth generally find a positive association with rural growth rates and a negative association with urban growth rates for the 1980s and 1990s (refs 20, 21), suggesting that urban to rural migration reduced pressure on forests in this time period. We conclude the opposite for 2000 to 2005. Collectively, these results indicate a shift from state-run road building and colonization in the 1970s and 1980s to enterprise-driven deforestation in later decades[22].

There are two major implications of these results. First, trajectories towards continuing urban growth and agricultural exports in tropical countries (Fig. 1) are at present associated with major pressures on forests. We cannot distinguish from this


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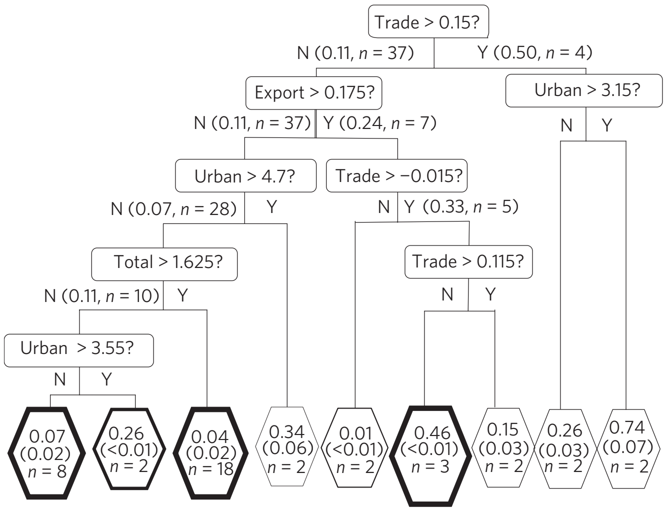


**Figure 2 | Regression tree derived from 10 demographic, agricultural and economic variables for countries in the study.** Each split lists the mean rate of annual forest loss for 2000–2005 and the number of countries. The hexagons are terminal nodes with mean forest loss and deviance in parentheses. The thickness of the lines represents the relative amount of remaining humid tropical forest in each node (see Supplementary Table S6 for countries and forest area in each node). The residual mean deviance is 0.007. Y: yes, N: no. Trade: net agricultural trade per capita, export: per cent of agricultural production exported, urban: urban population growth rate, total: total population growth. See Supplementary Table S2 for derivation of variables.

national-scale study whether urban growth and agricultural exports lead directly to forest conversion, or indirectly through conversion of non-forested lands that displaces other land uses into forested areas. The pressures from these direct and indirect forces probably vary among countries and require country-specific analysis to develop effective approaches to reduce deforestation. Nevertheless, in the absence of incentives to counter these pressures, future pressures will increase on remaining forest areas where pressures are low at present (Fig. 2).

Landscapes with stabilizing or depopulating populations are likely to exacerbate rather than reduce pressure to clear forests, primarily because urbanization raises consumption levels and increases demand for agricultural products. Urban consumers generally eat more processed foods and animal products than rural consumers, thereby inducing commercial production of crops and livestock[23,24]. This pattern contradicts the argument that pressures on forests will decline as local populations urbanize[10]. Nearly all population growth in the coming decades is projected to occur in urban rather than rural areas[8], which will place demands on rural landscapes for commercial food production. Competing land uses for other products such as biofuels[25,26] will exacerbate these pressures on tropical forests.

Second, demands for agricultural production and pressures to clear tropical forests are closely linked. Policies such as REDD aim to reduce deforestation through incentives to maintain standing forests. Such policies assume that the demand for agricultural production will be fulfilled elsewhere. Approaches to meet the dual goals of maintaining forest carbon and increasing agricultural production are needed as countries face pressures to clear more forests. Such approaches include incentives to maximize agricultural production on already-cleared lands while minimizing new forest clearing[27].

Urban growth and agricultural exports are positively and significantly correlated with forest loss, and tropical forests will continue to face large pressures as urban-based and international demands for agricultural products continue to increase. These patterns underscore the challenges that policy instruments such as REDD face in reducing deforestation. Policies need to be flexible and recognize that causes of deforestation vary through time and space. As demands for agricultural products accelerate in the future, policies designed to increase agricultural yields on already-cleared lands will have to accompany REDD policies to reduce forest clearing as a climate mitigation strategy.

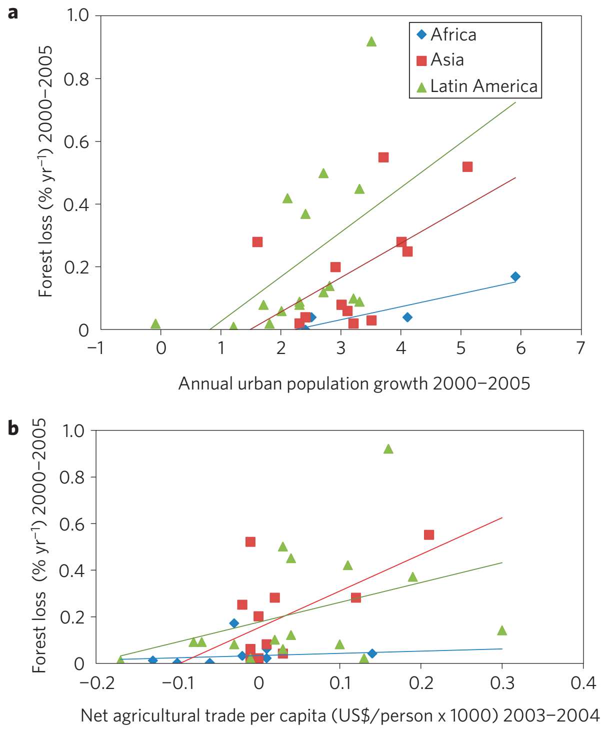


**Figure 3 | Per cent forest loss versus annual urban growth and agricultural trade by region. a**,**b**, Per cent forest loss versus annual urban growth (**a**) and net agricultural trade per capita (**b**) for countries in the three tropical regions. $n = 12$, 11 and 15 for African, Asian and Latin American countries respectively. $p = 0.006$, 0.06 and 0.05 respectively for annual urban growth rate. Only regression for Asian countries is significant ($p = 0.02$) for agricultural trade.

## Methods

We used previously published satellite-derived estimates of forest loss for 2000–2005 for the humid tropics aggregated to the country level[2]. The satellite data are derived from Landsat and MODIS data using regression estimators to estimate forest loss for the humid tropical biome per 18.5 by 18.5 km block. We calculated the area of forest loss by aggregating the blocks to the national scale. The rate of loss is calculated relative to the country's area within the tropical humid forest biome as determined from ref. 13 (see Supplementary Table S1).

We examined many possible correlates with forest loss at a national scale, including demographic, economic and agricultural production statistics. After eliminating variables that were highly correlated or poor data quality (see Supplementary Table S2 for list of variables, sources and derivations), we formally tested for collinearity using a number of regression diagnostics including variance inflation factors (Supplementary Table S4), and condition indexes (ratios of eigenvalues) and variance decomposition proportions of the design matrix (Supplementary Table S5; ref. 28). If the largest condition index is large (that is, 30 or higher), then there may be collinearity problems. All condition indices were less than five.

For each of the data sets, we carried out least-squares regression and derived regression trees using the R software package[29] with routines lm() and tree(). These approaches are complementary and are used together to lend robustness to the analysis. Unlike linear regression, regression trees are non-parametric, nonlinear and make few assumptions about the underlying relationship between the response variable and predictor[14]. We used four as the threshold for the minimum node size, as determined from the threshold that leads to the largest reduction in residual deviance. For the linear regression, independent variables were standardized and the dependent variable underwent arcsine transformation. We ran the linear



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regression with and without weighting by forest area in 2000. The same variables were significant in both (Supplementary Table S2), except in the linear regression with weighting one variable (per cent of agricultural production exported) was not significant. We report results without weighting.

The data sets used in this study have several limitations. The satellite-derived data set identifies gross forest loss for the humid tropics. The extent of abandonment and regrowth, which can partially offset emissions from deforestation, is not captured and remains a major uncertainty. Another limitation of the satellite-derived data set is that it provides estimates of forest loss rather than deforestation, and may be capturing plantation harvest, reclearing of secondary regrowth or forest loss from wildfires in some locations rather than clearing of primary forest. Finally, we cannot infer causal relationships based on the associations between forest loss and the independent variables. It cannot be determined, for example, whether the association between urban population growth and forest loss results from a 'pull' of farmers to cities with economic opportunities (thereby accelerating consumer demands for agricultural products) or a 'push' as higher agricultural prices attract large enterprises that drive small farmers off the land. These results indicate general patterns, but analyses of specific circumstances in individual countries are required to identify effective policies to reduce forest loss in different circumstances.

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## Author contributions

R.S.D. conducted data analysis and drafted the manuscript; T.R. participated in data analysis and writing; M.U. advised on statistical analysis and participated in writing; M.H. guided the use of the forest cover data and participated in writing.

## Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to R.S.D.



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