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Abstract

This article updates our previous comprehensive meta-analysis of what drives and stops deforestation (Busch and Ferretti-Gallon 2017). By including six additional years of research, this article more than doubles the evidence base to 320 spatially explicit econometric studies published in peer-reviewed academic journals from 1996 to 2019. We find that deforestation is consistently associated with greater accessibility (as influenced by natural features such as slope and elevation and built infrastructure such as roads, cities, and cleared areas) and with higher economic returns (from agriculture, livestock, and timber). Some demographic variables are consistently associated with less deforestation (e.g., Indigenous people, poverty, and age) or more deforestation (e.g., population), and others are not associated with the level of deforestation (e.g., education and gender). Policies that directly influence allowable land-use activities are associated with less deforestation (e.g., protected areas, enforcement of forest laws, payments for ecosystem services, community forest management, and certification of sustainable commodities). But policies and institutions that primarily seek other ends are not consistently associated with more or less deforestation (e.g., democracy, general governance, conflict abatement, and land-tenure security). We introduce reforestation and forest degradation as new dependent variables alongside deforestation. Greater population is consistently associated with more forest degradation, whereas steeper slope, greater distance from cities, and lower population are consistently associated with more reforestation.

What Drives and Stops Deforestation, Reforestation, and Forest Degradation? An Updated Meta-analysis

Jonah Busch* and Kalifi Ferretti-Gallon†

Introduction

Forests provide public benefits related to climate, biodiversity, water quality, and health, among other Sustainable Development Goals (Ferraro et al. 2012; Seymour and Busch 2016; Fisher, de Wit, and Ricketts 2021; Polasky and Daily 2021; Taye et al. 2021). Yet agriculture, ranching, mining, infrastructure, and urban settlements may offer greater private benefits. As a result, these land uses often outcompete forests.

The decisions people make about land use and land cover result in shifts over time in the spatial extent of forests, often described as a forest transition curve (e.g., Angelsen and Rudel 2013). First, forest degradation reduces tree cover, carbon stocks, biodiversity, or other services within forests. Then, degradation is followed by deforestation—the full transition of forests to other land use. Deforestation is sometimes, though not always, followed by reforestation—the transition from other land use to forests—with the resulting forests often providing a different array of attributes and environmental services than the original forest.

Increasing recognition of the public benefits of forests has led to multiple high-profile efforts to protect and restore them. Recent international public efforts include the United Nations Framework Convention on Climate Change, the New York Declaration on Forests, and the Bonn Challenge; international private efforts include the Trillion Trees initiative and corporate sustainability commitments through the Tropical Forest Alliance. National policies and programs to conserve forests have included protected areas, payments for ecosystem services (compensating households or communities for activities that improve forest condition),

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land-tenure reforms, and direct enforcement of forest-protection laws. Governments, companies, and conservation groups seeking to slow deforestation and speed forest recovery need to know which policies work and which do not.

There have been hundreds of primary studies of what drives and stops deforestation, reforestation, and forest degradation in specific contexts. These analyses in turn have led to review studies of drivers of deforestation (Angelsen and Kaimowitz 1999; Geist and Lambin 2002; Chomitz 2007; Rudel et al. 2009; Angelsen and Rudel 2013; Pfaff, Amacher, and Sills 2013; Busch and Ferretti-Gallon 2017; Min-Venditti, Moore, and Fleischman 2017; Börner and West 2018; Burivalova et al. 2019; Scullion et al. 2019; Börner et al. 2020). There are fewer reviews of the drivers of reforestation (Borda Niño, Meli, and Brancalion 2019). Review studies related to individual drivers of deforestation include the roles of protected areas (Dos Santos Ribas et al. 2020), payments for ecosystem services (Wunder et al. 2020), land tenure (Robinson, Holland, and Naughton-Treves. 2014), and governance (Wehkamp et al. 2018; Fischer, Giessen, and Gunter 2020).

The most comprehensive and quantitative review of drivers of deforestation was a meta-analysis (systematic and quantitative synthesis of multiple studies) by Busch and Ferretti-Gallon (2017), which identified, screened, coded, categorized, tabulated, and reported results from all spatially explicit (mapping variables to specific locations) econometric studies published before December 31, 2013—121 in total. That study identified two policy-relevant factors that consistently speed deforestation (roads and demand for agricultural products) and four policy-relevant factors that consistently slow deforestation (protected areas, payment for ecosystem services, law enforcement, and management by Indigenous peoples).

We are motivated to provide an update to Busch and Ferretti-Gallon (2017) for a number of reasons. First, spatially explicit econometric studies of deforestation have continued to proliferate, with the number of such studies more than doubling in the 6 years following the initial review (figure A1 [appendix is available online]). Second, a watershed publication of globally consistent data on annual tree-cover loss from 2000 to 2012 (Hansen et al. 2013) enabled spatially explicit econometric studies of deforestation outside of the handful of countries and regions where such data were previously available (Plantinga 2021). Third, parallel advances in remote sensing have led to expanded analysis of forest-cover changes in addition to deforestation—in particular, forest degradation and reforestation. Fourth, new topics in drivers of deforestation have emerged or expanded to a sufficiently large number of studies to allow meta-statistical analyses. These topics include temperature, supply-chain initiatives, commodity certification, livestock activity, livestock price, energy activity, agricultural yield, conflict, democracy, good governance, conservation programs, restrictive policies, trade openness, and gender. Finally, having created a widely used resource, we owe it to researchers and policy makers to keep our database and meta-analysis up to date.

Here we report the results of our updated and expanded meta-analysis, with an emphasis on new results and references to papers published within the 2014–2019 study period.

Methodology

In this section, we describe how we screened studies for inclusion in our database and how we constructed the database.

Criteria for Including Studies in the Database

Our methods replicate those of Busch and Ferretti-Gallon (2017), with one addition noted later. As in our previous analysis, we conducted an extensive literature search to identify candidate studies to potentially include in our database. Candidate studies were identified by the keyword search of terms related to our subject (table A1). They were included in the database only if they met the following criteria:

1. The study was published as an article in a peer-reviewed academic journal between January 1, 2014, and December 31, 2019. This period was bookended by the publication of Hansen et al. (2013) on November 15, 2013, and the end of the second decade of the twenty-first century. We excluded book chapters (e.g., Kolb et al. 2018), working papers, and policy reports. Application of this criterion resulted in 280 candidate studies.
2. The dependent (outcome) variable in the study was a direct indicator of forest cover, forest-cover loss, forest-cover gain, or forest degradation. We excluded other indicators such as forest fragmentation (e.g., Zhang, Liu, and Wei 2017), agricultural expansion (e.g., Hoyos, Cabido, and Cingolani 2018), habitat quality (e.g., Yan et al. 2018), and willingness to accept payment to avoid deforestation (e.g., Cacho et al. 2014). We did not distinguish between natural forests and plantations beyond the definitions applied in the original studies. Application of this criterion eliminated 16 studies, leaving 264 candidate studies.
3. Forest cover or forest-cover loss was remotely sensed (i.e., obtained from satellite or aircraft) and spatially referenced (i.e., mapped). We excluded studies where the forest indicator was based on field inventories (e.g., Bluffstone et al. 2018), census data (e.g., Davis et al. 2019), household surveys (e.g., Nguyen et al. 2014), or the Food and Agriculture Organization Forest Resources Assessment (e.g., Imai et al. 2018). Application of this criterion eliminated 23 studies, leaving 241 candidate studies.
4. The article included at least one table presenting the results of a multivariate econometric analysis (a statistical analysis including multiple independent variables), including significance at the 95 percent confidence level or test statistics from which significance at the 95 percent confidence level could be derived. As in Busch and Ferretti-Gallon (2017), we included both multiple regression analyses, which estimate the correlation of independent variables with deforestation and control for the influence of other independent variables, and multivariate matching analyses, which compare deforestation in areas affected by a policy to the rate of deforestation in unaffected areas with similar observable characteristics. In addition, we included regression discontinuity analyses, which compare deforestation on either side of a threshold, such as in space or time (e.g., Cuaresma and Heger 2019), and synthetic control, which artificially constructs control groups using weighted combinations (e.g., Carlson et al. 2018). We excluded experimental analyses (e.g., Jayachandran et al. 2017). Application of this criterion eliminated 40 studies, leaving 201 candidate studies.
5. The econometric model of forest-cover change included at least one anthropogenic independent (explanatory) variable. We excluded studies in which all independent variables were biophysical or chemical (e.g., Braun et al. 2014). Application of this criterion eliminated one study, leaving 200 candidate studies.

6. In addition, we eliminated one candidate study on the basis of a disqualifying methodological flaw. Although numerous studies contained debatable methodological decisions, we generally gave researchers the benefit of the doubt, unless the flaws invalidated the regression results. Such flaws included treating a categorical variable (in which the number arbitrarily assigned to a category is not meaningful) as a cardinal number. Application of this criterion eliminated one study, leaving 199 candidate studies.

The application of these six screens resulted in 199 studies published between 2014 and 2019. Combined with the 121 studies from Busch and Ferretti-Gallon (2017), the expanded database contained 320 studies (table A2), including 2,006 econometric analyses and 15,241 coefficients (estimates of the relationship between an independent variable and the dependent variable) on 3,410 explanatory variables (with 2,440 unique names).[1] We synthesize these results in this meta-analysis.

Constructing the Database

Our methods for constructing the expanded database followed those of Busch and Ferretti-Gallon (2017). First, for every coefficient on every explanatory variable in every results table in every study, we coded the sign and significance of the variable's association with deforestation (i.e., "negative and significant," "not significant," or "positive and significant" at the 95 percent confidence level). Where the dependent variable was related to forest cover, avoided deforestation, or reforestation (rather than deforestation or forest degradation), we inverted the coded sign.

Next, we assigned the 2,434 uniquely named explanatory variables to 55 categories. This included the 40 categories in Busch and Ferretti-Gallon (2017), plus 15 new categories. New categories are italicized in tables 1 and 2. For example, variables named "number of cows," "area in pasture," and "% of households with cattle" were all assigned to the new category of "livestock activity." We inverted the coded signs on coefficients as necessary to polarize all relationships between driver variables and deforestation in the same direction. For example, within the new category of "public land," the sign for the variable "private property" was inverted. We excluded from our analysis (but not from our database) those categories that we were unable to polarize (e.g., "soil class," "forest type," "land use type") and those categories for which there were fewer than 40 regression results (e.g., "mining activity," "agricultural exports," "household size"). We also excluded variables that were not easily categorized, as well as interaction terms (which analyzed the combined effects of variables). As a result, our meta-analysis includes 40 categories, composed of 1,630 uniquely named explanatory variables and 11,931 coefficients.

The old category of "previous clearing" was split into two new categories: distance from clearing and forest abundance. In a small number of cases, variables were recategorized from an old category into a new category. Recategorizations occurred from agricultural activity to agricultural exports, from agricultural activity to agricultural yield, from distance to urban area to distance to infrastructure, from population to household size, from land-tenure security to public land, and from protected area to other restrictive policy.

[1]The resulting database, the Database of Spatially Explicit Econometric Studies of Drivers of Deforestation, Reforestation, and Forest Degradation (the "SEED Database v2.0") is available online as appendix S1.

Table 1 Results, including disaggregations and sensitivities

	Overall	Including non-significant	Africa	Asia	Latin America/ Caribbean	Low income	Lower middle income	Upper middle income	High income	Multiple countries
Built infrastructure										
Nearer to roads	/	/	/	/	/		/	/	-	
Nearer to urban area	/	/	/	/	/		/	/	/	
Nearer to cleared land	/	/			/			/		
Market commodities										
Agricultural activity	/	/		/	/			/		/
Higher agricultural price	/	/		/	/			/		
Nearer to agriculture	/	/			/			/		
Timber activity	/	/		/				/		
Higher timber price	-	-		-	\			-		
Livestock activity	/	/			/			/		
Higher livestock price	-	-			-			-		
Energy activity	-	-								
Greater agricultural yield	-	-			-			-		
Supply chain initiative	\	\			\			\		
Commodity certification	\	\		\	/			\	/	
Demographics and socioeconomics										
Greater population	/	/	/	/	/		/	/	/	/
Larger property size	-	-			-			-		
Older	\	-								
Greater education	-	-			-			-		
Greater poverty	\	\	-	\	\			\		\
Indigenous peoples	\	\			\			\		
More women	-	-								
Land management and institutions										
More secure land tenure	-	-			-			-		
Community forest management	\	-		\	-		\	-		
Law enforcement	\	\			\			\		
Protected area	\	\	\	\	\		\	\		\
More democratic	-	-								-
General governance	-	-								\
Conflict	-	-								
Trade openness	/	-								
Policy										
Rural income support	/	/			/			/		
Payments (PES)	\	\			\			\		
Restrictive policy	\	\			\			\		
Biophysical characteristics										
Greater soil suitability	/	/		-	/			/		
Nearer to water	-	-		-	-			-		
Wetter	-	-		-	-			-	-	
Higher elevation	\	\	-	\	\		\	\	\	
Steeper slope	\	\		\	\		\	\	\	
Hotter	/	/		/	\			/	-	
Forest abundance	/	-		-	/			/		

Note: Regression-level results are shown. Cells with fewer than 40 observations are not shown. / denotes consistent positive association with deforestation; - denotes no consistent association with deforestation; \ denotes consistent negative association with deforestation. Driver variables in italics are new to this meta-analysis compared to Busch and Ferretti-Gallon (2017).

Table 2 Results, including disaggregations and sensitivities

	Focus of study	Not focus of study	Local	Regional	National	Econ*	Geog*	Neither
Built infrastructure								
Nearer to roads	/	/	/	/	/	/	-	/
Nearer to urban area	/	/	/	/	/	/	/	/
Nearer to cleared land		/	/	/		/		/
Market commodities								
Agricultural activity	/	/	-	/	/	/		/
Higher agricultural price	/	/		/	/	/		/
Nearer to agriculture		/	/					
Timber activity		/			/			/
Higher timber price	-	-		-		-		
Livestock activity		/		/				/
Higher livestock price		-		-		-		
Energy activity		-						
Greater agricultural yield		-						-
Supply chain initiative	\			\				\
Commodity certification	\				\			\
Demographics and socioeconomics								
Greater population	/	/	/	/	/	/		/
Larger property size		-	-					-
Older		\	-					\
Greater education		-	-					-
Greater poverty	/	\	\	\	-	\	-	\
Indigenous peoples	\	\	-	\		\		\
More women		-						
Land management and institutions								
More secure land tenure		-						-
Community forest management	\	-	-	\		\		\
Law enforcement		\		\		\		
Protected area	\	\	\	\	\	\		\
More democratic		-						-
General governance	-							\
Conflict								
Trade openness								
Policy								
Rural income support		/	-	/		/		
Payments (PES)	\		\		\	\		\
Restrictive policy	\			\				\
Biophysical characteristics								
Greater soil suitability		/	-	/	/	/	/	/
Nearer to water		-	-	-				-
Wetter		-	-	\	/	\		-
Higher elevation		\	\	\	\	\	\	\
Steeper slope		\	\	\	\	\	-	\
Hotter		/	-	\	/	-		/
Forest abundance		/	\	/	/	/		-

Note: Regression-level results are shown. Cells with fewer than 40 observations are not shown. / denotes consistent positive association with deforestation; - denotes no consistent association with deforestation; \ denotes consistent negative association with deforestation. Driver variables in italics are new to this meta-analysis compared to Busch and Ferretti-Gallon (2017).

For each category, we determined whether the driver variables in that category were consistently associated with higher rates of deforestation, lower rates of deforestation, or neither. Because many studies contained more than one regression, we produced one statistic at the individual regression level. Then, because the individual regression analyses in a study may not have been fully independent of one another, we produced a second statistic at the study level.[2] For variables that had a consistent association with deforestation at the regression level but not at the study level, we consider the evidence for these variables to be preliminary until confirmed by more studies, and we explicitly note such cases in the text.

In an additional approach since Busch and Ferretti-Gallon (2017), we add a new statistic that scores nonsignificant results as halfway between significant and nonsignificant rather than excluding nonsignificant results.[3] At the regression level, this new statistic makes a difference for three variables: forest abundance, age, and community forest management. We note these places in the text.

Trends in the Literature

Several trends occurred in the literature between the original study period of Busch and Ferretti-Gallon (2017; n = 121 studies 1996–2013) and the additional study period of this paper (n = 199 studies 2014–2019; table A3), which we summarize here.

Perhaps most notably, the new period saw a proliferation in studies using global, annual data on forest-cover change from Hansen et al. (2013), from no studies between 1996 and 2013 to 54 studies (27 percent) between 2014 and 2019. Use of Brazil's annual Project for Monitoring Deforestation in the Legal Amazon by Satellite (PRODES) data set also increased greatly, from two studies (2 percent) 1996–2013 to 22 studies (11 percent) 2014–2019.

The use of these data sources in turn improved the average spatial resolution from 218 to 62 m, increased the average number of forest-cover snapshots from 2.7 to 6.1, and updated the median start and end dates from 1989–2000 to 2000–2011.

The geographic distribution of studies broadened from 1996–2013 to 2014–2019. The number of studies from Asia increased from 28 (23 percent) published in the original study period to 62 (31 percent) published in the latter period. The proportion from Africa increased from 10 (8 percent) to 23 (12 percent); Europe, North America, and Oceania combined increased from 5 (4 percent) to 18 (9 percent); and multicontinental or global studies increased from 4 (3 percent) to 20 (10 percent). Only Latin America/Caribbean showed a decrease in proportion, from 74 (61 percent) to 75 (38 percent).

[2] At the regression level, we counted the number of times that the outputs from regression (or matching) analyses were negative and significant, not significant, or positive and significant. At the study level, we counted the number of times that the plurality of outputs from regression (or matching) analyses were negative and significant, not significant, or positive and significant. At both the individual regression level and the study level, we considered the driver variable to be consistently associated with deforestation if the fraction (associated with more deforestation)/(associated with less deforestation + associated with more deforestation) was significantly different from 0.5 in a two-tailed t-test at the 95 percent confidence level. For more detail, see annex I.

[3] That is, we considered the driver variable to be consistently associated with deforestation if the fraction (associated with more deforestation + 0.5 $\times$ nonsignificant association)/(associated with less deforestation + nonsignificant association + associated with more deforestation) was significantly different from 0.5 in a two-tailed t-test at the 95 percent confidence level. This statistic maintains the total number of observations and does not shift the balance toward either positive or negative association. The inspiration for this statistic derives from chess, in which wins are scored as 1, losses as 0, and draws as 0.5. For more detail, see annex I.

Of the single-country studies, those from upper-middle-income countries decreased in relative terms, from 79 (65 percent) to 104 (53 percent), and those from high-income countries increased from 8 (7 percent) to 23 (12 percent). There was negligible expansion in the share from low- or lower-middle-income countries, from 26 (22 percent) to 40 (20 percent).

Study areas increased from 1996–2013 to 2014–2019, from an average of 0.66 to 1.22 million km^2. The average percentage of a country covered by a study area increased from 25 to 36 percent, and the number of studies covering more than 90 percent of the land area of a country increased from 17 (15 percent) to 38 (23 percent). The number of studies covering less than 10 percent of the land area of a country decreased in relative terms, from 64 (57 percent) to 74 (45 percent).

Over time, the unit of observation chosen by study authors shifted. Pixel or grid cells became relatively less common, from 77 (64 percent) to 78 (40 percent), as did parcels or properties, from 17 (14 percent) to 14 (7 percent). Administrative units became more common, from 9 (7 percent) to 36 (18 percent), as did points, from 11 (9 percent) to 31 (16 percent), and countries, from 0 to 13 (7 percent).

There was a relative decline in studies that dealt in any way with potential spatial autocorrelation—that is, the concern that the significance of results could be inflated due to the similarity of characteristics of sites that are near each other. These declined from 53 (44 percent) to 76 (38 percent), including those that addressed the issue through sampling, from 20 (17 percent) to 15 (8 percent), and those that used the measure of spatial autocorrelation known as Moran's I, from 17 (14 percent) to 22 (11 percent). Studies that quantitatively addressed the leakage, displacement, or spillover of deforestation to new locations due to forest-protection interventions (Pfaff and Robalino 2017) increased, from 9 (7 percent) to 24 (12 percent), and studies that mentioned this possibility but did not analyze it increased, from 13 (11 percent) to 35 (18 percent).

The specialty of the journal in which papers were published shifted between study periods. Studies published in a journal with a title containing Environmental*, Econ*, Geog*, Manage*, and Agr* declined in relative terms, and studies published in a journal with a title containing Land*, Policy*, and Forest* increased.

The number of variables included in studies changed little, from a median of 10 to 9. The number of regression results reported did not change by much, from a median of 27 to 28. The number of studies that used matching increased from 8 (7 percent) to 41 (21 percent).

The number of studies that tested a hypothesis related to one or more specific driver variables increased from 49 (40 percent) to 127 (64 percent). The remainder of studies were generally not driver specific; they inquired into determinants of deforestation, projections of future land use, scenario-planning exercises, or quantitative model comparisons. Although this type of study decreased in relative terms, there was an expansion to many new countries, including Afghanistan (Najmuddin et al. 2017), Bolivia (Tejada et al. 2016), Ethiopia (Kindu et al. 2018), Ghana (Kleeman et al. 2017; Aduah, Toucher, and Jewitt 2018), India (Gayen and Saha 2018), Iran (Bavaghar 2015; Jahanifar et al. 2018), Ireland (Upton, O'Donoghue, and Ryan 2014), Laos (Phompila et al. 2017), Madagascar (Brinkmann et al. 2014), Malawi (Bone et al. 2017), Pakistan (Samie et al. 2017), Romania (Kucsicsa and Dumitrica 2019), South Korea (Kim et al. 2014), Spain (Corbelle-Rico et al. 2015; Molowny-Horas, Basnou, and Pino 2015), Tanzania (Nzunda and Midtgaard 2017), Thailand (Ongsomwang and Boonchoo 2016), Turkey (Viedma et al. 2017), Uganda (Call et al. 2017), and Vietnam (Vu et al. 2014; Nguyen 2019).

In light of increased interest in diversity, equity, and inclusion in economic research (e.g., Chevalier 2021; Rodrik 2021), we examined trends in author demographics. The percentage of first authors who are female increased slightly between 1996–2013 and 2014–2019, from 32 to 35 percent. The percent of first authors' institutions located outside of high-income countries increased substantially, from 24 to 33 percent.

Key Findings of the Meta-analysis

We first present findings on drivers of deforestation, synthesizing spatially explicit econometric studies from 1996 to 2019, where the dependent variable was deforestation or forest cover (figures 1, A2, A3). Next, we present findings for drivers of reforestation (figure 2), followed by drivers of forest degradation. We include both regression-level and study-level results. Where these two differ, we state this; otherwise, we do not. Where regression-level results are no longer significant following the inclusion of nonsignificant observations (coefficients), we state this as well.

Deforestation and Biophysical Characteristics

Biophysical characteristics influence deforestation through agricultural productivity, accessibility, and clearing costs (Busch and Ferretti-Gallon 2017). The new study period increased the number of studies that included biophysical characteristics from 96 to 216. Deforestation was again confirmed to be consistently lower at higher elevations and steeper slopes, with the interesting exception that steeper slopes experienced greater earthquake-induced forest loss (Li et al. 2019). Deforestation was again consistently higher on soil that was more suitable for

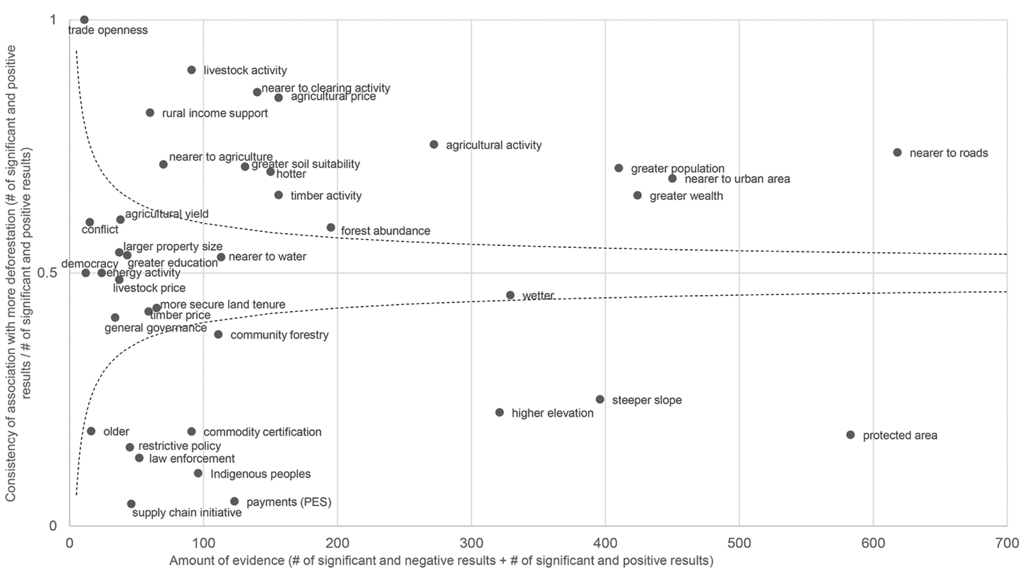

Figure 1 Consistency of association of driver variables with more deforestation (regression level; excluding nonsignificant results). Variables beyond the dashed lines have consistent associations with less or more deforestation that are statistically significant at the 95 percent level. PES = payments for ecosystem services. A color version of this figure is available online.

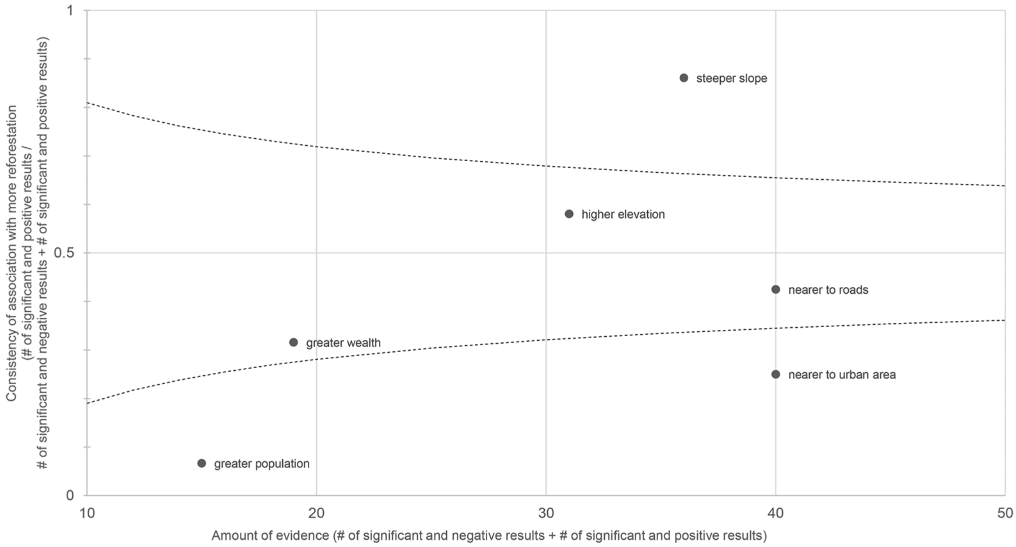

Figure 2 Consistency of association of driver variables with more reforestation (regression level; excluding nonsignificant results). Variables beyond the dashed lines have consistent associations with more or less reforestation that are statistically significant at the 95 percent level. A color version of this figure is available online.

agriculture. Proximity to water was again not consistently associated with either higher or lower deforestation. Unlike before, wetter areas were no longer associated with either higher or lower deforestation. As before, not many studies had biophysical variables as their primary focus. An exception was Desbureaux and Damania (2018), which found that deforestation in Madagascar was higher in exceptionally dry years.

A new variable, hotter temperature, was consistently associated with more deforestation at the regression level, though not at the study level. Heat as a biophysical driver of deforestation is worth investigating further, especially as it relates to expected climate change. Proximity to clearing activity was associated with higher deforestation, and forest abundance was associated with less deforestation at the regression level. Forest abundance was not associated with more or less deforestation at the study level, nor was the regression-level association robust to including nonsignificant results.

Deforestation and Market Demand for Commodities

Agriculture

Agriculture is the principal land use displacing forests across the tropics (Curtis et al. 2018). The new study period increased the number of studies that included agriculture as a variable from 55 to 146 and confirmed the findings of Busch and Ferretti-Gallon (2017) that agricultural activity (e.g., Wang and Qiu 2017; Beauchamp, Clements, and Milner-Gulland 2018; Keles et al. 2018; Ordway et al. 2019), agricultural price (e.g., Assunção, Gandour, and Rocha 2015), and proximity to agriculture (e.g., Shevade and Loboda 2019) are all consistently associated with greater deforestation. In addition to direct deforestation, soy cultivation has been found to indirectly displace deforestation to elsewhere in the South American Amazon (Richards et al. 2014) and Chaco (Fehlenberg et al. 2017).

New since the previous meta-analysis, agricultural yield was not consistently associated with either higher or lower deforestation. As explained by Pelletier et al. (2020), higher yield could decrease deforestation, by satisfying demand for cropland on less area (the Borlaug Hypothesis). This is more likely to occur where demand for food is inelastic (not very responsive to changes in price), as in remote locations. Or higher yield could increase deforestation by making agriculture more profitable (the Jevons Paradox). Higher yields were associated with more deforestation in Malawi (Place and Otsuka 2001) and Brazil (de Barros and Stege 2019); less deforestation in Mexico (Perez-Verdin et al. 2009) and Thailand (Felardo 2016); and neither higher nor lower deforestation in China (Li et al. 2013), Guatemala (Lopez-Carr et al. 2012), India (Raghavan and Shrimali 2015), and Argentina (Ceddia and Zepharovich 2017).

New since the previous meta-analysis, livestock activity was found to be associated with significantly greater deforestation (e.g., Carvalho et al. 2018; Correia-Silva and Rodrigues 2019), though livestock price was not. This discrepancy could perhaps be due to cattle ranching in some regions being a means of solidifying claims to land (Correia-Silva and Rodrigues 2019) more than seeking direct market returns.

Timber

Timber activity can increase deforestation directly through forest clearing or indirectly through the construction of access roads to remote areas. Conversely, timber activity can decrease deforestation by forestalling more rapid conversion of forest to other uses (Busch and Ferretti-Gallon 2017). In a change from the previous meta-analysis, timber activity was found to be consistently associated with greater deforestation; for example, logging in Democratic Republic of Congo (Samndong et al. 2018) and plantation conversion permits but not logging permits in Indonesia (Busch et al. 2015; Indarto, Kaneko, and Kawata 2015). However, timber price was not consistently associated with higher or lower deforestation; for example, increased timber demand was associated with more forest in India (Raghavan and Shrimali 2015) and Indonesia (Djaenudin et al. 2016).

Supply-chain initiatives

New since the previous meta-analysis, supply-chain initiatives, in which agricultural commodity companies committed to eliminate deforestation from their operations (Lambin et al. 2018), were associated with less deforestation at the regression level, though not the study level. Brazil's soy moratorium reduced deforestation in the Amazon (Jung and Polasky 2018) but with spillover of deforestation to the Cerrado found by Dou et al. (2018). There is disagreement on the effect of Brazil's cattle agreement, in which major beef buyers committed to sourcing cattle only from land deforested before 2009 (Alix-Garcia and Gibbs 2017; Dou et al. 2018).

Certification

New since the previous meta-analysis, commodity certification programs were associated with less deforestation at the regression level, though not the study level. Certification programs associated with less deforestation included shade-grown coffee in Ethiopia (Takahashi and Todo 2014), Roundtable on Sustainable Palm Oil–certified palm oil in Sumatra and Kalimantan (Indonesia; Carlson et al. 2018), "nonstate, market-driven" governance of timber in Chile (Heilmayr and Lambin 2016), and Forest Stewardship Council–certified timber in

Kalimantan (Miteva, Loucks, and Pattanayak 2015) and Cameroon (Panlasigui et al. 2018) but not Mexico (Blackman, Goff, and Planter 2018). Where certified commodities had less deforestation, researchers face the challenge that producers that select to be certified may be different from other producers, for example, more remote in Cameroon (Panlasigui et al. 2018) or with less remaining forest in Indonesia (Carlson et al. 2018).

Emerging topics

Emerging research on agricultural exports and deforestation found that exports of palm oil to India (Sommer, Restivo, and Shandra 2019a), timber to China (Fuller et al. 2018), and forestry products to China (Shandra, Restivo, and Sommer 2019) were associated with increased deforestation across nations, though the effects of exports on deforestation have been found to vary by forest area (Leblois, Damette, and Wolfersberger 2017) and by biome (Rudel 2017). Emerging research has also investigated the effects of fuelwood collection (e.g., Raghavan and Shrimali 2015), off-farm employment (e.g., Sellers 2017), tourism (e.g., Hoang et al. 2014), industrial activity (e.g., Miyamoto et al. 2014), and mining (e.g., Butsic et al. 2015) on deforestation.

New since the previous meta-analysis, energy activity (e.g., oil and gas wells, drilling fields, and pipelines) was not consistently associated with either higher or lower deforestation.

Deforestation and Built Infrastructure

Roads and urban areas increase deforestation by reducing costs to access markets and reducing barriers to migration into forested areas (Busch and Ferretti-Gallon 2017). The new study period increased the total number of studies that included a variable related to built infrastructure (from 95 to 208 studies) and confirmed that proximity to roads and urban areas is consistently associated with higher deforestation. Several new studies modeled the effects of planned road expansion on deforestation—for example, in Peru (Arima 2016) and Democratic Republic of Congo (Li et al. 2015; Damania et al. 2018). Others distinguished the effects of major and minor roads on deforestation in China (Hu et al. 2016) or the different effects of roads on deforestation based on level of prior development in the Brazilian Amazon (Pfaff et al. 2018). Although urban areas were consistently associated with higher deforestation (e.g., Lin et al. 2019), after controlling for urban size, urban density was associated with slower deforestation across counties of the United States (Clement, Ergas, and Greiner 2015).

Emerging studies of other types of infrastructure found deforestation to be significantly higher near dams in Ghana (Kleeman et al. 2017) and railways in Tanzania (Nzunda and Midtgaard 2017), though not near ports in Brazil (Dou et al. 2018), Malaysia (Shevade and Loboda 2019), or Turkey (Ustaoglu and Aydinoglu 2019); airports in Turkey (Ustaoglu and Aydinoglu 2019); or irrigation canals in China (Zhao et al. 2018) or Chile (Manuschevich and Beier 2016).

Deforestation and Institutions and Policy

Community forest management

Community forest management can reduce deforestation through better forest governance, or it can increase deforestation by encouraging the expansion of cultivated lands and pasture (Busch and Ferretti-Gallon 2017). In a change from the previous meta-analysis, community forest management is now consistently associated with less deforestation at the regression level, though still not the study level. The regression-level association was not robust to including nonsignificant results. Community forest management was associated with less deforestation in Mexico (Ellis et al. 2017) and Nepal (Shrestha, Shrestha, and Bawa 2018; Fox et al. 2019; Oldekop et al. 2019), more forest in India (Raghavan and Shrimali 2015) and Thailand (Chankrajang 2019), and more reforestation in Nepal (Shrestha, Shrestha, and Bawa 2018; Fox et al. 2019). However, community forest management did not have a significant effect in Colombia (Bonilla-Mejia and Higuera-Mendieta 2019) or Mexico (Torres-Rojo, Moreno-Sánchez, and Amador-Callejas 2019) and was associated with more deforestation in Cambodia (Lonn et al. 2018).

Land-tenure security

Land-tenure security can reduce deforestation by increasing the present value of standing forests and discouraging the conversion of land to reduce expropriation risk, or it can increase deforestation by encouraging greater investment in agriculture (Busch and Ferretti-Gallon 2017). The new study period confirmed the previous finding of no consistent association between more secure land tenure and higher or lower deforestation. Land occupations increased deforestation in the Brazilian Amazon (Brown 2016), land titling reduced deforestation in Ecuador (Holland et al. 2017), and customary and traditional tenure had greater deforestation relative to private land in Uganda (Call et al. 2017). Nevertheless, land ownership in Pakistan (Zeb, Armstrong, and Hamann 2019), enrollment in land registries in Brazil (Cisneros, Zhou, and Börner 2015), and years that a household was living on a farm in Ecuador (Sellers 2017) made no significant difference in deforestation.

Conflict

New since the previous meta-analysis, conflict was found not to be consistently associated with more or less deforestation. For example, civil war fatalities were associated with higher deforestation in Democratic Republic of Congo (Butsic et al. 2015; Damania et al. 2018), and a higher rate of homicides was associated with higher deforestation in Brazil (Sant'Anna 2017). But the presence of rebels was associated with decreased deforestation in Sierra Leone (Burgess, Miguel, and Stanton 2015).

Governance

New since the previous meta-analysis, general good governance was found not to be consistently associated with more or less deforestation. This category refers to general conditions such as rule of law, political stability, and control of corruption, rather than forest-specific governance. For example, good governance was associated with increased timber harvest in Russia (Wendland, Lewis, and Alix-Garcia 2014), but corruption was associated with increased deforestation across low- and middle-income nations (Sommer 2017, 2018a). Similarly, greater democracy was not consistently associated with higher or lower deforestation. This is comparable to a meta-analysis of governance and deforestation by Wehkamp et al. (2018), who found that stronger environmental governance was associated with reduced deforestation and stronger general governance was associated with increased deforestation.

Trade openness

New since the previous meta-analysis, a country's openness to trade was found to be consistently associated with more deforestation at the regression level, though not at the study level.

For example, in a global study, deforestation increased following the enactment of regional trade agreements (Abman and Lundberg 2019), although not with greater trade liberalization in the former Soviet Union (Alix-Garcia et al. 2016). The regression-level association was not robust to including nonsignificant results.

Protected areas

Protected areas remain one of the most studied policies for forest protection, with the new study period increasing the number of studies that included protected areas as a variable from 34 to 96. Overall, protected areas were associated with lower deforestation, as in Panama (Vergara-Asenjo and Potvin 2014), Russia (Jones and Lewis 2015), Ecuador (Holland et al. 2014; Cuenca, Arriagada, and Echeverría 2016), Mexico (Pfaff, Santiago-Ávila, and Joppa 2016), Chile (Arriagada, Echeverria, and Moya 2016), Peru (Schleicher et al. 2017), Colombia (Cuenca and Echeverría 2017), Philippines (Apan et al. 2017), and 23 African countries (Bowker et al. 2017), but not in Mexico (Blackman et al. 2015), Yunnan (China; Brandt et al. 2015), or Russia (Wendland et al. 2015). The impact of protected areas varied by baseline levels of deforestation threat in Brazil (Pfaff et al. 2014), protected-area type in Thailand (Sims 2014), GDP (Heino et al. 2015), management effectiveness in Cambodia (Beauchamp, Clements, and Milner-Gulland 2018), and across space and time in Panama (Haruna et al. 2014), Brazil (Pfaff et al. 2015), and Indonesia (Shah and Baylis 2015; Poor et al. 2019). Strictly protected areas were found to be more effective in stemming deforestation than mixed-use protected areas in Brazil (de Marques, Schneider, and Peres 2016; Amin et al. 2019), West Java (Indonesia; Higginbottom et al. 2019), Colombia (Bonilla-Mejia and Higuera-Mendieta 2019), and worldwide (Leberger et al. 2019), though the opposite was found in Guatemala (Blackman 2015). Protected areas were consistently associated with lower deforestation in both matching and nonmatching analyses.

Law enforcement

As in the previous meta-analysis, increased enforcement of forest laws was consistently associated with less deforestation at the regression level, though not at the study level. Field-based inspections reduced deforestation in the Brazilian Amazon, though more effectively in some states than others (Börner et al. 2015).

Other restrictive policies

New to this analysis, other restrictive policies besides protected areas were also consistently associated with lower deforestation. A Brazilian blacklist on high-deforesting municipalities (Cisneros, Zhou, and Börner 2015; Assunção and Rocha 2019; Koch et al. 2019), logging bans in Yunnan (China; Brandt et al. 2015) and Thailand (Felardo 2016), China's Natural Forest Protection Program (Shi, Yin, and Lv 2017), and land-clearing restrictions in Queensland (Australia; Marcos-Martinez et al. 2018; Simmons et al. 2018) were all associated with lower deforestation, and a logging ban increased forest cover in Iran (Zeb 2019). Conversely, compliance with Brazil's forest code was not associated with significantly more or less deforestation (Jung and Polasky 2018).

Emerging topics

Emerging research on international conservation programs has analyzed the effects of debt-for-nature swaps, in which debt was canceled in exchange for land conservation (Sommer, Restivo, and Shandra 2019b), environmental provisions in trade agreements (Peinhardt, Kim, and Pavon-Harr 2019), bilateral aid (Restivo, Shandra, and Sommer 2018; Sommer, Restivo, and Shandra 2019b), and environmental nongovernmental organizations (Brinkmann et al. 2014; Restivo, Shandra, and Sommer 2018; Sommer 2018b; Shandra, Restivo, and Sommer 2019).

Emerging research has also analyzed differences between public and private land (e.g., Alix-Garcia et al. 2016; Cvitanovic, Blackburn, and Jepsen 2016; Ellis et al. 2017; Marcos-Martinez et al. 2018) and the influence of decentralization of forest governance (Larcom, van Gevelt, and Zabala 2016; Wright et al. 2016).

Deforestation and Demographic and Socioeconomic Characteristics

The new study period increased the number of studies including demographic characteristics as an independent variable from 77 to 197.

Indigenous peoples

Indigenous territories can have lower deforestation due to either traditional land-management practices that favor forests or the relative remoteness and lower agricultural suitability of such lands (Blackman and Veit 2018). The new studies show Indigenous peoples to be associated with less deforestation not only at the regression level, as previously, but at the study level as well. Indigenous areas had lower deforestation in Panama (Vergara-Asenjo and Potvin 2014), Ecuador (Holland et al. 2014), and Peru (Schleicher et al. 2017), and Indigenous management reduced deforestation in Bolivia, Brazil, and Colombia but not Ecuador (Blackman and Veit 2018). Titling of Indigenous lands reduced forest clearing in Andean countries (Blackman et al. 2017) but not in Argentina (Ceddia and Zepharovich 2017).

Population

The new study period confirms that greater population is associated with greater deforestation (e.g., Schneider and Peres 2015; Ryan et al. 2017). Cause and effect run in both directions, with population increasing the supply of labor and local demand for agricultural products and with cleared land being able to support more people (Busch and Ferretti-Gallon 2017). New studies have begun to untangle this two-way causality by examining the effects of changes from the outside; for example, international out-migration increased forest cover in Nepal (Oldekop et al. 2018), but family planning did not have an effect on deforestation in Ecuador (Sellers 2017).

Poverty and wealth

Greater poverty (less wealth) is once again consistently associated with lower levels of deforestation, at both the regression level and the study level, as found in Turkey (Elburz, Çubukçu, and Nijkamp 2018), though not Pakistan (Zeb 2019). In Bolivia and Laos, the accessibility of forests, rather than poverty, was a driver of deforestation (Boillat et al. 2015).

There is, once again, mixed empirical support for the idea that deforestation first rises, then falls, as national wealth increases. There is evidence of this so-called environmental Kuznets curve for forests in Malaysia (Miyamoto et al. 2014), the Brazilian region of Matopiba (de Barros and Stege 2019), and across 189 international border regions (Cuaresma et al. 2017) but not in the Congo Basin (Bakehe 2019).

The effect of poverty and wealth on deforestation is confounded by another two-way cause-and-effect situation: greater wealth can increase deforestation by allowing the purchase of more machines and the hiring of more laborers to clear land, and deforestation can increase wealth through revenues from greater economic activity (Busch and Ferretti-Gallon 2017). Clearer evidence of the effect of wealth on deforestation comes from changes to wealth that come from outside with no relationship to forest condition, such as rural income support.

Rural income support

Rural income support was once again associated with greater deforestation at both the regression level and the study level. For example, remittances sent home by migrant family members are associated with increasing deforestation in the Congo Basin (Bakehe 2019), and reduced access to rural credit is associated with reduced deforestation in Brazil (Assunção et al. 2019).

Payments for ecosystem services

Payments for ecosystem services (PES) are voluntary transactions between ecosystem service users and providers that are conditional on agreed rules of natural resource management (Wunder et al. 2020). The number of studies that included PES expanded from 6 to 20. PES is now associated with lower deforestation not only at the regression level, as previously, but also at the study level. PES was associated with lower deforestation in Ecuador (Jones and Lewis 2015; Jones et al. 2017), Mexico (Alix-Garcia, Sims, and Yañez-Pagans 2015; Le Velly, Sauquet, and Cortina-Villar 2017; Von Thaden et al. 2019), and China (Zhao et al. 2018; Fu et al. 2019), supplementing previous evidence from Costa Rica and Mexico. However, the effects of PES stopped after the program ended in Mexico (Le Velly, Sauquet, and Cortina-Villar 2017).

Other demographic variables

With the addition of new studies, the demographic variables education and property size were once again not associated with either higher or lower deforestation. A new variable, gender, also did not play a role; more women were not associated with either higher or lower deforestation. In a change from Busch and Ferretti-Gallon (2017), older age is now associated with significantly lower deforestation at the regression level, though not at the study level, nor was the regression-level association robust to including nonsignificant results. Research is emerging on the effects of inequality and deforestation (Sant'Anna 2017).

Reforestation

The new study period increased the number of studies that included reforestation as a dependent variable from 7 to 35. There are now six categories for which the number of individual regression results surpassed 40—our arbitrary threshold above which categories are no longer considered "emerging" and, therefore, the results preliminary. These categories are slope, elevation, distance to cities, distance to roads, population, and poverty.

Steeper slopes were consistently associated with more reforestation, as in Jamaica (Newman, McLaren, and Wilson 2014), Korea (Kim et al. 2014), Colombia (Rubiano et al. 2017), France (Abadie et al. 2018), and Mexico (Guerra-Martinez et al. 2019). Greater distance from cities was also consistently associated with more reforestation, as in Jamaica (Newman, McLaren, and Wilson 2014), Korea (Kim et al. 2014), and Bolivia (Boillat et al. 2015), though not Laos (Boillat et al. 2015) or Uganda (Call et al. 2017). Greater population was consistently associated with less reforestation, as in Croatia (Cvitanovic, Blackburn, and Jepsen 2016), China (Viña et al. 2016), and Malawi (Bone et al. 2017). Higher elevation, greater distance from roads, and higher poverty were not consistently associated with either more or less reforestation.

Our analysis of reforestation aggregated all tree-cover gain as defined by individual studies. Thus, it includes both natural forest regrowth (e.g., Rubiano et al. 2017) and commercial plantations (e.g., Sloan 2016). It is possible—even likely—that these different forms of forest-cover gain are driven by different factors (e.g., Manuschevich and Beier 2016), with natural forest regrowth more likely to occur in remote and economically marginal lands and commercial plantations more likely to be established in accessible and high-suitability lands.

Forest Degradation

The new study period increased the number of studies that included forest degradation as a dependent variable from 4 to 14. A few preliminary findings of consistent drivers of forest degradation begin to appear, though the number of individual regression results exceeds 40 only in the case of population—again, 40 is our arbitrary threshold above which categories are no longer considered emerging and results preliminary. Greater population density was consistently associated with greater forest degradation, as in Oaxaca (Mexico; Guerra-Martinez et al. 2019), Jiangxi (China; Jiang et al. 2015), Nepal (Tachibana and Adhikari 2009), and rural Vietnam (Vu et al. 2014), though not in urban Vietnam (Vu et al. 2014), western Mexico (Morales-Barquero et al. 2015), or Madagascar (Grinand et al. 2019). Emerging categories with fewer than 40 but more than 20 regression results show that roads were consistently associated with more forest degradation and PES and Indigenous peoples were consistently associated with less forest degradation. Slope, elevation, poverty, and distance to urban areas were not consistently associated with more or less forest degradation. As the number of studies is small, more study of drivers of forest degradation is a research priority.

Sensitivities and Heterogeneous Effects

As in our previous study, we address potential problems of meta-analyses. These include biases, variations in quality across studies, and varying effects across studies. We conducted several analyses to see whether our results are sensitive to these concerns.

Potential Sources of Bias

As stated previously, the studies in a meta-analysis may be systematically biased toward geographical locations where the findings were extreme rather than representative (sample bias) or were the review process for publication may have been biased toward supporting or refuting particular theories (publication bias). If such biases were persistent in the studies in our database, then the findings of our meta-analysis would also be biased (Ropovik, Adamkovic, and Greger 2021). To examine the potential for sample bias and publication bias, we compared results for studies in which a variable was the primary focus versus studies in which that variable was included only as a control. The idea is that a discrepancy between the two might indicate persistent bias, because we assumed that control variables would be less likely to be characterized by bias. However, it is also possible that studies in which a variable was the primary focus may have been more careful in their design and analytical methods to generate credible results for that variable. Our sensitivity analysis shows that nearly all results were robust across whether variables were included as the primary focus versus as a control, with two exceptions: poverty and community forest management (table 2). There was also no evidence that the studies in our database were persistently biased toward the publication of significant results. In fact, variables that were the focus of a study were significant slightly less often (53 percent) than variables that were not the focus of a study (57 percent).

Another source of bias could arise if researchers systematically chose to study particular subregions within a country based on where an effect was thought to be more pronounced. To address this issue, we split results by the extent of the studies' coverage of the country in which they took place, with the assumption that local studies covering less than 10 percent of a country's area were more susceptible to this type of bias than national- or regional-scale studies. Alternatively, the effect of some variables on deforestation could be dependent on the scale of the study. Our results were robust to whether analyses were site scale or national scale, with five exceptions: agricultural activity, poverty, wetness, temperature, and forest abundance (table 2).

Variable Study Quality

As with any meta-analysis, we faced the challenge of variation in methodological quality across studies. There is no systematic index of quality for spatially explicit econometric studies, such as exists for clinical studies (Wells et al. 2000). As we did previously, we split studies according to the discipline of the journal in which they were published, with the idea that peer review of econometric issues was generally likely to have been more stringent in economics journals and peer review of spatial issues was generally likely to have been more stringent in geography journals. Our results were robust across disciplines, with six exceptions: proximity to roads, poverty, soil suitability, slope, temperature, and forest abundance (table 2).

Heterogeneous (Varying) Effects

To examine the possibility that drivers of deforestation may have had different effects in different locations, we split our results by region. Results varied across regions for the following variables: timber price, commodity certification, poverty, community forest management, soil suitability, and temperature (table 1). To examine the possibility that drivers of deforestation may have had different effects in countries at different levels of development, we split results by national income level (low, low-middle, upper-middle, upper). Results varied across income levels for the following variables: proximity to roads, commodity certification, community forest management, and temperature (table 1).

Caveats and Limitations

Some of the same caveats and limitations of the previous meta-analysis remain, and some have been partially ameliorated through six additional years of studies. One limitation of the previous meta-analysis was a paucity of multicountry studies, meaning we were unable to examine the influence of country-level variables on deforestation. The new study period increased the number of multicountry studies from 8 to 40, allowing us to now present results related to variables such as democracy and general governance.

Some potentially important drivers of deforestation had not been studied using spatial data or had been studied in few instances (<40 observations). Although six additional years of studies let us add several new variables that were previously excluded (e.g., livestock, energy), some other potential drivers remain unstudied or understudied (e.g., mining, mills and processing facilities, off-farm income opportunities).

Many of the studies in our database did not report using any technique to test for or address spatial autocorrelation, meaning that the significance of variables may have been consistently overestimated. As mentioned in the summary statistics, the share of studies addressing spatial autocorrelation declined in the new study period.

In some cases, we made subjective judgment calls in organizing the names of variables used in primary studies into the categories of variables used in this meta-analysis.

We were unable to produce statistics on the magnitude of effects, as in, for example, Börner et al. (2020), because of the wide variation across studies in both the independent variables included within each category and the dependent variables related to forest-cover loss. This means we were unable to quantify the relative impacts of different categories of variables on deforestation. We were also not able to provide insights on the size of the effects that categories of variables have on forests; this is of interest to decision makers for whom only a sufficiently large effect would justify the costs of a policy intervention. Meta-analyses such as ours that use "vote counting" (i.e., comparing the number of significant and positive versus significant and negative results) have the drawback of discarding information that could be gleaned from aggregating nonsignificant results. For more on vote counting, see McKenzie and Brennan (2021).

Variables may have different associations with deforestation in different contexts. We separated and systematically examined differences of association across several potentially important differences (e.g., global region, national income level, and study area). However, there were many other potentially important differences that we did not systematically examine (e.g., accessible versus remote settings, baseline level of threat to forests, and the presence of enabling conditions).

Finally, we included only econometric studies. When it comes to fully understanding complex phenomena at individual sites, qualitative case studies may offer superior or complementary evidence.

Concluding Discussion and Directions for Future Research

As found previously, deforestation is consistently associated with accessibility and economic returns from commodity markets. Accessibility through both natural features (e.g., flatter slope and lower elevation) and built infrastructure (e.g., proximity to roads, cities, and cleared areas) encourages deforestation and discourages reforestation. Markets that drive deforestation include agriculture, livestock, and, to a lesser extent, timber.

Some demographic variables influence deforestation. Greater population is consistently associated with more deforestation, as well as with more forest degradation and less reforestation. Greater wealth is associated with more deforestation, and Indigenous people and older people are associated with less deforestation. Other demographic variables such as education, gender, and property size do not have a consistent association with forest outcomes.

Policies and institutions that directly influence allowable land-use activities are associated with less deforestation. These include protected areas, enforcement of forest laws, PES, community forest management, and certification of sustainable commodities. However, policies and institutions that are primarily aimed at other ends do not show a consistent association with deforestation; examples include democracy, general good governance, conflict abatement, and land-tenure security.

Our findings are broadly consistent with those of previous reviews of drivers of deforestation (Angelsen and Kaimowitz 1999; Geist and Lambin 2002; Chomitz 2007; Rudel et al. 2009; Angelsen and Rudel 2013; Pfaff, Amacher, and Sills 2013; Busch and Ferretti-Gallon 2017; Min-Venditti, Moore, and Fleischman 2017; Börner and West 2018; Burivalova et al. 2019; Scullion et al. 2019; Börner et al. 2020; tables 3, 4), as well as reforestation (Borda Niño, Meli, and Brancalion 2019; table 4) and forest degradation (Burivalova et al. 2019; table 3). One exception is poverty; previous reviews found either a positive or ambiguous association between poverty and deforestation, but we found that greater poverty was consistently associated with lower deforestation. Another exception is general governance; previous reviews found a negative association between stronger general governance and deforestation, whereas we found no consistent association.

Eight of the categories we analyzed had never been previously included in a review of drivers of deforestation. These were agricultural yield, conflict, democracy, energy activity, gender, supply-chain initiatives, temperature, and trade openness. Conversely, several other drivers have been reviewed by others but not us, including infrastructure, mining, decentralization, and fire.

One difference between our meta-analysis and other reviews is that ours systematically and comprehensively considers all studies in which a driver was included as an independent variable—not only studies in which a driver was the focus of study. As described earlier, an advantage of this approach is that it reduces potential publication bias; a disadvantage is that it dilutes the weight of studies that were intentionally designed to identify credible results for an individual driver. Either effect could change the conclusion about the direction of a driver's association with deforestation—for example, for poverty and community forest management.

Directions for Future Research

Although the range of drivers studied has broadened considerably since the previous meta-analysis, there are still a number of emerging themes where more research would be welcome. The role of noncrop commodities (e.g., livestock, timber, mining, energy) in driving deforestation is understudied relative to the role of agricultural crops. So, too, is the role of

Table 3 Comparison of findings across meta-analyses

	Degradation		Deforestation						
	Busch and Ferretti-Gallon 2023 (R)	Burivalova et al. 2019	Busch and Ferretti-Gallon 2023 (R)	Busch and Ferretti-Gallon 2023 (S)	Börner et al. 2020	Scullion et al. 2019	Burivalova et al. 2019	Börner and West 2018	Min-Venditti et al. (2017)
Built infrastructure									
Nearer to roads			/	/					
Nearer to urban area			/	/					
Nearer to cleared land			/	/					
Nearer to infrastructure						/			
Market commodities									
Agricultural activity			/	/		/			
Higher agricultural price			/	/		/			
Nearer to agriculture			/	/					
Timber activity			/	-		/		-	
Higher timber price			-	-		/			
Mining activity						/			
Livestock activity			/	/		/			
Higher livestock price			-	-		/			/
Energy activity			-	-					
Greater agricultural yield			-	-					
Supply chain initiative			\	-					
Commodity certification		\	\	-	-		-		
Demographics and socioeconomics									
Greater population	/		/	/		/			
Larger property size			-	-					
Older population			\	-					
Greater education			-	-					
Greater poverty			\	\		/			
More Indigenous peoples			\	\	\				
More women			-	-					
Land management and institutions									
More secure land tenure			-	-	-			-	-
Community forest management		\	\	-			\		\
Law enforcement			\	-		\		\	
Protected area			\	\	\	\	\	\	\
Decentralization					\			-	
More democratic			-	-					
Stronger governance			-	-	\	\			
Conflict			-	-					
Trade openness			/	-					
Policy									
Rural income support			/	-					/
Payments (PES)			\	\	\		\	\	\
Restrictive policy			\	\				\	-
Biophysical characteristics									
Greater soil suitability			/	/					
Nearer to water			-	-					
Wetter			-	-					
Higher elevation			\	\					
Steeper slope			\	\					
Fire						/			
Hotter			/	-					
Forest abundance			/	-					

Note: / denotes positive association with forest degradation, deforestation, or reforestation; - denotes no association or mixed or ambiguous association; \ denotes negative association. Driver variables in italics are new to this meta-analysis compared to Busch and Ferretti-Gallon (2017). (R) = regression-level analysis; (S) = study-level analysis.

Table 4 Comparison of findings across meta-analyses

	Deforestation								Reforestation	
	Busch and Ferretti-Gallon 2017 (R0)	**Busch and Ferretti-Gallon 2017 (S)**	**Pfaff et al. 2013**	**Angelsen and Rudel 2013**	**Rudel et al. 2009**	**Chomitz 2007**	**Geist and Lambin 2002**	**Angelsen and Kaimowitz 1999**	**Busch and Ferretti-Gallon 2023 (R)**	**Borda Niño 2019**
Built infrastructure										
Nearer to roads	/	/	/	/	/	/	/	/	-	/
Nearer to urban area	/	/				/	/	/	\	\
Nearer to cleared land	/	-					/	/		
Nearer to infrastructure										
Market commodities										
Agricultural activity	/	/	/		/	/	/	/		
Higher agricultural price	/	-		/		/	/	/		
Nearer to agriculture	/	/					/	/		
Timber activity	-	-	/		/	-	/	-		
Higher timber price	-	-		-		-	/	-		
Mining activity										
Livestock activity										
Higher livestock price										
Energy activity										
Greater agricultural yield										
Supply chain initiative										
Commodity certification										
Demographics and socioeconomics										
Greater population	/	/			/	/	/	/	\	
Larger property size	-	-			/	-		-		
Older population	-	-								
Greater education	-	-	\							
Greater poverty	\	\				-	/	-	-	
More Indigenous peoples	\	-				\				
More women										
Land management and institutions										
More secure land tenure	-	-	-	-		-	-	-		
Community forest management	-	-	\		-					
Law enforcement	\	-				\				
Protected area	\	\	\	\	\	-				/
Decentralization										
More democratic										
Stronger governance										
Conflict										
Trade openness										
Policy										
Rural income support	/	/				/	/			
Payments (PES)	\	-	-	\		-				
Restrictive policy										
Biophysical characteristics										
Greater soil suitability	/	/					/	/		\
Nearer to water	-	-						/		/
Wetter	\	-								\
Higher elevation	\	\			\	\	\		-	/
Steeper slope	\	\			\	\	\		/	/
Fire										
Hotter										
Forest abundance										/

Note: / denotes positive association with forest degradation, deforestation, or reforestation; - denotes no association or mixed or ambiguous association; \ denotes negative association. Driver variables in italics are new to this meta-analysis compared to Busch and Ferretti-Gallon (2017). (R) = regression-level analysis; (S) = study-level analysis.

potential alternative development paths, such as those related to industry, tourism, or off-farm employment. Further research can bolster the understanding of international connections, through trade, treaties, investment, and development cooperation, in driving and slowing deforestation. Impact evaluations of specific policy initiatives, especially using experimental or quasi-experimental methods, will always be valuable.

Conversely, a number of fields of study can now be considered mature, based on the large number of observations on these drivers of deforestation (i.e., more than 250 observations in figure 1). It has been consistently established that agricultural activity, population, and proximity to roads and cities are associated with greater deforestation, and slope, elevation, poverty, and protected areas are associated with less deforestation. Further inquiry into such topics should focus on policy-relevant distinctions (e.g., strict versus multiple-use protected areas or large versus small roads) or disentangling two-way effects; for example, does a larger population cause more deforestation, or does more deforestation bring about an increase in population?

The geographic concentration of the evidence base has broadened since the last meta-analysis, when more than half of the studies were from Mexico, Brazil, Costa Rica, Indonesia, Thailand, and China. These six countries accounted for just 35 percent of the newer study period. These countries, along with four additional countries (Bolivia, Ecuador, Democratic Republic of Congo, Peru), constitute the 10 most studied countries; they make up 54 percent of the overall evidence base. Although the evidence base has broadened, more work is needed to extend the geographic concentration of studies beyond the three tropical regions of Latin America/Caribbean, Africa, and Asia and beyond upper-middle-income countries. Researchers are enabled to study these regions not only by the data set produced by Hansen et al. (2013) but also by newer high-resolution spatial data sets, such as those from the European Union's Sentinel system and Planet Labs.

Finally, although the number of studies of drivers of reforestation and forest degradation has increased, it lags far behind studies of deforestation. Additional studies would provide a more complete picture of land-use changes along the forest transition curve.

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