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The drivers of tree cover expansion: Global, temperate, and tropical zone analyses

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ABSTRACT

This paper uses new, high resolution satellite-derived data to explore recent cross-national differences in expanding tree cover. Increases in tree cover have concentrated in nations with recent histories of extensive deforestation, humid climates, high crop yields, and small numbers of farm workers. The associations of expanded tree cover with high yields for cereal crops and small populations of cultivators suggests a dynamic, sometimes referred to as a forest transition, in which urbanization and industrialization promote a long-term expansion in tree cover on certain types of land. The association of tree cover gains with tree cover losses and humid climates suggests a second dynamic, a churning, treadmill-like production of wood products from lands subjected to recurring harvests of wood products followed by tree cover gains in the recently harvested areas. The forest transition dynamic suggests that many smallholders would allow tree cover to expand on their lands if payments for environmental services were available. The salience of the treadmill dynamic of tree cover losses followed by tree cover gains underscores the importance of questions about the implications of commercial tree monocultures for biodiversity, carbon sequestration, and social justice.

1. Introduction and rationale

As the destruction of tropical rain forests has proceeded over the past four decades, the significance of forest regeneration for global environmental change has increased. In places where forests regenerated, they protected watersheds, sequestered carbon, and restored some biological diversity to disturbed landscapes (Wright and Muller-Landau, 2006; Asquith et al., 2008; Grau et al., 2008; Meyfroidt and Lambin, 2011; Chazdon, 2014; Putz and Romero, 2014). The carbon sequestering capacity of regenerating forests, in particular, attracted the attention of policymakers because, by reducing CO_2 levels in the atmosphere, it would counter climate change. A better understanding of the forces that drive forest regeneration would facilitate the design of policies to accelerate forest regrowth. With this end in mind, this paper uses new remote sensing data to analyse the global and regional-scale drivers of tree-cover expansion.

Efforts to understand the dynamics that have driven tree cover expansion have been seriously handicapped during the past three decades by definitional and assessment issues (Chazdon et al., 2016). For example, increases in tree cover in a place can signal either natural forest regeneration or the establishment of tree plantation monocultures. While satellite observations of increases in tree cover have long been possible with early satellite imagery, as well as at increasingly larger scales since the advent of moderate-resolution MODIS imagery in 2000 (Hansen et al., 2002), the coarse resolution and/or limited spatial coverage of the satellite imagery made it difficult to detect regrowth reliably over time at large scales (Lucas et al., 1994; Lucas et al., 2000a,b; Sloan, 2012). These impediments to global-scale analyses of secondary forest cover were substantially reduced in 2013 when a team lead by Matthew Hansen (Hansen et al., 2013) released a global-scale data set of tree cover dynamics (loss and gain) derived from higher resolution Landsat images for 2000–2012.

In Hansen's maps a tree cover gain occurs when a satellite detects a canopy of >50% tree cover in a 30-m pixel that did not contain >50% tree cover in the previous year. As with other remotely-sensed definitions of tree cover gain, this definition lumps together a wide range of changes in tree cover. Increases

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in tree cover could involve either species rich, spontaneously-generated secondary forests on abandoned agricultural lands, agro-biodiverse forest gardens, recovering heavily logged forests, or commercial tree plantation monocultures. We refer to all such forests detected by the Hansen data as 'new tree covers'. We draw a further distinction between new tree covers subject to frequent perturbation and recovery such as cyclically logged forests and new tree covers that naturally regenerate on abandoned agricultural lands and represent longer-term increases in tree cover. The Hansen data do not permit the distinction between newly planted trees and spontaneously regenerated trees, but circumstantial evidence like the size of the commercial forestry sector in a nation or the locations of oil palm or short-rotation forestry concessions can be used to strongly infer whether or not planted trees or spontaneously regenerated trees make up most of the new tree cover in a country.[1]

The environmental services provided by the different types of new tree cover vary dramatically (Tropek et al., 2014). Particularly in the tropics, spontaneously generated second-growth forests support more diverse biota than tree plantation monocultures (Poorter et al., 2016). The effects of these trees on watersheds varies with the species composition and structural complexity of the new tree cover. *Eucalyptus* plantations, for example, reduce runoff from precipitation while spontaneously regenerated secondary forests may reduce fluctuations in the volume of runoff during rainy seasons (Samra et al., 2001). Trees, in spontaneous natural regeneration and even more so in high yield plantations, sequester carbon (Kirby and Potvin, 2007), so, in an era of climate change, they all provide at least one valuable environmental service. Regenerating forests sequester carbon at higher rates than do old growth forests, and the amounts of carbon sequestered in regenerating tropical forests are sufficient to offset most of the greenhouse gas emissions associated with tropical deforestation (Pan et al., 2011; Reich, 2011; Bongers et al., 2015). Particularly in steep topographies, the new tree cover improves watershed conservation by reducing soil erosion. The beneficial ecological effects of second-growth forests and agro-forests make it important to understand the mix of social and ecological forces that foster expansions of tree cover. This understanding should aid policymakers in drafting policies to promote tree cover expansion.

To understand how social changes, coupled with ecological forces, produce global scale landscape transformations, data sets must contain measures of both ecological and social variables at the same scale that, when combined, suggest socio-ecological dynamics that play out at regional and global scales. The ecological data in this instance come from Hansen's global scale remote sensing of tree cover gains and losses, with the changes in tree cover broken down into aggregates for each country. Comparable social data for countries comes from censuses of human activities conducted and reported by national governments. Variations from nation to nation in these social aggregates may suggest, when analysed alongside changes in forest cover, how social forces have spurred tree cover expansion in different sets of countries.

Using this mix of data, we describe the extent of new tree cover and assess explanations for the differential prevalence of these new forests across the global landscape. Given the importance of tropical forests in the provision of environmental services and the sharp declines in tropical forest cover over the past half century (Sloan and Sayer, 2015), it would be important to capture differences, if any, between the dynamics of tree cover expansion in tropical and temperate biomes. For this reason we carried out additional analyses of countries in each of these biomes. The paper begins with a discussion of theoretical approaches to understanding expansions in tree cover. Then we discuss measures for the variables and methods for analysing the data. We subsequently present the results from our analyses of new tree cover globally as well as in temperate zones and tropical zones. Finally, we discuss the implications of these findings for understanding and promoting tree cover expansion.

2. New tree cover: theoretical expectations

Global patterns of new tree cover reflect large scale changes in the shape and scale of human activities during the past two centuries. The morphology of human societies began to change during the 19th century when people began to reorganize themselves around industrial activities in cities. The scale of human activities also increased. Both the human population and the private enterprises that organized capitalist production grew tremendously in size, a change that observers have recently begun to refer to as 'the great acceleration' (Steffen et al., 2015). In this context new tree cover occurs across a range of situations that can be construed as a continuum that stretches from spontaneously regenerating forests without human intervention to planted forests that only spread through extensive human intervention. As outlined below, spontaneous regeneration has occurred in many fields in places experiencing urbanization, industrialization, and a decline in the extent of agricultural lands. These associated processes of land cover change are referred to as the forest transition (Mather, 1992; Mather and Needle, 1998). Human engineered forest plantations have become more common during the past forty years, particularly in the tropics, as logging firms have shifted from extracting old growth trees from a diminishing number of unexploited frontier forests to growing timber in forest plantations (Boyd et al., 2001; Marchak, 1995). The corporate leadership of these companies have designed these tree farms to produce an unending stream of forest products, so the metaphor of an out-of-doors assembly line operating like a treadmill captures the essential features of this productive process. Between the transitions with little human intervention and the treadmills with extensive human intervention, there are intermediate forms of new tree cover. For an example, many forest owners in the American South sell timber from their lands to pulp and paper companies, but they do not consider the income from timber sales to be the primary reason for owning forested lands and do not manage their forests for the sole purpose of generating revenue from timber sales (Butler, 2008). To define the end points of the continuum between forest transitions and the forest product treadmill, we outline below the dynamics that drive the transitions and the treadmills.

2.1. New tree cover in old agricultural zones: a forest transition

In some situations landscapes undergo historical transitions in which forests first decline and then expand in extent when agriculture contracts to selected, relatively fertile lands. Sometimes referred to as 'the forest transition' (Mather, 1992; Mather and Needle, 1998), this historical process has entailed, at first, the rapid destruction of forests and expansion of agricultural lands. Landless peasants from densely settled regions of Southeast Asia or Latin America, often with state sponsorship, moved during the 1970s and 1980s into predominantly forested regions and laid claim to land by clearing the forests (Rudel, 2005). A large fraction of these recently cleared lands reverted to forest because, as in the eastern Brazilian Amazon (Moran et al., 2000; Vieira et al., 2014), their new owners discovered that the lands did not produce as well as anticipated

[1] Globally, naturally regenerated forests are approximately ten times greater in extent than planted forests. Only in the Far East do planted forests begin to approach naturally regenerated forests in extent. See Table 2.9 in the FRA 2010 report (FAO, 2010). .

or because, as in the Western Ecuadorian Amazon (Rudel, 1983), the settlers cleared land only to establish a claim to it and did not have the capital necessary to productively farm the land. Differences between tracts of land in their market access, in the extent of flat terrain suitable for mechanized agriculture, and in their water supplies also persuaded cultivators over time to consolidate their operations on a smaller number of favoured tracts of land.

The gains in tree cover on abandoned croplands and pastures also occur through slower historical processes in which farmers gradually get to know their lands better over time and then consolidate their operations (Mather and Needle, 1998). Farmers become more aware of differences in the productivity of the lands that they cultivate. These differences may occur between two fields on a single farm or between farms in different regions. Farmers sow these fields with seeds from the one or two crops that produce best under the agricultural conditions of their farms (Reardon and Barrett, 2000). The concentration of agriculture on these fields, along with technological improvements in seeds, pesticides, and fertilizers, leads to increases in yields of staple crops from these lands. In a dynamic outlined by Borlaug (2007), the downward price pressure created by increases in crop yields makes it difficult to profit from the cultivation of marginally productive lands. Similarly, growth in the non-farm sector of the economy, concentrated in cities, creates attractive alternative livelihoods for farm workers and raises their wage rates. When farm workers move to the cities to take urban sector jobs, farmers have to raise wages to retain the remaining farm workers which in turn makes it more costly to employ them to work marginal croplands. For all of these reasons farmers may choose to retire marginal agricultural lands from production. Sprouting tree seedlings then begin to repopulate the now abandoned croplands (Chazdon, 2014; Sloan, 2015).

Following this line of reasoning, countries with high per hectare yields of agricultural commodities would exhibit more forest gains because the high yields would create downward pressures on agricultural commodity prices which in turn would induce the abandonment of marginal croplands (Meyfroidt et al., 2010; Jadin et al., 2016). Abandonment would also tend to occur in rural places losing population or in rural places that have small numbers of economically active people working in agriculture. Extending this same line of argument, tree cover would be less likely to expand in nations where rural populations are increasing and where the proportion of the population economically active in agriculture is high. Both rural population growth and large numbers of economically active people in agriculture suggest socio-ecological conditions in which forest transitions and the associated urbanization and industrialization have not begun.

Following this line of reasoning further, agricultural abandonment and forest recovery would tend to occur in upland areas where steeper slopes, colder temperatures, rockier soils, and higher transport costs would discourage continued cultivation and encourage out-migration (Aide and Grau, 2004). An association between forest regrowth and the extent of mountainous terrain would suggest the presence of a forest transition dynamic across nations. If this pattern prevailed across the continents, it would give credence to assertions that a global forest transition is under way (Meyfroidt et al., 2010; Meyfroidt and Lambin, 2011).

In sum, these arguments about new forests and the forest transition suggest that areas with higher cereal yields, smaller numbers of farmers, and more rugged terrain should all be associated with areas of tree cover gains during the 2000–2012 period.

2.2. Tree cover replacement: a corporate treadmill for new tree production

Rather than occurring along the interface between agriculture and forests, new tree cover in some places merely replaces recently destroyed forests with no intervening agricultural land use. Tree replacement would characterize places where disturbances like fires or storms have triggered cycles of forest destruction followed by regrowth (van Lierop et al., 2015). Shifting cultivation (Conklin, 1957) also involves a cyclical pattern in which, after burning a patch of forest, cultivators grow crops on the burned swiddens for several years and then abandon them. Trees then regenerate on these lands, in effect replacing the earlier, burned stands of forest. Timber companies now do tree replacement on a large scale. The companies grew in size and in profitability during the past century, first by extracting timber from frontier forests and, increasingly thereafter, establishing commercial tree plantations (Langston, 1995; Marchak, 1995; Dauvergne and Lister, 2011).

In already settled, humid places where trees grow rapidly, loggers and land managers earn income from their lands through repeated harvests of trees followed in many instances by replantings designed to expedite the growth of a new crop of trees. A treadmill of wood product production characterizes these lands. Tree covered districts become cutover districts at frequent intervals (Marchak, 1995; Dauvergne, 2001; Kroger, 2012). The owners and managers of these enterprises typically seek as many profit opportunities as possible through logging, planting, and harvesting agricultural-like commodities (Kroger, 2014). In effect the companies in these places have organized an industrial treadmill of tree growth, extraction, and regrowth. The harvested trees return revenue to the companies through the sale of wood, paper, and other forest products to consumers (Schnaiberg, 1980; Gould et al., 2008). Investments of capital in particular tracts of land make it possible for the managers, through the application of highly rationalized procedures (Weber, 1920), to boost the production of wood products from tracts of land that they own.[2] The planting of monocultures of genetically selected tree seedlings results in a much lower biodiversity compared to other forest types.

Managers pursuing this strategy take steps to spur continued production from sites. Scandinavian foresters after more than a century of forestry have shown a renewed interest in the productivity of their lands for timber over the past three decades (Marald et al., 2016). Similarly, in the outer Islands of Indonesia loggers convert recently cutover tracts into sites for oil palm plantations as rapidly as economic and ecological conditions permit (Casson, 1999; Rival and Lavang, 2014). These landscapes would therefore exhibit high rates of turnover in tree cover. In some instances landowners with this orientation might expand the size of their plantations into areas without recent tree cover, as has occurred in the Ecuadorian Andes (Farley, 2007). In these instances treadmill processes expand tree cover.

The expansion to a global scale of markets for wood products and for edible oils has encouraged the spread of treadmill like, industrial forestry model for the production of forest products. Investors, oftentimes from overseas, would acquire lands in humid climates where the abundant moisture would accelerate tree growth and reduce the time between harvests (Dauvergne, 2001). In times series of satellite images tree cover losses from a harvest of trees at time 1 would predict tree cover gains at time 2 in the same location, either as natural forest recovery following harvest or as newly established commercial tree plantations. Recent remote sensing studies in Cambodia found a pattern consistent with this overall dynamic. Foreign investors cleared tropical forests at higher rates during the 2000–2012 period than did other landowners (Davis et al., 2015).

These treadmills of tree harvesting and subsequent regrowth occur in a variety of forms. Companies acquire natural forest

[2] These processes are sometimes referred to as 'the real subsumption of nature' in Marxist thinking (Boyd et al., 2001).

concessions within which they harvest trees. Then, depending on a host of situation specific factors, the concession holders or landowners either allow trees to regenerate or plant new trees. These corporate-led routines of harvest and regrowth extend beyond lands directly controlled by the companies. Particularly in temperate countries, large numbers of non-industrial, private forest owners work cooperatively with the industrialized, paper mill and wood product producers. For example, in the southern United States almost 60% of all forest land is owned by families, many of which sell the wood on their lands at regular intervals to timber companies that maintain nearby paper mills (Price et al.,2006; Butler, 2008). In Southeast Asia almost half of all of the oil palm produced in the region comes from smallholders, who like the family forest owners in the U.S. South, have their oil palm processed at industrial sized processing mills owned by oil palm companies (Rival and Lavang, 2014). Although these smaller scale forest landowners have ties to corporate owned mills, they may not manage their forests as intensively for production as the corporations do on their own lands.

If industrial, treadmill-like activities of forest harvest and plantation establishment explain the distribution of new tree cover across nations, then tree cover expansion should concentrate in nations that have experienced large losses of forest, most likely from some form of forest harvesting, or agro-forestry on large landholdings or leases. Tree cover expansion would also concentrate in nations with humid climates, not only because humid climates accelerate regrowth, but because the rapid growth in humid settings would attract investors intent on reaping profits from the rapid growth of the trees. While the forest transition could, theoretically, lead to tree cover expansion as farmers abandon marginal agricultural lands, the treadmill dynamic in contrast produces tree cover replacement. Tree plantations replace natural forests, and this change represents a continuation of the rationalization of production that has historically accompanied industrialization in all of its forms.

These expectations about the association between new tree cover, the forest transition, and the corporate led treadmill dynamic can be put to a test through multivariate analyses of the recently released remote sensing based maps of new tree cover around the world.

3. Materials and methods

As noted above, the following analyses of the differential extent of tree cover expansion across nations have only become possible through the recent creation and dissemination of global scale land cover maps based on 30-m resolution Landsat satellite imagery (Hansen et al., 2013). Prior to the creation of this global Landsat data set, global scale analyses of reforestation had to rely on national reports of forest cover change from the FAO's FRA (Forest Resources Assessment) (FAO, 2010) or on coarse or moderate-resolution satellite imagery, namely the AVHRR (Advanced Very High Resolution Radiometer) or MODIS (Moderate Resolution Imaging Spectroradiometer) imagery (DeFries et al., 2010). None of these data sets proved to be adequate for the task. Despite efforts by FAO staff to impose some consistency on the FRA data, it still came from individual countries that calculated forest areas in different ways, so the measures of forest area were inconsistent across nations or over time (Keenan et al., 2015). Coarse-resolution satellite sensors like the AVHRR have consistent global coverage of dynamic forest cover, but their relatively coarse spatial resolution (>4 km pixels) and the sub-pixel mixing of spectrally-similar primary and secondary forest covers means that any derived estimates of forest regrowth extent across countries would be highly uncertain. Finer-resolution MODIS data (250 m–1 km pixels) have been used to estimate the extent of forest regrowth in Latin America (Aide et al., 2013) and within agricultural landscapes globally (Zomer et al., 2014) since 2000. MODIS estimates of annual percent tree cover now exist, and they might be used to generate global scale estimates of regrowth, but these estimates would still entail uncertainties about the actual extent and distribution of the new forests given the resolution of the images. The higher resolution time-series Landsat imagery now available (Hansen et al., 2013) reduces this uncertainty, making it possible, for example, to estimate relatively reliably the area of new tree cover arising on cleared lands adjacent to pre-existing forests.

The Landsat data do present analysts with some challenging measurement issues. As outlined above, there is good reason to believe that a disproportionate amount of new tree cover has emerged on higher elevation lands that are more likely than other places to be covered by clouds (Aide et al., 2013). For this reason extensive cloud cover at higher elevations could lead to underestimates of new tree cover in nations with rugged topography. This potential effect would introduce a conservative and spatially uneven bias into Landsat based analyses of the association between rugged terrain and new forests. There is also a possible underestimation of forest cover in arid zones because Hansen's Landsat data set requires 50% tree cover in a pixel before it declares an area to be forest. Another widely used international forest cover data set, the FAO's Forest Resources Assessment, defines a landscape as 'forested' when tree canopy covers more than 10% of an area. Taken together, the aforementioned considerations suggest that, while the use of Landsat data presents some complications for global analysis, it still represents the best global scale data set for assessing patterns of tree cover gain across nations.

The data set analyzed below contains the satellite derived estimates of new tree cover – the variable of interest – as well as tree cover losses between 2000 and 2012. The data set also includes a mix of social, economic, and ecological variables, namely average precipitation, average cereal yields for the nation's croplands, rural population growth between 2000 and 2005, the proportion of a country's labor force that was economically active in agriculture in 2000, and the proportion of a country's land area that exceeds 30° in slope. These data are available for all countries with the exception of the French colonial dependencies like French Guiana. The productivity index for cereals combines data for wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains. It is reported to FAO by ministries of agriculture. The population data comes from national censuses conducted using standardized procedures and reported to the UN. The economically active population in agriculture includes urban and peri-urban farmers as well as rural cultivators. It comes from farm surveys and agricultural censuses done in different countries (Hitimana et al., 2011).

Table 1 lists the sources for these data. We analyze the relationships between these variables in three groups of nations: all nations, temperate zone nations, and tropical zone nations. The Tropics of Capricorn and Cancer distinguish the temperate zone nations from the tropical zone nations in the following analyses. Nations with a majority of their lands between the two latitudinal lines (∼23.5°N and ∼23.5°S) were identified as tropical zone nations. Nations to the north and south of these lines were categorized as temperate zone nations.

An inevitable amount of imprecision comes with the use of countries as units of analysis and national averages as the values of variables. Given the highly aggregated nature of these variables, ecological fallacies (Robinson, 1950; King, 1997) represent a potential problem. These fallacies occur when analysts argue that a relationship between variables at an aggregate scale indicates a similar relationship between the same variables at a lower level of aggregation. For example, associations across nations between the proportion of sloped land and the amount of new tree cover are used analytically to argue that this same relationship exists in

Table 1
Variable Definitions and Data Sources.

Cereal Yields, 2000. Cereal yield in kilograms per hectare of harvested land. A composite measure of yields from wheat, rice, maize, barley, oats, millet, sorghum, buckwheat, and other grains. Accessed at http://data.worldbank.org/indicator/ag.yld.crel.kg.
Population Economically Active in Agriculture, 2000. The proportion of the nation's population that was economically active in agriculture in 2000. Source: FAOSTAT, Food and Agricultural Organization of the United Nations. Accessed at: http://faostat.fao.org/site/375/default.aspx.
Forest Gains, 2000–2012. Establishment of a tree canopy where none previously existed at a pixel (30 m) scale. Supplementary materials, Table S3, in Hansen et al. (2013). Accessed at www.sciencemag.org/content/342/6160/850/sppl/DCl.
Forest Losses, 2000–2012. Complete removal of a tree canopy at a pixel (30 m) scale. Supplementary materials, Table S3, in Hansen et al. (2013). Accessed at www.sciencemag.org/content/342/6160/850/sppl/DCl.
Land Areas with Slopes >30°, Extent of. Data Source: GAEZ 3.0 (Global Agro-ecological Zoning), Land Resources, Terrain Resources. Accessed at: http://www.fao.org/nr/gaez/en/.
Changes in Rural Populations (%) between 2000 and 2005 – Data Source: United Nations, Population Division. Accessed at: http://www.un.org/popin/data.html.

individual watersheds across these nations. Concerns about these fallacies can be allayed to some extent through the use of regression tree analyses that identify trends existing across smaller subsets of nations. Evidence about the relationships between forest gains and their drivers from local level case studies that are consistent with the patterns in the aggregated data would allay concerns about ecological fallacies. We pursue these analytic strategies in the results and discussion sections below. In assessing the overall value of these cross-national analyses, it is important to remember that what one loses with the imprecision of aggregated analyses is recouped in part by the value of conducting global scale analyses that provide empirical bases for global generalizations.

One might raise questions about causal order in an analysis relating tree-cover gain with population change and agricultural employment. Both forest transition theory (Mather and Needle, 1998) and case studies of forest regrowth (Kuemmerle et al., 2011; Sloan, 2015) suggest that out-migration from a region or a country as well as local shifts away from agricultural employment would precede the spontaneous forest regrowth that typically follows land abandonment. Accordingly, we measured population change for the first five years of the twelve year period of forest cover change, in effect allowing for population change to have a lagged effect on forest cover. Similarly, we measured agricultural employment at the beginning of the observation period. These differences in the periods for population change, agricultural employment, and tree cover expansion make it unlikely that reverse causation, with tree cover expansion causing population losses or reduced agricultural employment, would occur (Greenwood, 1975). A similar kind of argument about causal sequences in the cereal yield – tree cover expansion relationship could be made. By using cereal yield data for 2000 and tree cover change data for the subsequent 2000–2012 period, we address these concerns about simultaneity biases.

The analyses begin by describing large regional differences in tree cover gains throughout the world. Then the focus shifts to bivariate relationships, portrayed in Figs. 1–3, between tree cover gains and rural population growth in South and Southeast Asia (Fig. 1), between tree cover gains and terrain in Sub-Saharan Africa (Fig. 2), and between tree cover gains and economically active populations in agriculture in Eurasia (Fig. 3). These region-specific bivariate relationships suggest substantial variation across groups of countries in the drivers of tree cover expansion. Regression tree analyses, with their foci on differences in explanatory patterns across subsets of countries, provide a way to parsimoniously capture both the larger, cross-national explanatory patterns of tree cover gain as well as patterns that pertain in smaller, regional subsets of nations. Regression tree analyses recursively partition a single set of countries (global, tropical, or temperate) into increasingly smaller and generally more homogenous subsets on the basis of a series of critical binary thresholds in the explanatory variables.

All variables are candidates for defining a threshold value that partitions a subset of countries into two smaller subsets, where the ultimate threshold value selected is that which minimizes the sum

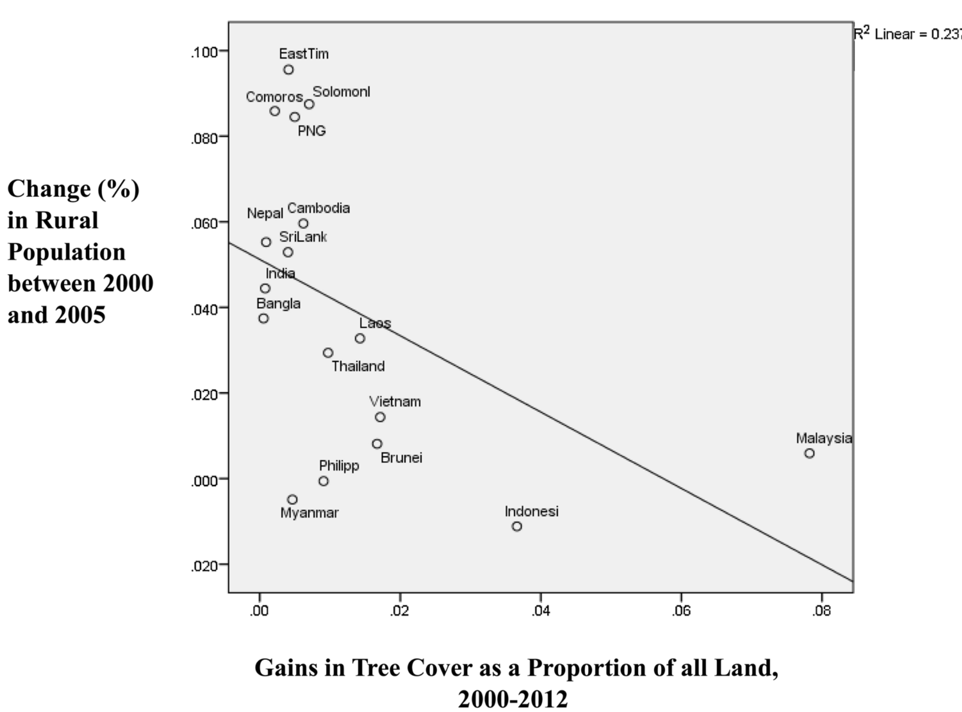

Fig. 1. Rural Population Change and Tree Cover Gains in South and Southeast Asia.

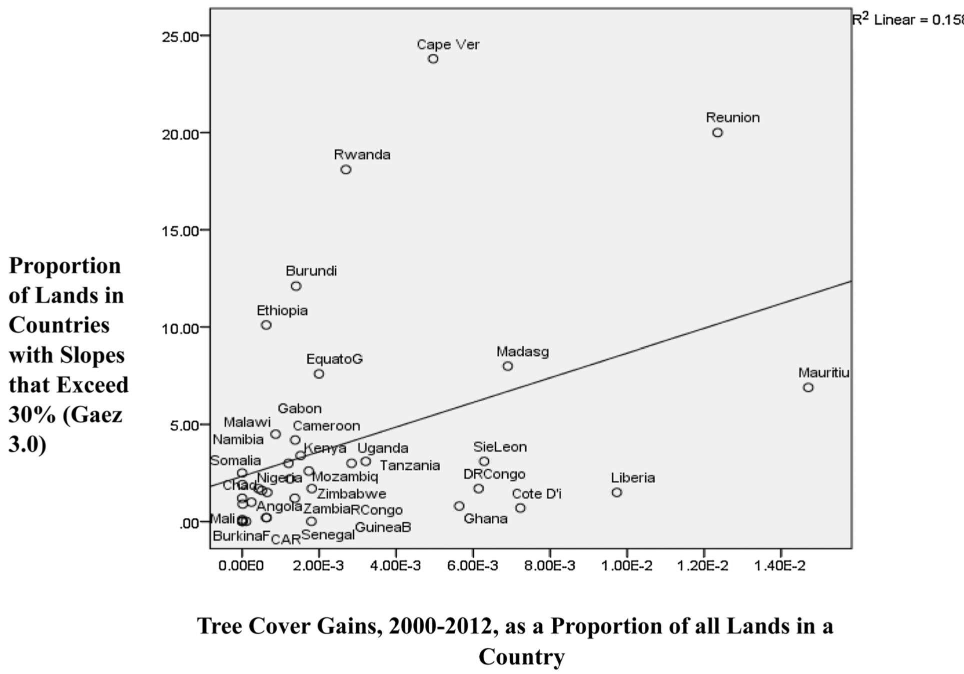

Fig. 2. Rugged Topography and Tree Cover Gains in Sub-Saharan Africa, 2000–2012.

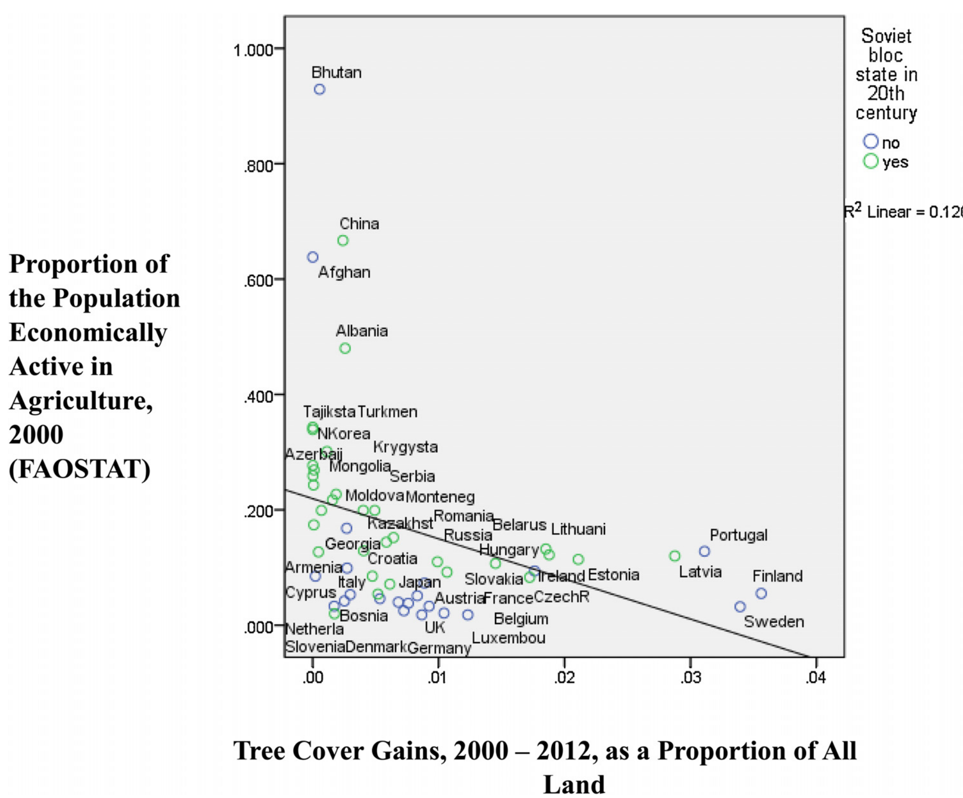

Fig. 3. The Size of Farming Populations in 2000 and Tree Cover Gains in Eurasia, 2000–2012.

of squared errors (residuals) in the two subsets resulting from the partition (Yohannes and Hddinott, 1999). An interpretive 'reading' of the resultant tree allows one to identify divergent trajectories of forest gain by the interactions of successive threshold values of the driver variables as well as by the types of countries grouped into different subsets. In all of the regression tree analyses we weighted cases by the land areas of countries. Each of the regression trees contains a measure of the total variance explained (R^2) by the explanatory variables and a measure of the relative importance of each of the explanatory variables. If a variable does not enter a given regression tree, no critical value of that variable could reduce the variance of the designated subset of countries to a greater degree than the variables that already define the partitions. The analysis entails no assumptions concerning the nature and distribution of the data, and it is insensitive to outliers.[3]

4. Results

Only 18 of the 165 countries in the analysis showed net tree cover gains between 2000 and 2012 in the Hansen data. The eighteen countries that gained tree cover had smaller proportions of their populations employed in agriculture (Eta = 0.233, p = 0.003) and exhibited slower rates of rural population growth during the 2000–2005 period (Eta = 0.172, p = 0.028). Two clusters of geographically similar countries were apparent amongst the 18 countries reporting net gains in forest cover: a set of post-Soviet sphere countries (Bosnia, Cuba, Moldova, Hungary, and Serbia) and a set of semi-arid or arid countries (Cape Verde, Egypt, Palestine, Tunisia, and Iraq).

Amongst world regions, Southeast Asia contained the most extensive areas of new tree cover, at 1.75% of the land area. North America, with 1.25%, and Europe, with 0.99%, also contained appreciable areas of new tree cover. The concentration of new tree cover in Southeast Asia most likely represents the expansion of industrial-scale tree, rubber, and oil palm plantations in degraded or recently deforested areas in Vietnam (McElwee, 2016), Indonesia (Abood et al., 2014), and Yunnan province in southern China (Xu et al., 2007; Sloan and Sayer, 2015). In keeping with our theorizing, Southeast Asia also had the highest rate of forest losses of any region between 2000 and 2012. Forest losses amounted to 4.09% of the region's land area between 2000 and 2012. Southeast Asia also has the most extensive commercial tree plantations in the world (Rudel, 2009; Payn et al., 2015). Much of the regrowth observed in North America and Europe stems from the reforestation of managed forests after clear cutting by logging companies (Sloan and Sayer, 2015). Natural regrowth on abandoned agricultural lands is also appreciable in Eastern Europe (Kuemmerle et al., 2011). Sub-Saharan Africa and South Asia, the two poorest regions, had the lowest incidence of new forests (0.33% of their land area versus 0.75% of the land area for other regions, p < 0.01). Rural residents comprise about 65.4% of the populations in the regrowth-scarce regions of Sub-Saharan Africa and South Asia compared with 39.4% of the populations in the other regions (p < 0.001).

Figs. 1–3 provide more evidence of region-specific drivers of new forest gains. The scatterplot in Fig. 1 illustrates the relationship between changes in tree cover and rural population growth in South and Southeast Asia. Countries with more rural population growth had smaller gains in tree cover.[4] The scatterplot in Fig. 2 portrays a relationship between steep slopes and new tree cover in Sub-Saharan Africa. The economies of two mountainous islands, Reunion and Mauritius, both of which exhibited extensive tree cover gains, have transitioned away from agriculture and towards non-farm activities like tourism. The scatterplot in Fig. 3 shows the relationship between labour force participation in agriculture and new forests in Eurasia. Finland and Sweden have large areas of new tree cover and small numbers of workers in their agriculture and forestry sectors. These numbers reflect the small numbers of workers necessary to run the highly mechanized logging operations that prepare the ground for new trees in these countries.

Without a doubt the strongest single finding that runs through the multivariate regression tree analyses in Figs. 4–6 is the positive, cross-national association between tree cover loss (% of land area)

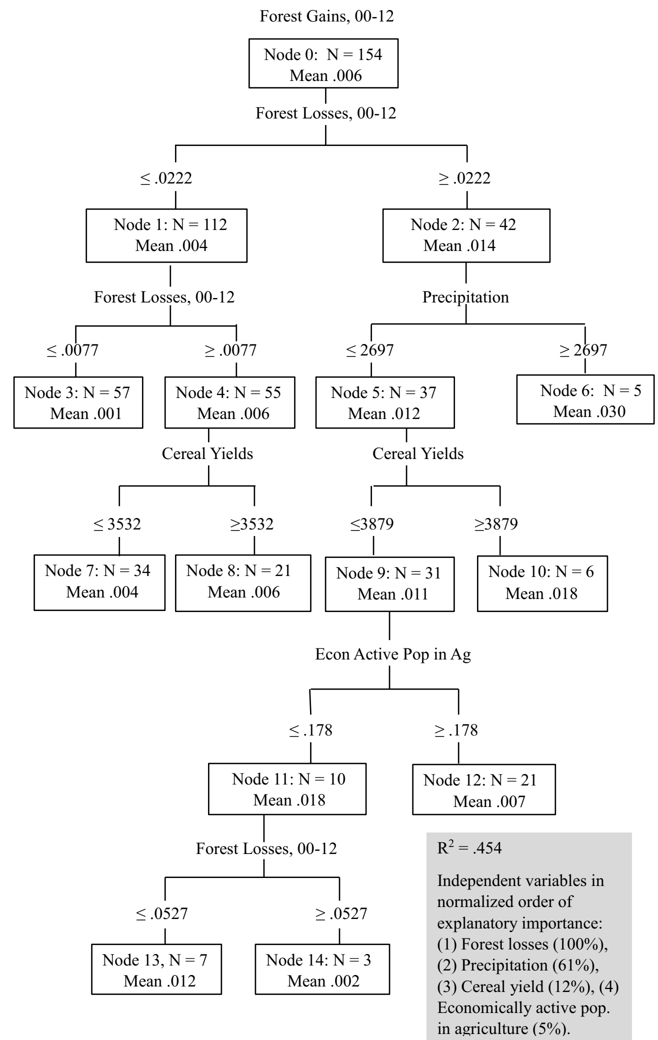

Fig. 4. Tree Cover Gains across all Nations: A Regression Tree Analysis.

and tree cover gain (% of land area) (r = 0.717, p < 0.001 globally). As indicated by a comparison of the mean forest gains in nodes 1 and 2 of the global regression analysis, portrayed in Fig. 4, countries with higher rates of deforestation also have relatively extensive areas of new tree cover. As a comparison of nodes 5 and 6 in the same figure indicates, high deforestation countries with humid climates have still more extensive areas of new tree cover. These patterns are consistent with the forest product treadmill dynamic. Lower cereal yields associate with less new tree cover (node 9 compared to 10), as do larger populations working in agriculture (node 11 compared to 12). Both the positive effects of cereal yields and the negative effects of agricultural population size on the extent of new forests are consistent with the forest transition dynamic.

Fig. 5 presents the regression tree analysis for temperate zone countries and, with one exception noted below, it exhibits the same patterns as the global scale analyses. New areas of tree cover concentrate in countries like those in the Baltic region that have recently lost large amounts of forest (node 5 compared to 6), have humid climates (node 3 compared to 4), and attain higher agricultural yields from their lands as in Germany and other western European countries (node 7 compared to 8). A deviant pattern shows expanding tree cover in a small number of countries with growing rural populations and relatively large agricultural populations like Ireland, Uruguay, New Zealand, and Chile (node 11 compared to 12 and node 13 compared to 14).

[3] For an example of this type of analysis, see DeFries et al. (2010).

[4] Dropping the two outliers, Indonesia and Malaysia, from the scatterplot does not change the overall relationship between rural population growth and increases in tree cover.

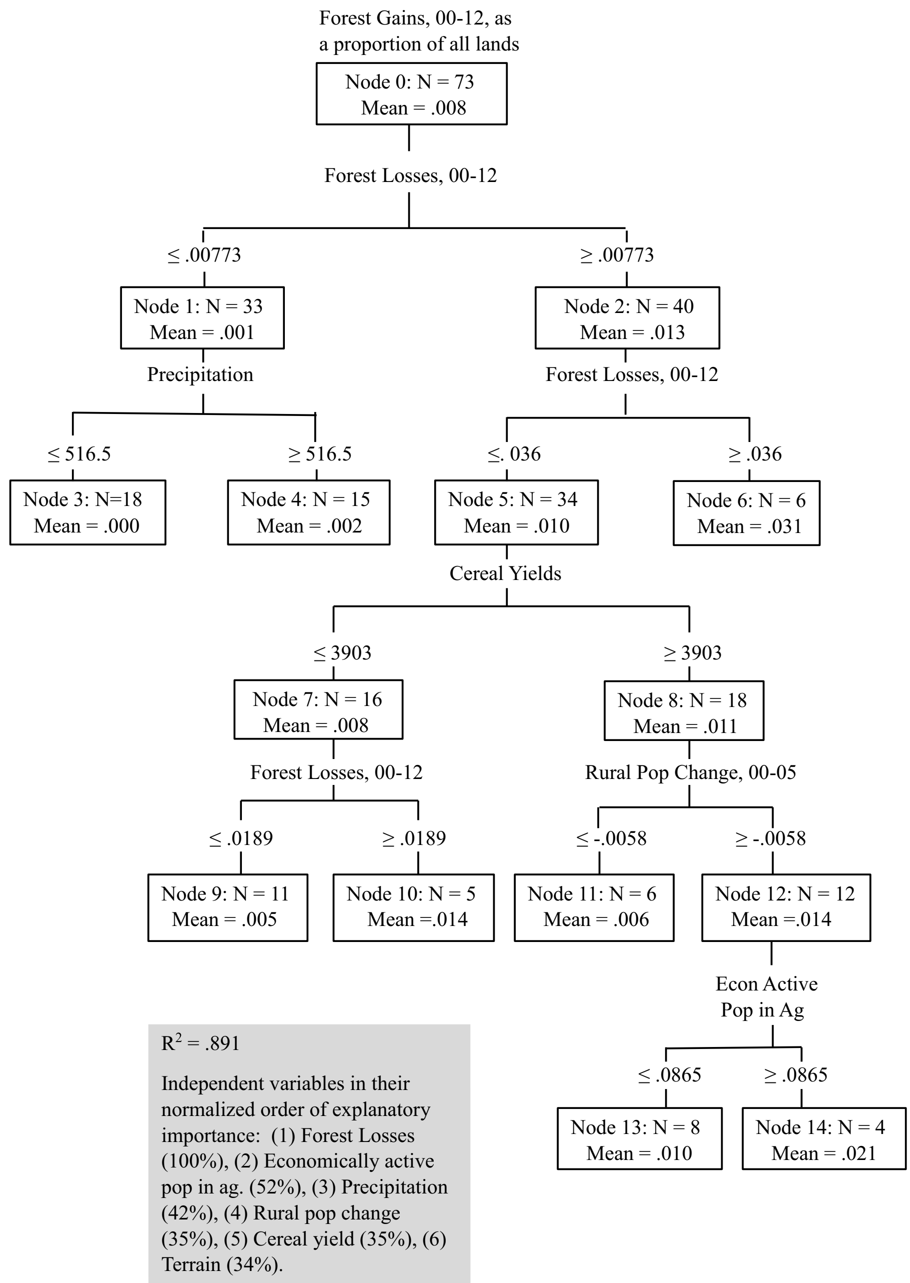

Fig. 5. Tree Cover Gains in Temperate Countries: A Regression Tree Analysis.

Fig. 6 presents the analyses for the tropical zone countries. Here too tree cover losses explain most of the variance in tree cover gains. Countries with very high deforestation rates like Indonesia, Malaysia, and Paraguay contain the most extensive areas of new tree cover (node 1 compared to 2). Among high deforestation countries (node 4) a humid tropical or a wet subtropical climate associates with relatively extensive areas of new trees compared with drier subtropical or arid zones (node 7 compared to 8). Among those countries with relatively small losses in forests, the largest gains in forests occurred in those countries with the highest yielding cereal crops (node 5 compared to 6). Growing rural populations associated positively with tree cover gains (node 11 compared with 12), contrary to theoretical expectations, but consistent with the temperate country analysis. Among countries with stable or growing rural populations, those with larger numbers of people pursuing agricultural livelihoods showed less extensive new tree cover than other countries (node 13 compared to 14). Among those countries with relatively low deforestation rates (node 3), the largest gains in new tree cover occurred in those countries with the highest yielding cereal crops (node 5 compared to 6). Surprisingly, the association between rugged terrain and new forests evident in Sub-Saharan Africa scatterplot (Fig. 2) does not enter the regression tree for the entire tropical zone, presumably because other variables like precipitation substituted for the terrain variable.

5. Discussion

5.1. Forest transitions

Relatively high rates of tree-cover gain occur where tree-cover loss is low only if cereal yields in a country are relatively high. In the tropics (Fig. 6), rates of tree-cover gain in high-yield, low forest

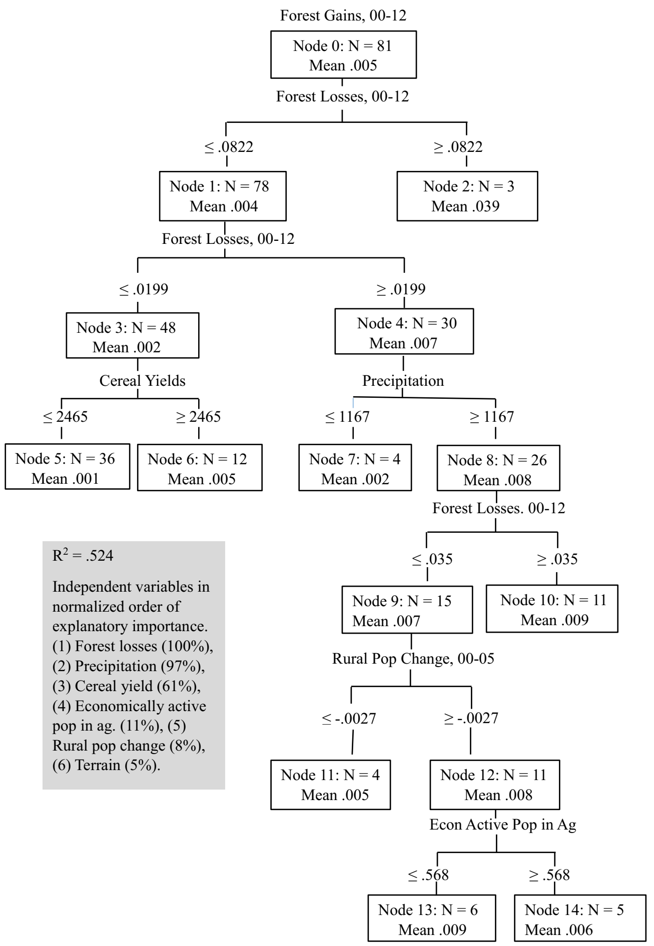

Fig. 6. Tree Cover Gains in Tropical Countries: A Regression Tree Analysis.

loss countries (node 6) average 0.005% compared to only 0.001% in low-yield, low forest loss countries (node 5). In temperate countries (Fig. 5), this effect is apparent but less pronounced than it is in the tropical set of countries. Amongst temperate countries with relatively moderate rates of tree cover loss (Fig. 5, node 5), countries with higher cereal yields (node 8) have greater rates of tree-cover gain than low cereal yield countries, at 0.011% vs 0.008%. The positive association of cereal yields with new forests in all three regression trees suggests a Borlaug like dynamic, consistent with forest transition theory, in which high yields on some agricultural lands encourage agricultural abandonment and the spontaneous regeneration or planting of forests on other lands. For example, in Vietnam intensified rice cultivation in the northern lowlands after 1990 prompted agricultural abandonment and tree planting in adjacent upland areas (Sikor and Dao, 2002).

Rural and predominantly agricultural populations appear to have a mixed effect on the prevalence of new tree cover. Consistent with expectations, in both the global analysis (Fig. 4) and in the tropical analysis (Fig. 6) countries with large agricultural populations had less new tree cover than other countries (see nodes 11–14 in Fig. 4 and nodes 13–14 in Fig. 6). These countries include the Democratic Republic of the Congo, Madagascar, and Sierra Leone, and they suggest a positive relationship between poverty and deforestation in which large rural populations harvest valuable forest products, including trees, as they emerge. In so doing, these people prevent the expansion of tree cover on these lands. In contrast a small number of temperate zone countries, as noted above (Fig. 5, nodes 11–14), with stable or growing rural and agricultural populations have larger areas of new tree cover. Wood scarcity and profitable prospects for fruit production may have induced expansions in forest plantations and orchards in these places. This pattern would also be consistent with a forest transition, although the scale of these new forests in places like Uruguay and Ireland may be quite small. The coincidence of rural population growth and forest cover gain in the tropical biome (Fig. 6, nodes 11 and 12) is more difficult to interpret. It does follow the pattern observed by Sloan (2015) in Panama where forest gain seemed to stem from local migration coupled with growing non-farm labour markets in otherwise rural areas leading to land abandonment. Further enquiry is necessary to know whether this explanation holds at the cross-national scale.

While the patterns described above tend to support Mather's forest transition model, the absence of significant associations between montane settings and new forests in the regression tree analyses is puzzling, especially in light of the bivariate association in Fig. 2 between new tree cover and montane settings in Sub-Saharan Africa. The absence of findings here may be artefactual to some degree, a product of the difficulties associated with getting cloud-cover free Landsat imagery for montane regions, the use of national scale data, and the weighting of analyses by the land areas of countries. Many salient examples of the association of montane settings with reforestation have occurred in relatively small nations like Mauritius and Reunion in Fig. 2, the Central America states (Redo et al., 2012), and Puerto Rico (Lugo and Helmer, 2004). Another study has shown the same pattern for all of Latin America (Aide et al., 2013). A more conclusive investigation of this relationship at the global scale would require less aggregated units of analysis. With the exception of the montane – new tree cover relationship, the findings from the regression trees for the various indicators of forest transition dynamics suggest substantial support for forest transition theory.

Substantive conclusions about the drivers of tree cover gains have to be tempered by the realization that the high level of aggregation in this study probably masks the heterogeneity of new tree cover in places. Field studies of landscape mosaics in Southeast Asia point to the presence of contrasting kinds of new tree cover managed by shifting cultivators, smallholder oil palm producers, and large scale oil palm plantation managers within the rural sector of a single country like Indonesia or Malaysia (Curran et al., 2004; Abood et al., 2014). A somewhat different association of new tree cover with densely populated rural areas has emerged in Mesoamerica where most new tree cover has emerged in the long settled and densely populated upland regions (Redo et al., 2012; Aide et al., 2013; Chazdon, 2014; Sloan 2016). These matrices of different types of new tree cover within the agricultural sector of a single country, like Indonesia, make it necessary for observers to walk a 'fine line' in interpreting the cross-national patterns presented here. The large scale patterns seem consistent with theories about forest transitions and enterprise-led regrowth, but findings at smaller scales, including field based studies of regrowth (Lerner et al., 2015) suggest more diversity in the dynamics that drive tree cover expansion.

5.2. Tree cover replacement and treadmills of production

The findings from the regression tree analyses underscore the global salience of the link between preceding tree cover losses, humid climates, and subsequent tree cover gains. Logging companies embody this pattern, especially in wealthier Northern countries, where they engage in serial deforestation and reforestation on the same lands. In these instances, new tree cover is merely replacing former tree cover, rather than leading to net gains in tree cover (Zhai et al., 2012; Margono et al., 2014; Zhai et al., 2014). Precipitation predicts tree cover gains in all three regression tree analyses. The salience of the precipitation variable in predicting forest gains follows directly from the growth accelerating effects of a humid climate on trees, so it would be expected from an ecological point of view. It would also be consistent with dynamics in which loggers and planters play an important role in creating the new forests. The growth-accelerating effects of abundant rainfall would increase rates of profit from plantations and logging operations by increasing the frequency of harvests. In effect humid climates accelerate the corporate treadmill and enlarge the associated profits. For this reason, plantations and industrial logging activities would cluster in accessible regions with humid climates.

In Indonesia and Malaysia, for example, large scale oil palm plantations as well as timber plantations have accounted for the loss of appreciable amounts of old growth forests since 2000, and the plantation monocultures that replaced old growth forests accounted for a substantial amount of the new tree cover (Abood et al., 2014; Lee et al., 2014). The conversion to an industrialized, treadmill-like pattern of land use sometimes occurs in circuitous ways. In Panama, for example, state-backed loggers opened forest frontiers to agriculturalists who in turn deforested them, and new state-backed timber interests are now establishing tree plantations in the same frontiers in the name of commercial forest landscape restoration (Sloan, 2016).

6. Research and policy implications

The preceding pages have focussed on the empirical bases for generalizations about the drivers of tree cover gains because knowledge about the drivers could have utility if policymakers want to accelerate processes of tree cover gain. The impetus for accelerating these processes exists because increases in tree cover represent one of the very few ways to decrease atmospheric carbon in the short term. For this reason, forest gains became an integral part of the global UN-sponsored REDD+ initiative (Reducing Emissions from Deforestation and Degradation) during the 2008 IPCC meetings. The original component, RED (Reducing Emissions from Deforestation), proposed in 2005, focussed on reducing emissions by preventing the clearing of old-growth forests (CIFOR, 2014), largely through payments for the ecosystem services, including carbon sequestration, provided by standing, old growth forests. Over the course of the next three years the projected program expanded to include a reversal of forest degradation, thereby adding a second D to the acronym, and expanded again to include the conservation and enhancement of forest carbon stocks as well as the sustainable management of forests. To reflect these last additions, REDD became REDD+ in 2008.[5]

The inclusion of enhanced forest-carbon stocks in REDD+ has potentially important equity implications because it would permit payments for additional ecosystem services from the largely deforested lands of smallholders that may be undergoing some reforestation as smallholders, coincident with urbanization, become more focussed on non-farm sources of income. The biodiversity and watershed conservation returns from forest gains on these farms could also be considerable (e.g. Pagiola et al., 2005; Asquith et al., 2008). The small scale of these farms would, however, elevate the transaction costs of delivering payments for ecosystem services to farmers, an obstacle that is far less formidable for the plantation sector (Sloan, 2016). If these organizational obstacles can be overcome, a smallholder constituency evident in the ties between forest gains, higher cereal yields, and rural population losses reported above could benefit from REDD+ payments and enhance carbon sequestration. These prospects remain uncertain because, to date, the focus of most REDD+ policy and practice has been centered on avoiding forest losses rather than promoting forest gains (Ma et al., 2014).

[5] See http://theredddesk.org/what-is-redd.

The strong associations between large forest gains, large forest losses, and humid climates suggests the presence of a corporate-led treadmill dynamic, but the aggregated nature of the present analysis makes it more useful as a prod for further research than as a direct source for policy implications. Three questions in particular need further attention. First, what role have large-scale natural disasters like fires and storms played in the cycles of forest destruction and regrowth reported in the above analyses? Second, what role does shifting cultivation play in the cycles of forest destruction and new tree cover reported here? Recent meta-analyses suggest that the extent of swidden cultivation may be declining in Southeast Asia (van Vliet et al., 2012), but the magnitude of these trends and the degree to which swidden cultivation has been limited by the recent spread of corporate-led, industrial operations that produce a very different kind of new tree cover remains open to question and important to answer. Third, the apparent salience of corporate managed treadmills in the production of new tree cover raises questions about the various forms that it takes. How often does it begin with the destruction of primary forests? What kinds of variations, if any, occur in the distributive effects of these treadmills for timber production, particularly in those instances where smallholders provide a significant amount of the raw materials that keep the corporate owned mills running at full capacity.

More generally, the arguments derived in part from the global scale analysis of tree cover expansion require refinement and cross-validation from smaller scale studies of the socio-ecological dynamics of tree cover expansion. Hopefully, a coincidence of findings from studies at different scales would then enable us to build a fuller, credible, and actionable understanding of the social and ecological conditions that promote the expansion of tree cover.

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