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Comparative assessment of global wood fiber and forest carbon sequestration prospects

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ABSTRACT

We assessed the relative capacity of key global wood baskets in Latin America and Asia to determine their ability to meet increases in demands for pulp and paper, or to grow trees to store forest carbon. Drawing from the Trillion Trees proposal in 2020, a central aim of the research was to determine if a single country could plant an additional 10 million hectares (ha) by 2030. We analyzed secondary information from publicly available literature about the forest sector, forest plantations, and forest restoration in various countries. We screened land use types from the FAO data base to estimate forest restoration opportunities and compared those results with previous literature. These analyses helped determine the countries in Asia and Latin America with sufficient non-forested land (mainly shrub, herbaceous, or grassland areas) and the right environmental conditions to plant trees to meet the 10 million ha goal, or at least have good potential for large-scale tree planting. The study revealed that Argentina, Brazil, China, Colombia, Indonesia, India, Lao PDR, and Vietnam had the best prospects for large-scale afforestation and reforestation. Cambodia, Chile, Mexico, Myanmar, Paraguay, Thailand, and Uruguay also showed high potential based on the presence of large areas of grassland that might be suitable for tree planting. The research showed that while no single country is likely to plant 10 million ha of forests in the next decade, many could support hundreds of thousands or millions of ha, sufficient to support new pulp and paper mills, solid wood forest manufacturing, or major forest carbon plantings.

Keywords

forest carbon sequestration, forest restoration, planted forests, principal countries, wood fiber production

Citation

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INTRODUCTION

This research was performed to identify the most suitable countries in Latin America and Asia for large-scale tree planting for fiber production and carbon sequestration. With natural forests becoming less available for wood supply due to deforestation and restrictions on cutting to protect ecosystems, plantations are expected to have a comparatively more prominent role in wood production in the future. In addition to the dwindling wood supplies from natural forests, populations and consumer needs for wood and paper products continue to rise at moderate rates. Korhonen et al. (2021) and Nepal et al. (2019) projected that by 2070, 379 to 475 million ha of planted forests will be established to meet global demands for forest products and ecosystem services—an increase of 31% to 64% more than 2020 levels of 290 million ha (FAO 2020).

Underscoring this need is the emergence of multiple international, national, and regional proposals to plant vast areas of trees to capture carbon for mitigating climate change. These include the New York Declaration on Forests (NYDF), which was first endorsed at the United Nations climate summit in 2014 (UN 2014), and the Bonn Challenge, which is a platform to achieve multiple restoration targets under one initiative (IUCN 2015). The most ambitious proposal is the Trillion Trees project (1t.org 2020), put forward at Davos during the World Economic Forum in 2018, which proposes the planting of one trillion trees (World Economic Forum 2020). Based on a typical planting density of 1000 trees per ha, a trillion trees would require about one billion ha of land. This is an immense goal and an unprecedented challenge.

The world currently has about 4 billion ha of natural and planted forests (FAO 2022). Therefore, planting a billion ha would increase the entire forest area of the planet by about 25 percent. If the Trillion Trees project were to include substantial areas of restoration planting or interplanting in standing forests, the number of ha required for the project could exceed one billion ha. Existing stands are unable to accommodate the planting of as many trees per ha as more conventional plantations established in open areas, and consequently would require a larger planting area.

Mathematically, at least 100 countries, each with the potential to accommodate an additional 10 million ha of planted forests, would be required to comprise an area large enough to meet the requirements of the One Trillion Trees project. Thus to help organize our research and identify and rank a list of candidate countries for large-scale tree planting, we used the theoretical area of

10 million ha as a practical target. Only a handful of countries, however, actually have enough land suitable for planting 10 million ha of trees. In fact, identifying a dozen countries with the clear potential to host such an immense area of commercial plantations over the near term proved impossible.

A project of the magnitude of One Trillion Trees would also need to take into account other factors as well as land suitable for planting (Brancalion et al. 2017, Holl and Brancalion 2020, Shyamsundar 2022). These include land tenure and property rights issues, competing land uses, the environmental setting, financial resources, governance, institutional capacities and the regulatory framework, among others. Similarly, in reviewing the outcomes of large-scale tree-planting efforts, Lamb (2014) points to their utility in directing public attention to the value of forests and reforestation. However, he notes various issues bear consideration. An emphasis on planting a large number of trees risks overlooking long-term sustainability concerns. When programs are hurried to meet targets, they may end up reforesting sites that are the most convenient, rather than where trees are most needed. Planting stock can also suffer if insufficient time is allocated to collect the best seeds and cultivate high-quality seedlings.

An additional complication is that establishment costs often run considerably higher for restoration planting compared to planting monocultures in open areas. Cubbage et al. (2022) report average costs of US $1,534 per ha for establishing monoculture plantations across 16 countries and 47 planted species and management regimes. In contrast, ITTO (2020) reports an average cost of US $7,000 per ha for restoration plantings in the tropics, and a survey of 59 restoration projects in temperate forests in New Zealand documented costs ranging from US $14,281 to US $17,755 per ha (Forbes Ecology 2022)[1].

Although solid wood products could also be produced in most of the study areas, the research focused exclusively on identifying land for growing trees for fiber and/or carbon sequestration. We also briefly considered the opportunities to grow long fiber—pines or conifers for pulp, paper, and container operations and markets. Our analysis assumed that northern hemisphere countries, which have established land markets and extensive development, were less likely to accommodate

[1] Unlike commercial plantations, costs for restoration plantings have not been well systematized or extensively documented, making it difficult to extrapolate findings from one country and situation to another. In addition, local conditions and the degree to which planting sites have been degraded can vary widely, complicating the development of global benchmark costs for restoration.

major increases in the area of planted forests, so were excluded from the analysis. Africa was also excluded, largely due to increased risks and uncertainties related to governance, property rights, and financing challenges, and the low likelihood of significantly expanding the area of existing planted forests and woodlots (Payn et al. 2015).

METHODS

We first approached this question of how to plant much greater incremental areas of trees in Latin America and Asia in any single country by analyzing secondary information from publicly available literature about the forest sector, forest plantations, and forest restoration. Then, we developed another approach and screened land use types from the FAO land cover database to estimate forest restoration opportunities. Last, we compared our results with the previous literature to draw more robust and country-specific conclusions.

Figure 1 depicts the research process and methods we used to assess the most likely places in Latin America and Asia to plant new acres for industrial wood fiber or for carbon sequestration. Our approach to finding possible places to plant trees in these regions started with a review of the recent global planted forest literature providing future trajectories of planted forest area by countries under varying socioeconomic futures (e.g., Korhonen et al. 2021 and Nepal et al. 2019). We then sorted and ranked these available global planted forest projections by highest to lowest projected planted forest area in Latin America and Asia. This was followed by a review of literature and screening FAO databases providing an estimate of forest area restoration potential globally (e.g., Shyamsundar et al. 2021, Fagan et al. 2021, FAO (2023) FAOSTAT databases on land cover). Finally, we combined these key sets of information to identify countries in Latin America and Asia with the largest incremental forest planting forest restoration potentials. Those planting opportunities could fall under policy and management alternatives for forest regeneration and restoration, improved forest management, or forest conversion. Both large-scale and small-scale owners are needed to plant large areas.

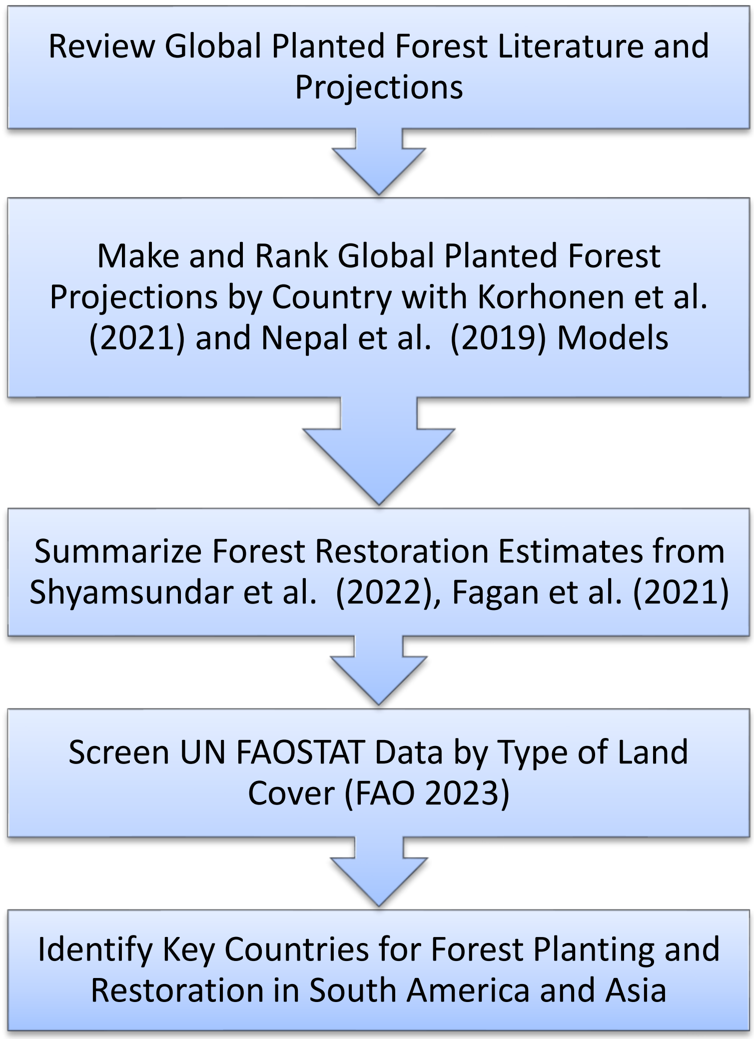

Figure 1. Process for identifying best-planted forest country prospects.

Global planted forest projections by country

Various efforts and approaches have been used to estimate forest plantation areas and to make future projections of planted areas. The standard and largely accepted measure of planted forest areas is that made by the Food and Agriculture Organization of the United Nations (FAO) as part of their estimates made every five years. Based on those data, various researchers have made projections of future planted forest areas by country (Payn et al. 2015, d'Annunzio et al. 2015, Buongiorno and Zhu 2014, and Carle and Holmgren 2008), which were updated and expanded in Nepal et al. (2019) and Korhonen et al. (2021).

The country-level data we utilized were collected by FAO for 2015 and projected to 2070 in Nepal et al. (2019) and 2100 in Korhonen et al. (2021). Nepal (2019) and Korhonen et al. (2021) were used as a primary source for planted forest area projections by country, which relied on similar data and approaches. They used the FAO planted forest data up to 2015 and the economic and demographic projections represented by the five U.N. Shared Socioeconomic Pathways (SSPs) to derive their planted forest area projections under varied sets of assumptions for the amount of global GDP growth and distribution of income, as well as the varied SSP economic, institutional and environmental policies as drivers for planted forests.

Condensing the description from Korhonen et al. (2021), SSPs describe different socio-economic, technological, environmental, and policy futures of the world, with varying degree of challenges for climate change mitigation and adaptation. SSP1 and SSP5 represent visions of the wealthiest and most equal future worlds with the least population growth. While SSP5 envisions a world that is reliant on fossil fuels, SSP1 characterizes a more sustainable outlook for the world, emphasizing the de-carbonization of society through low consumption growth and improved energy efficiency. SSP2 represents a world vision that more closely reflects a continuation of recent historical socio-economic trends. In contrast, SSP3 and SSP4, compared to other SSPs, envision poorer and unequal worlds, where SSP4 represents the most unequal world in terms of economic and technological development, investment in human capital and environmental emissions (O'Neill et al. 2017). We used SSP2 as the base for the analyses and comparisons we made in this paper.

Nepal et al. (2019) also used the Global Forest Products Model (GFPM) to forecast the total forest area for all regions of the world as a separate component, based on the plantation projections. Nepal et al. (2019) assumed increases in global population and economic development would largely drive linear proportional increases in planted forest areas for the rest of the century. Korhonen et al. (2021) focused only on forest plantations, positing that increases in planted forest area would follow a quadratic "Kuznet's curve" approach in relation to per capita income, where increases in planted areas by country increased initially as the population in a country became wealthier, and then diminished with increasing economic development.

Nepal et al. (2019) evaluated how planted forests lead to different global forest product market outcomes for each SSP, compared to corresponding outcomes where planted forests are not considered separately. The projected global planted forest area in 2070 ranged from 379 million ha for SSP3 (a relatively poor and unequal world) to 475 million ha under SSP5 (a relatively wealthier and more equal world), representing respective increases of 46% and 66% compared to 2015. SSPs with the highest planted forest area increases have the lowest product prices (down by 12% by 2070, compared to SSP5 without planted forests) and higher global forest products production and consumption quantities (by as much as 3.3% by 2070, compared to SSP5 without planted forests). However, production did not increase in all countries by similar amounts, due to changes in relative advantages in production brought about by reduced product prices.

Korhonen et al. (2021) estimated increasing global planted forest area trends for the next three to four decades and declining trends thereafter, commensurate with the quadratic functions employed. The projections indicated somewhat less total future planted forest area than prior linear forecasts. Compared to 293 million ha of planted forests globally in 2015, SSP5 (a vision of a wealthier world) projected the largest increase (to 334 million ha, a 14% gain) by 2055, followed by SSP2 (a continuation of historical socio-economic trends, to 327 million ha, or an 11% gain), and SSP3 (a vision of a poorer world, to 319 million ha, a 9% gain). The projected trends for major world regions differed from global trends, consistent with differing socio-economic development trajectories in those regions.

The projections by both papers started at the same base data levels and gradually diverged over the 21st century as global economic development increased moderately. Since we were really interested only in finding non-industrialized countries or regions that might have the capacity to plant 10 million ha in the short run—say 10 or 20 years—both the Nepal et al. (2019) and Korhonen et al. (2021) projections were useful as they remained relatively close for this time period. Korhonen et al. (2021) had data for more countries, made longer projections, and focused only on planted forest trends, so we used those projections to search for the most likely countries.

Historical and projected planted forest area data

The combined historical and projected data on planted forests were available at five-year intervals from 2015 to 2100 for major world regions and selected countries. We sorted the files first by the total planted forest area by country in the base year of 2020 for our study to understand where planted forest areas were already most common, assuming that the countries that already had sufficient land, climate, precipitation, institutional, governance, and interest in planting trees would probably be most likely to increase that effort with the right public and private cooperation and incentives. In fact, empirical data on past forest plantation areas essentially incorporate all global and country biological, economic, social, and institutional factors into their outcomes, and statistical projections of those trends should be the best indicator of future plantation areas, ceteris paribus.

These projections also provide some guidelines on constraints and opportunities by country. The total land area can provide an absolute limit on the area that can be planted (e.g., Central America), and even in countries with large amounts of land (e.g., Brazil), other more valuable agricultural land uses (e.g., soybeans, sugar cane) will prevent many conversions to planted forests.

Similarly, countries that do have large areas of forests also may have opportunities to increase or enhance their forest area. This could occur through (1) afforestation more new forests; (2) reforesting existing forests after harvests; or improved forest management of existing stands—based on using current forest lands or converting other suitable land uses entirely into forests or into mixed agroforestry lands. These approaches could produce roundwood for timber or household consumption, biodiversity, or ecological services, including forest carbon storage. The existing forest area is also indicative of the current climate conditions in countries and presents a clear limit (e.g., Australia) or opportunity (e.g., Indonesia) for planting more new forests and having them survive and prosper.

In addition to the cooperative research team efforts by Korhonen et al. (2021) and Nepal et al. (2019) on global forest plantation trends and projections, Fagan et al. (2021) examined the historical expansion of tree plantations across tropical biomes. Third, Shyamsundar et al. (2022) published a seminal article that covers possible forest restoration efforts for small forest land or tenure rights owners throughout the world. We review these past efforts here to provide prior estimates of past reforestation efforts. Then we describe a new approach that we developed based on Korhonen et al. (2021) projected FAO planted forest trends and additional FAO land cover data in order to provide quantitative estimates of the potential for global tree planting. Last, we compare the estimates from these four approaches to make conclusions about the prospects for individual countries to plant 10 million ha of forests, or other possible major incremental forest land expansions.

Identifying the best regions and countries for smallholder forest restoration

Concurrent with the work by Korhonen et al. (2021), Shyamsundar et al. (2022) summarized extensive research about the prospects for planting or restoring forests as partial stands or dispersed trees or monocultures throughout the world on smallholdings, which is a key to at least part of our project goal to find the desired millions of hectares anywhere. In addition, Fagan et al. (2021) studied the historical expansion of tree plantations across tropical biomes. We also summarized those publications about global planted forests expansion patterns as part of our research methods.

In their research approach, Shyamsundar et al. (2022) identified a large amount of potential area for forest restoration that could be economically and socially attractive to grow planted trees to store carbon with an incentive payment of $20 per ton of carbon equivalent in excess of business as usual (BAU), in various systems on smallholder lands throughout the tropics. This large total area of 546 million ha of land includes a range of three sources for reforestation—crop, pasture, and degraded forest land with less than 30% forest or tree cover—and four levels of reforestation intensity—agrosilviculture, silvopasture, woodlot/plantation, and forest restoration (Figure 2). Most of these include mixed use of people, homes, villages, and scattered trees, so they would not be equivalent to industrial plantation efforts.

Figure 2. A depiction of how forestlands that underwent land use change to become croplands, pasturelands, or degraded forestlands can incorporate smallholder tree cover restoration to become agrosilviculture, silvopasture, woodlots or plantations, or restored forests (Shyamsundar et al. 2022).

Screen UN FAO data for restoration prospects on brush and pasture lands by country

Areas that would be useful for planting new trees, either in monocultures, less dense agroforestry configurations, or to increase stocking in savannahs, would certainly be most likely in regions that have large amounts of degraded forests or other poorly stocked areas where forest restoration could occur. These areas would already be biophysically capable of producing forests—the minimum criterion needed for tree planting. Furthermore, although they might be degraded, cutover, or partially occupied by current populations, restoration or enrichment planting within standing forests might also be possible if the tricky social mix between forests and restoration, use, establishment costs, property rights, and harvest were resolved. That is no guarantee of success, but it should be the right place to start.

In order to find areas that had substantial areas of degraded, brushy, or cutover forest lands, we used an excellent FAO (2023) land cover database that identifies all major land cover types in the world by country.

Our integrative review started with the global planted forest area projection data by country reported by Korhonen et al. (2021) and screened it in Excel to find the best biophysical characteristics for tree planting for countries in Latin America and Asia. The data and separate tabs for each step are contained in the supplementary material titled: "Projected planted forest area for SSP2, based on quadratic model." SSP2 is a projection of approximate current global economic and social trends.

Then we supplemented that data with the FAO (2024) data on Land Cover Types from FAO (2023). We screened that data for Asia and Latin America, in order to merge the detailed planted forest data from Korhonen et al. (2021) and the current land uses by country. The steps we followed are summarized in Figure 3. Appendix A lists the specific steps taken to perform the analyses.

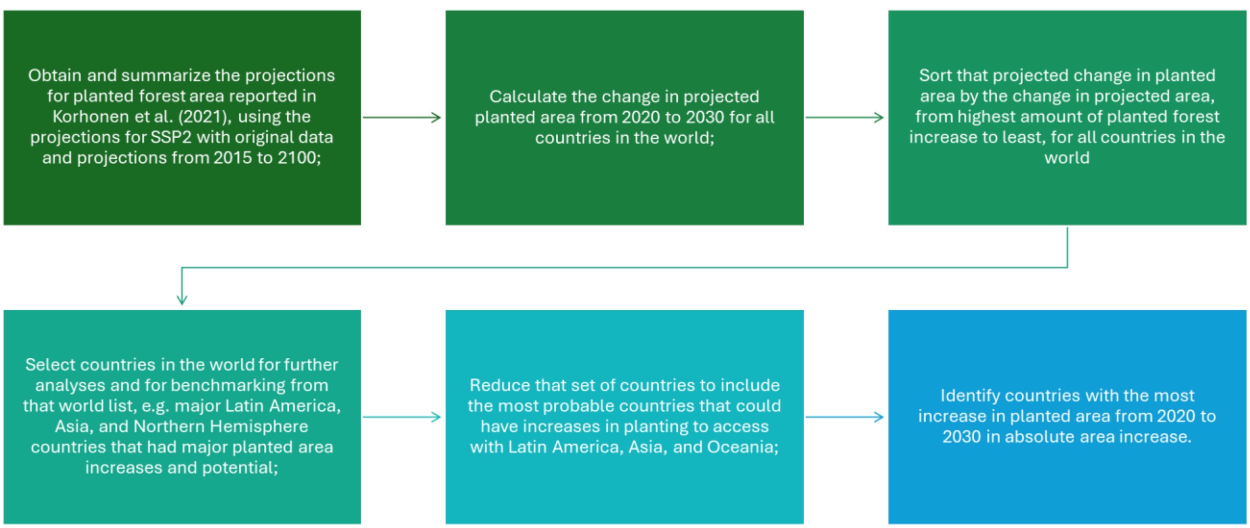

Figure 3. Our empirical research methods summary for estimating possible land areas for additional planted forests.

We used the FAO (2023) data to identify which countries had the most numerical potential areas of degraded areas, brushy areas, grasslands, or existing forests. This final third Excel tab then provided an integrated basis for analyzing the countries in Latin America and Asia with the most projected increase in planted forest area by Korhonen et al. (2021) and the relevant FAO areas of their key shrub and grassland total area—which would meet the criteria of areas that might have biophysical prospects for forest restoration or planting.

RESULTS

Our results section begins with a summary of the research by Shyamsundar et al. (2022) and Fagan et al. (2021). The section continues with quantitative summaries drawing from our prior research by Korhonen et al. (2021). The results then close with detailed summaries of our new calculations derived from the FAO data of 2023.

Smallholder tree cover restoration

Shyamsundar et al. (2022) estimated the areas of low-cost forest restoration, which they defined as requiring incentives to small-holders that do not exceed US$20 tCO_2^{-1}. They concluded that by 2050, low-cost restoration will be feasible within 280, 200, and 60 million hectares (540 million ha total) of tropical croplands, pasturelands, and degraded forestlands, respectively. These areas potentially affect 210 million people in croplands, 59 million people in pasturelands and 22 million people in degraded forestlands (Table 1). In countries with low-cost tropical restoration potential, smallholdings comprise a significant proportion of agricultural lands in Asia (~76 %) and Africa (~60 %) but not the Americas (~3%). Thus, while the Americas account for approximately half of 21^{st} century tropical deforestation, smallholder-based reforestation may play a larger role in efforts to reverse recent forest loss in Asia and Africa than in the Americas. Shyamsundar et al. (2022) show that countries with low-cost restoration potential largely lack policy commitments or smallholder-supportive institutional and market conditions generally considered necessary to provide sufficient incentives for tree planting.

Table 1. Potential low-cost (US$20 tCO_2^{-1} incentives) forest restoration areas by type of land use in each continent.

Tropical Regions	Crop		Pasture		Degraded		Total	
	Million Ha	%	Million Ha	%	Million Ha	%	Million Ha	%
Asia	94.1	72%	25.4	19%	11.0	8%	130.5	100%
Africa	93.3	39%	108.9	45%	39.1	16%	241.2	100%
Latin America	96.8	56%	69.9	40%	7.7	4%	174.3	100%
Total	284.1	52%	204.2	37%	57.7	11%	546.0	100%

Source: Totals in hectares converted from km^2 in Shyamsundar et al. (2022)

Based on their integrated social-economic research, Shyamsunder et al. (2022) also estimated the area for 83 countries with the most low-cost reforestation potential, as well as for the 20 countries with the most potential area that could support and be converted to some type of reforested area, as reproduced in Table 2.

The Shyamsundar research and identification of the 20 most promising countries for forest restoration does provide a good reference for the countries that might achieve the target 10 million ha goal. However, it does not focus narrowly on industrial wood fiber potential nearly as much broad forest carbon, nor just on forest plantations. It also includes all tropical forest regions in the world and large amounts of cropland areas that might be available for low-intensity forest restoration efforts but not for commercial forest plantations. It did not include some countries that also could provide industrial wood fiber, such as Argentina, Uruguay, and Paraguay, and included other prospects that are not politically feasible for foreign investors or for sufficient domestic capital, such as Venezuela.

Table 2. "Policy, institutional and market context for 20 tropical countries with the largest low-cost restoration potential. One-third of the countries have a reforestation-related quantitative NDC policy commitment. No country falls within the top quartile for any governance or market indicator, pointing to policy and institutional barriers to smallholder tree-cover restoration. (Shyamsundar et al. 2022)."

	Restoration potential (km^2)	Quantified NDC	Governance index	Tenure security index	Score for enabling business of agriculture	Minutes to market from reforestable areas
Brazil	843,253		-0.18	74	75	87
Congo, Dem. Rep.	809,997	✓	-1.61	NA	30	127
Indonesia	423,308		-0.17	63	NA	68
Angola	305,239	✓	-0.87	NA	27	187
Colombia	221,888		-0.14	65	82	96
Tanzania	216,290		-0.56	64	57	113
Mexico	200,519		-0.37	79	69	53
Central African Republic	147,531	✓	-1.58	NA	NA	150
Côte d'Ivoire	130,496		-0.50	59	46	44
Myanmar	124,620		-0.95	75	31	127
Venezuela, RB	116,186		-1.78	72	NA	109
Thailand	115,404	✓	-0.20	72	59	36
Cameroon	107,934		-1.12	55	22	87
Mozambique	106,571		-0.77	57	51	119
China	105,041	✓	-0.36	75	70	63
Philippines	104,861		-0.31	51	68	28
India	94,434	✓	-0.11	64	62	46
Malaysia	85,336		0.43	54	52	52
Vietnam	85,206	✓	-0.33	82	61	35
Zambia	82,834		-0.45	70	64	106

*"**Color code.** For restoration potential: is >250,000 km^2; is 100,000-250,000 km^2, is 50,000-99,999 km^2, and below 50,000 km^2 (in SI only) (source: Fig. 1, Busch-Erbaugh dataset). For the other indicators, colors show whether the country falls within the 4th (in SI only); 3 rd ( ); 2 nd ( ) or 1 st ( ) quarter of countries for the indicator. Quarters are calculated based on the available data from all countries worldwide (between 101 and 202 country depending on the indicator). **Definitions. Reforestation potential:** the total area (km) in a country that could be reforested with a US$20 tCO_2^{-1} incentive in Fig. 2 (Busch-Erbaugh dataset). **Quantified Nationally Determined Contributions (NDC):** Countries whose NDCs include an explicit quantitative target on reforestation related to mitigation and/or adaptation (source: (IUCN, 2020)). **Governance Index:** the average score of the six World Governance Indicators of the World Bank in 2019. These indicators are voice and accountability; political stability and absence of violence; government effectiveness; regulatory quality; rule of law; and control of corruption. **Tenure Security Index:** the percentage of people who believe it is very unlikely or unlikely that they could lose the right to use their property or part of it against their will in the next 5 years (source: PRINDEX, https://www.prindex.net/data/). **Score for enabling the business of agriculture:** the average 2019 country score calculated by the World Bank (https://eba. worldbank.org/en/eba). It is based on eight core indicators for supplying seed; registering fertilizer; securing water; registering machinery; sustaining livestock; protecting plant health; trading food; and accessing finance. **Distance to market in restoration areas:** the median travel time, in minutes, between a town or city and the areas with restoration potential of Fig. 2 (Source: own calculation based on the Busch-Erbaugh dataset and distance to market from (Nelson et al., 2019)." **Cubbage et al. author note for area conversions:** There are 100 ha in a km^2. Thus, Brazil would have 84 million ha of potential; Indonesia 42 million ha; Zambia 8 million ha, etc.*

Of the areas identified by Shyamsundar et al. (2022), 58 million ha are degraded forest lands, and 204 million are pasture lands. These areas are the most likely prospects for commercial or industrial plantations. They are not, however, suggested to be best for monoculture industrial wood fiber per se. As shown in Figure 2, they might have a mix of silvopasture, agrosilviculure, woodlots and plantations, and restored natural forests.

Shyamsundar et al. (2022) also present and discuss a pithy diagram of the factors that present problems for forest restoration programs. That is reproduced here as well for reference as Figure 4. As it states, to achieve forest restoration, programs must solve technical and biophysical challenges; economic and financial factors; social and cultural factors; and policy and institutional components. Overcoming all of these factors would require an effort far greater than just finding land that was biologically and technically suitable, and would require overcoming immense socioeconomic challenges.

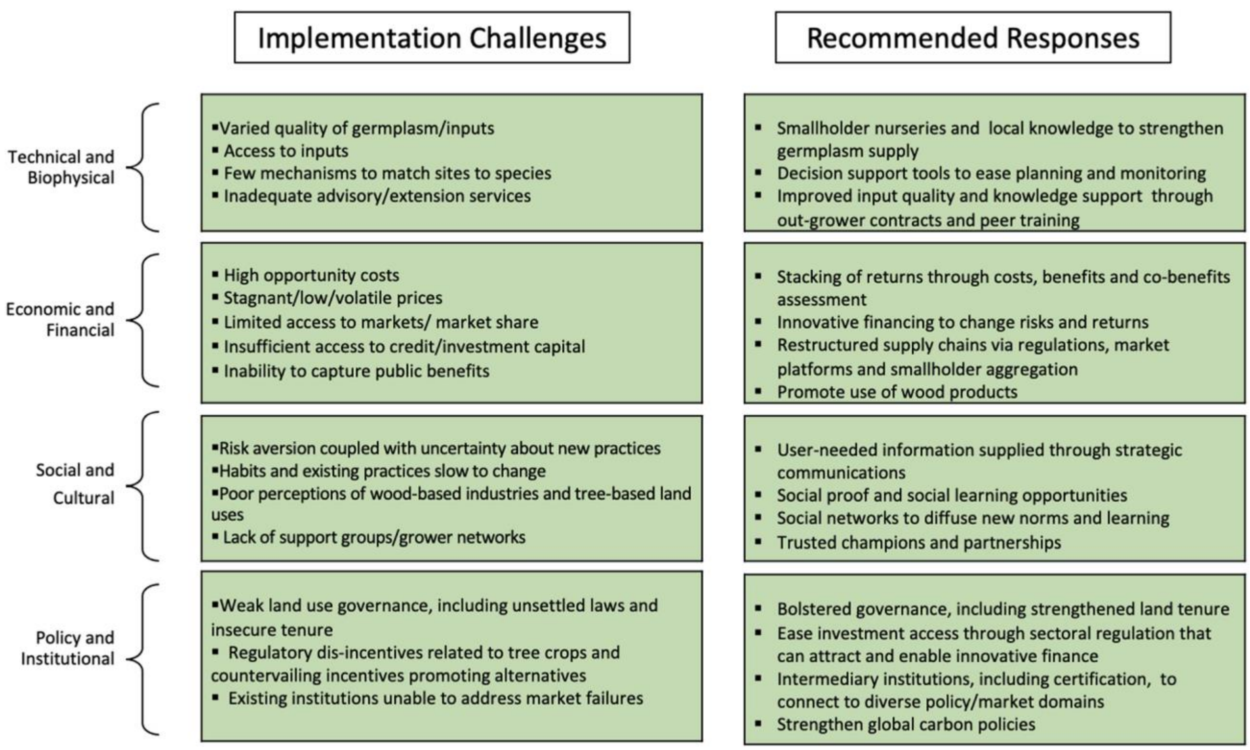

Figure. 4. "A typology of challenges and potential and demonstrated solutions associated with implementing smallholder tree cover restoration projects based on discussions with experts. (Shyamsundar et al. 2022)."

Any of these challenges could and has presented high hurdles to overcome, so the current planted and restored forest area is much less than the prospective areas that Shyamsundar et al. (2022) have identified. Overcoming all of these challenges would require unprecedented global, country, organizational, and small-landholder cooperation and funding. An increase to achieve these areas or to meet the 10 million ha target for industrial wood fiber or forest carbon sequestration in any country also would require extensive private investment levels and supportive public policies. However, the Shyamsundar research objective does clearly identify the possibilities and set an aspirational policy goal for forest carbon restoration for global consideration and development in order to ameliorate global climate change.

There are other constraints or more details that can be added to those in Figure 4. While not the only constraint, simply establishing seedling nurseries in each country with sufficient land and capacity to scale up to such large production numbers is a foundational technical challenge that must be surmounted. Others include unclear property rights and land titling; environmental impacts from planting monocultures or exotics, perceived or real, and competing land uses (mainly livestock and agriculture). In addition, planting at these large levels would increase the demand for inputs and the marginal costs for forest planting and restoration, reducing affordable tree planting as well.

In addition, there are many challenges in working with small producers. These include the need to implement effective outreach and extension programs targeted to their skill levels, cultural, and socioeconomic situation; reconcile competing land uses at the farm level; and manage increasing transaction costs that come from multitudes of small operators and landowners, rather than a few large ones. They also must resolve land tenure problems, to ensure that landholders have rights to plant, manage, and perhaps harvest or utilize trees for forest carbon and wood products. Forest planting costs also will differ by land area, with larger tracts presumably being less expensive per ha since they spread fixed administrative costs over a larger land base.

Tropical forest restoration

Fagan et al. (2021) studied the historical expansion of tree plantations across tropical biomes. Their extended summary of results about global expansion patterns also bears quoting for its description of regions and countries where plantations occurred between 2000 and 2012, which provides empirical insights about where they might be viable in the near future as well, as paraphrased below:

Between 2000 and 2012, tree cover gains from plantations were similar to those from natural forest regrowth, with about 32.2 million ha of new plantations and 31.6 million ha of natural regrowth observed globally. Although there were a large number of persistent natural regrowth patches, individual plantation patches were more numerous and about 4.9 times the size of regrowth areas. Most plantation expansion happened in Asia and Latin America, driven by the cultivation of a few key tree crops, such as oil palm and rubber, particularly in Asia and Latin America. In Africa, the plantation expansion represented a significant portion of the land area in several countries. Although the predicted expansion was the smallest, Africa is emerging as a new frontier for oil palm expansion.

The expansion of tropical tree plantations was noticeable in the humid tropical biome, although plantations also expanded to non-humid biomes, especially in grasslands, savannas and shrublands in eastern Africa and southeast Latin America (14% of the predicted global plantation area), with variability in area estimates. Plantation expansion was concentrated in biodiversity hotspots such as the Sundaland, Cerrado and Atlantic Forest ecosystems—collectively 92.8% of the total plantation area. Natural regrowth was distributed more evenly across all biomes.

The majority (82.8%) of the increased plantation area was in Indonesia, Brazil, Malaysia, and China, with plantations generally located near navigable waterways and in highly human-dominated landscapes, reflecting the influence of global trade. Meanwhile, natural regrowth was more commonly observed along deforestation frontiers, with overlapping occurrence of plantation expansion and natural regeneration in specific areas like Indonesia and Western Africa.

Projected planted forest trends in South America and Asia

The broad analyses and screens described above are contained in the paper's two supplementary material appendices as Excel spreadsheets, as is a third summary spreadsheet that has the highlights for the best 29 countries that have complete data, and two that are similar and bear listing for later if desired. These supplementary spreadsheets are:

1. Projected Global Planted Forest Area by Country, which has the various screening tabs described above,
2. Projected Global Planted Forest Area and Other Land Cover Types from FAO (2023) with Potential for Tree Planting, and
3. Projected Planted Forest Area, Cover Types, Forest Area, and Land Area for the Best Countries for Tree Planting.

The third attached spreadsheet has the key summary statistics and is used here for excerpts to look at quickly and discuss about which key countries we selected for detailed analyses. Table 3 shows the list of the top 25 countries in the world in rank order by their total planted forest area as of 2020. It also includes the projected planted area change from 2020 to 2030, taken from Korhonen et al. (2021). Table 4 presents a list of the top 25 countries in Asia and Latin America, and six other relevant countries for benchmarking, which we selected as prospects for increasing planted forest area.

Table 3. Top 25 countries in the world with planted forests, 2015-2030 (drawn from Korhonen et al. 2021).

Country / Region	2015	2020	2030	Change (2020-2030)
	------------------------Thousand ha-------------------			
China	78,982.00	82,027.46	83,445	1,417.70
United States of America	26364.00	27,017.44	28,187.28	1,169.84
Russian Federation	19,841.00	19,916.69	19,808.90	-107.79
Canada	15,784.00	16,308.99	17,217.95	908.96
India	12,031.00	13,389.82	15,301.45	1,911.64
Sweden	13,737.00	14,063.43	14,576.25	512.81
Japan	10,270.00	10,198.50	9,945.94	-252.56
Poland	8,957.00	9,017.83	8,958.08	-59.75
Brazil	7,736.00	8,035.37	8,484.72	449.35
Sudan	6,121.00	6,818.33	8,241.97	1,423.64
Finland	6,775.00	6,869.47	7,021.03	151.56
Indonesia	4,946.00	5,368.47	5,931.01	562.54
Germany	5,295.00	5,285.68	5,260.15	-25.53
Ukraine	4,860.00	4,961.50	4,990.17	28.68
Viet Nam	3,663.00	4,058.37	4,537.20	478.83
Thailand	3,986.00	4,111.41	4,297.80	186.38
Turkey	3,386.00	3,540.19	3,807.66	267.47
Chile	3,044.00	3,145.83	3,316.64	170.81
Spain	2,909.00	2,945.89	2,982.84	36.94
United Kingdom	2,716.00	2,764.76	2,831.01	66.24
Czech Republic	2,643.00	2,678.61	2,732.21	53.60
Malaysia	1,966.00	2,076.47	2,286.18	209.71
New Zealand	2,087.00	2,159.03	2,279.76	120.73
Australia	2,017.00	2,106.53	2,264.19	157.66
France	1,967.00	2,002.11	2,054.55	52.44
South Africa	1,763.00	1,843.91	1,984.58	140.67

Table 4. Ranked list of 25 key countries in Asia and Latin America with planted forests and country comparisons, 2015-2030 (drawn from Korhonen et al. 2021).

Country / Region	2015	2020	2030	Change (2020-2030)
	------------------------Thousand ha-------------------			
China	78,982.00	82,027.46	83,445	1,417.70
India	1,2031.00	13,389.82	15,301.45	1,911.64
Brazil	7,736.00	8,035.37	8,484.72	449.35
Indonesia	4,946.00	5,368.47	5,931.01	562.54
Viet Nam	3,663.00	4,058.37	4,537.20	478.83
Thailand	3,986.00	4,111.41	4,297.80	186.38
Chile	3,044.00	3,145.83	3,316.64	170.81
Spain	2,909.00	2,945.89	2,982.84	36.94
Malaysia	1,966.00	2,076.47	2,286.18	209.71
New Zealand	2,087.00	2,159.03	2,279.76	120.73
Australia	2,017.00	2,106.53	2,264.19	157.66
South Africa	1,763.00	1,843.91	1,984.58	140.67
Philippines	1,245.00	1,358.58	1,573.44	214.85
Argentina	1,202.00	1,245.29	1,309.37	64.07
Peru	1,157.00	1,209.88	1,276.82	66.94
Myanmar	944.00	1,032.28	1,151.90	119.62
Uruguay	1,062.00	1,082.40	1,101.26	18.85
Portugal	891.00	900.20	912.37	12.17
Venezuela	557.00	594.01	653.73	59.72
Lao PDR	113.00	122.63	134.55	11.92
Paraguay	98.00	104.52	118.46	13.94
Mexico	87.00	90.91	97.63	6.72
Panama	80.00	84.61	91.77	7.16
Cambodia	69.00	77.25	90.71	13.45
Colombia	71.00	74.88	81.46	6.58
Ecuador	55.00	58.36	64.32	5.96
Nicaragua	48.00	50.82	56.23	5.41
Costa Rica	18.00	18.90	20.43	1.54
El Salvador	16.00	16.28	16.71	0.43
Belize	2.00	2.12	2.32	0.20
Honduras	na			
Papua New Guinea	na			

Table 5 presents the same list of countries, sorted in alphabetical order, and background information on total forest and land area also for reference.

Table 5. Alphabetical list of 25 key countries in Asia and Latin America with planted forests and 6 country comparisons (planted forests and projections from Korhonen et al. 2021, forest areas from FAO 2020).

Country / Region	2015	2020	Planted area Change (2020-2030)	Forest area 2020	Country area (FAO 2004)
	---Thousand ha---				
Argentina	1,202.00	1,245.29	64.07	28,573	273,669
Australia	2,017.00	2,106.53	157.66	134,005	768,230
Belize	2.00	2.12	0.20	1,277	2,280
Brazil	7,736.00	8,035.37	449.35	496,620	845,942
Cambodia	69.00	77.25	13.45	8,068	17,652
Chile	3,044.00	3,145.83	170.81	18,211	74,880
China	78,982.00	82,027.46	1,417.70	219,978	932,742
Colombia	71.00	74.88	6.58	59,142	103,870
Costa Rica	18.00	18.90	1.54	3,035	5,106
Ecuador	55.00	58.36	5.96	12,498	27,684
El Salvador	16.00	16.28	0.43	584	2,072
Honduras	na	0.00		6,359	11,189
India	12,031.00	13,389.82	1,911.64	72,160	297,319
Indonesia	4,946.00	5,368.47	562.54	92,133	181,157
Lao PDR	113.00	122.63	11.92	16,596	23,080
Malaysia	1,966.00	2,076.47	209.71	19,114	32,855
Mexico	87.00	90.91	6.72	65,692	190,869
Myanmar	944.00	1,032.28	119.62	28,544	65,755
New Zealand	2,087.00	2,159.03	120.73	9,893	26,799
Nicaragua	48.00	50.82	5.41	3,408	12,140
Panama	80.00	84.61	7.16	4,214	7,443
Papua New Guinea	na	61.00		35,856	45,286
Paraguay	98.00	104.52	13.94	16,102	39,730
Peru	1,157.00	1,209.88	66.94	72,330	128,000
Philippines	1,245.00	1,358.58	214.85	7,189	29,817
Portugal	891.00	900.20	12.17	3,312	9,150
South Africa	1,763.00	1,843.91	140.67	17,050	121,447
Spain	2,909.00	2,945.89	36.94	18,572	49,944
Thailand	3,986.00	4,111.41	186.38	19,873	51,089
Uruguay	1,062.00	1,082.40	18.85	2,031	17,502
Venezuela	557.00	594.01	59.72	46,231	88,205
Viet Nam	3,663.00	4,058.37	478.83	14,643	32,549

Next, for reference, Table 6 presents the list of possible planted areas in the world by continental region.

Table 6. Areas potentially suitable for tree planting by continental region (drawn from Korhonen et al. 2021).

World Region	2015	2020	2030	Change (2020-2030)	2040	Change (2020-2040)	2050
	--Million ha------------------------------------						
Africa	16.28	17.95	21.31	3.36	24.59	6.64	27.59
Asia	128.75	134.97	140.76	5.79	141.51	6.54	139.31
Europe	85.59	86.54	87.37	0.82	87.49	0.95	87.60
N/C America	43.31	44.53	46.66	2.14	48.36	3.83	49.77
Oceania	4.34	4.51	4.82	0.30	5.06	0.55	5.27
South America	15.02	15.59	16.45	0.86	16.99	1.40	17.25
World	293.28	304.10	317.37	13.27	324.00	19.90	326.79

Analyses of FAOSTAT (2023) land cover types with tree planting potential

Last, Table 7 presents the summary Land Cover Type Analyses for Areas that might have tree planting potential based on screening the FAOSTAT (FAO 2023) data, with the countries that we consider most likely to be able to plant large areas (although probably not 10 million ha) of forests highlighted in bold. For reference, Figure 5 presents information about precipitation patterns from Cobon et al. (2017), which are a key limit on forest distribution.

Table 7. Summary of land cover type with tree planting potential for selected key countries (drawn from FAO 2023).

Country / Cover Type	Shrub	Shrub &/or herbaceous veg.	All shrub total	Grassland	All shrub & grass total	Herbaceous crop	Tree-covered areas	All possible cover types
				Thousand ha				
Argentina	**63,979**	**2,394**	**66,373**	**85,952**	**152,325**	**34,827**	**61,415**	**248,567**
Australia	449,889	623	450,512	175,941	626,453	30,192	83,924	740,568
Belize	-	6	6	227	233	12	1,882	2,127
Brazil	**3,129**	**2,455**	**5,584**	**187,473**	**193,057**	**38,703**	**604,831**	**836,591**
Cambodia	7	157	164	2,872	3,036	5,062	9,545	17,643
Chile	4,160	1,288	5,447	9,202	14,650	613	23,689	38,951
China	**1,374**	**2,212**	**3,585**	**277,435**	**281,020**	**135,074**	**270,468**	**686,563**
Colombia	**378**	**241**	**619**	**9,193**	**9,812**	**586**	**99,970**	**110,367**
Costa Rica	2	4	5	320	325	52	4,057	4,434
Ecuador	75	106	181	1,751	1,932	801	20,340	23,074
El Salvador	0	10	10	34	43	256	1,439	1,738
Honduras	2	27	29	562	591	248	10,199	11,038
India	**9,246**	**741**	**9,987**	**21,529**	**31,516**	**195,711**	**54,918**	**282,145**
Indonesia	**32**	**568**	**600**	**3,726**	**4,326**	**8,901**	**155,078**	**168,305**
Lao PDR	**1**	**51**	**52**	**2,363**	**2,415**	**585**	**20,063**	**23,062**
Malaysia	1	37	38	936	974	311	29,448	30,733
Mexico	41,130	371	41,501	44,622	86,124	13,259	82,975	182,358
Myanmar	5	328	333	4,064	4,396	13,461	47,305	65,162
New Zealand	18	121	139	8,513	8,652	102	14,261	23,015
Nicaragua	11	26	38	809	846	430	10,208	11,485
Panama	1	6	7	259	266	36	6,145	6,447
Papua N.G.	7	87	94	689	782	82	39,934	40,798
Paraguay	-	146	146	3,834	3,980	2,520	33,364	39,864
Peru	3,964	290	4,254	32,761	37,015	1,175	79,259	117,448
Philippines	1	85	86	1,304	1,390	3,330	17,741	22,462
Portugal	16	34	50	2,226	2,276	1,398	4,639	8,313
South Africa	46,795	40	46,836	57,312	104,147	7,214	7,242	118,603
Spain	5,229	118	5,346	12,432	17,779	13,349	16,235	47,363
Thailand	29	236	266	3,387	3,653	21,074	24,690	49,417
Uruguay	0	90	90	10,649	10,740	634	6,116	17,489
Venezuela	235	262	497	20,744	21,241	981	67,307	89,529
Vietnam	**10**	**796**	**806**	**1,794**	**2,600**	**5,405**	**21,783**	**29,788**

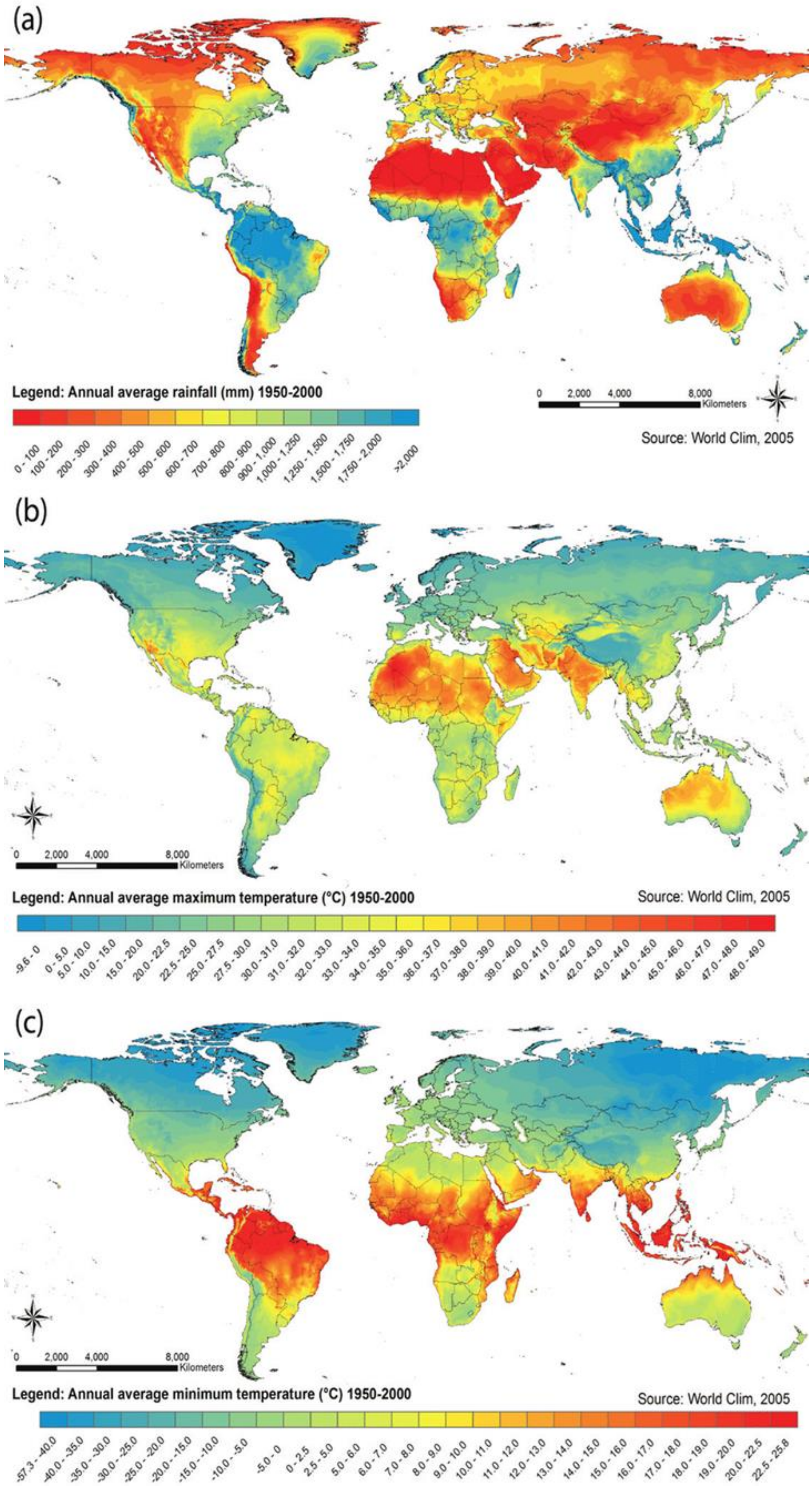

Figure 5. Global precipitation and temperature maps (Cobon et al. 2017).

DISCUSSION

After these extensive background efforts at collecting and analyzing the existing literature, secondary information, and the data analyses presented above, we can make some suggestions about countries that possibly can plant large areas of new forests, and indeed, if we wanted to make a longer list, those that cannot.

Two of the research efforts reviewed above—Korhonen et al. (2021, Tables 4 and 5) and Shyamsundar et al. (2021, Table 2) report projected and possible tree planting areas, respectively, for individual countries in Asia and Latin America. Fagan et al. (2022) did not publish results by country. Our analyses of land cover types with tree planting potential based on FAOStat data are summarized in Table 7. The specific countries that were considered by each study differed somewhat, so direct comparisons of the total area identified for tree planting are not possible.

In general, the projections by Korhonen et al. (2021) based on the UN SSPs had the lowest level, with modest linear increases in plantation area from 2020 to 2030. Shyamsundar et al. (2021) were consistently more optimistic about the area possible for forest restoration, with identified opportunities of area increases of up to ten times or more greater than the Korhonen et al. (2021) data. Our empirical estimates of the "All shrub and grassland" areas available for planting were mixed. All of our country estimates were greater than Korhonen et al. Some of our countries had less potential area than Shyamsundar et al., and a few large countries in particular—Brazil, China, and Argentina—had much greater potential areas than Shysamsundar et al.

Can we plant 10 million ha per country?

First, the extensive efforts made to summarize existing data about planted forest data indicate that the likelihood of any country planting an additional 10 million ha of forests in the next decade is extremely small. Despite the apparent inability to find 10 million ha to plant in any single country in the near future, there are many places where substantial areas could be planted or restored, as indicated by Shyamsundar et al. (2022) and Fagan et al. (2021) articles, and our FAOSTAT data analyses. In addition, if one were seeking large-scale commercial planting sufficient for forest products mills, much smaller areas of, say, 100,000 to 150,000 ha of fast-growing plantations would be needed to support them. In the case of forest carbon plantings, "smaller" holdings of

10,000 ha or more would be significant, and a large number of those or even smallholder farm ownerships could be assembled to achieve large tree plantings in aggregate.

Second, those countries with the most opportunities are apt to plant deciduous or hardwood species such as Eucalyptus spp. or Acacia spp. In contrast, there are few countries with large tree planting potential that are likely to plant long fiber/coniferous species in Latin America or Asia. There still may be opportunities for industrial manufacturing expansion from northern hemisphere natural softwood forests or from the United States.

Third, if the global community wants to plant 1 trillion trees of any species, or the equivalent of about 1 billion ha, the prospects seem very unlikely. As noted, it would take 100 countries planting an additional 10 million ha to reach such a goal. As of 2020, there are only seven countries in the world that have planted 10 million ha in the last 50 years or more (see Table 3). In order, these include China, the United States of America, the Russian Federation, Canada, India, Sweden, and Japan (Table 3). There almost surely is not enough degraded, poorly stocked, or open land, willing owners, institutional capacity, infrastructure, talent, government and public willpower, or money to even come close to the about 100 countries to plant this much new forests to reach the 1 trillion tree goal.

Fourth, if one wanted to seek to plant more trees, our approach of detailed forestry and institutional knowledge of most important countries; conversations with other experts; and analysis of FAO planted forest and land cover data can help narrow the list of about 180 countries in the world down to a small number that could accommodate substantial increases in planted forest, or even natural forest, cover. This could include the 20 tropical countries, including in Africa, identified by Shyamsundar et al. (2022) that could economically restore more than 8 million ha each.

Alternately, the 25 key global countries that already have the most planted forests—of 2 million ha or more—as summarized by Korhonen et al. (2021); or the somewhat similar 31 Latin America, Asian, and benchmark countries from FAO and Korhonen et al. (2021) would be reasonable places to plant more, although many of those are in the northern hemisphere. And our FAO data screening suggests that there are about 20 countries in Asia and Latin America that have enough shrubland and pasture land (~5 million ha or more) or total shrub, grass, and forest land area (20 million ha) and precipitation to plant 10 million ha.

These three approaches generate overlapping countries, with perhaps about 30 countries in the world with significant biological and institutional capacity to plant 10 million ha with concerted increases in policy, technical, and financial efforts. This would achieve 30% of the Trillion Trees goal, with massive new efforts and funding. In addition, it would approximately double the current planted forest area in the world in a short time, which would be a substantial accomplishment itself.

Where can we plant the most?

Based on our summary of planted forest FAO data, there are about 13 countries in the world with more than 5 million ha of planted forests, including the seven 10 million ha countries above. The rest are Poland, Brazil, Sudan, Finland, Indonesia, Germany, and the Ukraine. Nine of these 13 countries with more than 5 million ha of planted forests are actually temperate northern and developed countries that have been planting forests for decades or even a century. China reports that it has about 80 million ha of planted forests. This would lead the world with more than one-quarter of the global current planted forest area of about 300 million ha. However, very little of that area consists of commercial industrial forest plantations—probably less than 5 to 10 million ha, but this is not identified separately in their statistics.

The projections by Korhonen et al. (2021) in Table 3 indicate that only India (1.9 million ha), China (1.4 million ha), Sudan (1.4 million ha) and the United States of America (1.2 million ha) were projected to have an increase in forest cover of more than 1 million ha from 2020 to 2030, followed closely by Canada with 0.9 million ha. Indonesia, Sweden, and Vietnam were projected to increase their area of forest by about one-half million ha in this period. All of the other countries were projected to increase by less than about 0.25 million ha of planted forests, and Russia and Japan were projected to decrease slightly. And the recent civil war in Sudan surely will both destroy forests and halt any significant new planting forests.

Based on past trends and biophysical and economic conditions, Korhonen et al. (2021) projected all global planted forest areas to increase 13.26 million ha from 2020 to 2030, and 19.9 million ha from 2020 to 2040. No single continent was projected to increase its planted area more than six million ha during this decade, or the next (Table 6). So, based on global trends and country conditions, planting 10 million ha of trees in any single country, much less in multiple countries is not only unlikely, it is unachievable. The top 30 or so could biologically and geographically have enough land area for the restoration of forests, but of course, there are still competing current uses of those lands and challenges engaging with landholders with diverse tenure rights and ownership objectives. The technical, financial, social, and policy constraints for planting trees on this land still would need to be overcome, in countries with scarce resources of all of these factors.

The integrated remote sensing, economic analyses, and expert opinion approach used by Shyamsundar (2022) estimated the most potential area of 540 million ha for several types of forest restoration in the tropics, including on cropland, pasture land, and degraded forest land (Table 3). In Latin America and Asia, the greatest prospects from Shyamsundar et al. (2022) were Brazil (84 million ha), Indonesia (42 million ha), Colombia (22 million ha), Mexico (20 million ha), and Myanmar, Venezuela, Thailand, China, Philippines, India, Malaysia, and Vietnam (12 million ha to 9 million ha).

While the list of prospective countries identified by Shyamsundar et al. (2022) seems reasonable, their estimate of the very large area available for planting or restoring forests on lands held by small-scale farmers in those countries seems quite optimistic. It is worth noting that the 540 million ha total would comprise about one-half of the Trillion Trees (billion ha) goal, which also is an encouraging aspirational goal. And having such estimates can help inform discussions of how to overcome the four broad classes of biophysical, economic, social, and institutional challenges.

The analysis by Fagan et al. (2021) in the Pantropics provided data for the increase in planted forests and natural forests between 2000 and 2012, which provides a good benchmark for our 10 million ha target. They found that there were quite similar gains in the area of planted forest and persistent natural growth, of about 32 million ha each, during this period. They found that expansions were predicted to increase the most in Asia, followed by Latin America. Their predicted plantation expansion was concentrated (83%) in four large countries—Indonesia, Brazil, Malaysia, and China. Tree plantation expansion was significantly higher in humid tropical biomes. Plantations were more likely than natural growth to occur near navigable waterways and highly human-dominated landscapes. However, they found that there was a planted forest expansion of 32 million ha in 12 years for the world (2000-2012). While this provides empirical evidence that planted forests increased significantly over the 12-year period, the total area would still only amount to three 10 million ha increments spread over the world—not in three countries.

Table 7, which we derived from FAO (2023), does present a huge number of shrub or herbaceous areas of 40 million ha or more in some countries, including Australia, Argentina, Mexico, and South Africa, although many of these areas may be too dry to be suitable for forests. It also finds that there are very large shrub or herbaceous areas of about 4 million ha or more in Brazil, Chile, China, India, Peru, and Spain. The reported grassland cover areas are less predictable about being suitable for forest cover, especially due to limited rainfall. But these shrub or herbaceous areas are the least likely to have competing agriculture grazing or possible crop uses.

The tree-covered areas reported in Table 7 are also quite large, and a total of 1.8 billion ha in South America and Asia. These lands can biologically grow forests, but whether they can be converted to planted forests; how much is degraded and usually politically acceptable for such conversions; and the technology, accessibility, and capital required to do so are major questions. There also are issues with real or perceived environmental impacts with planting monocultures or exotics and the need for environmental assessments and mitigation measures. Opposition by environmental groups and nongovernment organizations to the conversion of grasslands and peatland to planted forests also is apt to constrain planting in these ecosystems.

Recall that our analysis focused largely on tree planting efforts on open or cleared lands, presumably of monocultures of exotic or native species. Shyamsundar et al. (2022) examined a much broader range or forest restoration efforts, and were able to identify larger land areas that could support some amount of restoration at much lower tree densities, and thus would generate less wood fiber or forest carbon. Improved forest management (IFM) of existing forests also is another approach that could store forest carbon, or perhaps produce more commercial wood fiber and preserve or manage current forest land more efficiently. For example, the forest loss in the tropics between 2002 and 2023 was around 3 million acres per year (WRI 2024), negating any carbon sequestration from planted trees. These complexities of planted forests, forest restoration, and IFM contributions to forest carbon storage and their costs surely would require substantial further analyses. In addition, avoided conversion of forest lands to other uses is the third major component of keeping forests and the carbon they store, albeit beyond the scope of this paper.

CONCLUSIONS

Overall, planting 10 million ha of trees in any single country in Latin America or Asia by 2030 is extremely unlikely, and there is surely no chance that coniferous or pine species, the preferred pulp and paper source with stronger long fibers for kraft bag and box products, will increase by that much. While no single country is apt to plant 10 million ha of forests in the next decade, many could assemble substantial areas of a hundred thousand to several million ha that would be sufficient to support new pulp and paper mills, solid wood forest products firms, or major forest carbon plantings.

In terms of the physical planting area, the prospective area for planting monoculture wood fiber plantations is less than for establishing agro/silvopasture plots and restoring forests. On the other hand, planting trees for carbon sequestration in areas where timber markets are weak or nonexistent could potentially lead to large increases in planted areas. Shyamsundar et al. (2022) suggest that smallholders can plant trees in a variety of configurations at reasonable incentive costs in addition to business as usual (BAU). However, they list a large number of implementation challenges to overcome, with considerable costs and institution-building and reform. Forest carbon storage payments also are quite low, and would need to increase to be attractive for many owners. The average price for one ton of CO_2e sequestered from forestry and land use projects in the Voluntary Carbon Market is about US $5.80 (Forest Trends' Ecosystem Market Place 2022). In comparison, the World Bank (2023) estimates that a price of about US $61-$122 per ton of CO_2e would be needed to incentivize the development of carbon sequestration projects.

As always, there are many opportunities for further research both on the potential biological area for forest plantations, or on the substantial economic, technical, institutional, cultural, or policy constraints that limit such massive plantings. These issues will be additional crucial challenges that must be overcome to reach any of the ambitious goals identified in all tree-planting initiatives and on-the-ground efforts. These subjects are beyond the scope and length of this paper but surely need to be resolved or improved for expanded forest restoration everywhere in the world.

In summary, our analyses can help understand where prospects for significant tree planting could potentially take place. We examined several key references that projected planted forest areas, identified past trends and increases in forest areas, or analyzed global forest and rural land data and socioeconomic databases and social science surveys. These provide a robust picture of increasing planted forests in the world and identify key constraints and opportunities. Nonetheless, one must conclude that the prospects for achieving massive increased planting, such as proposed by the Trillion Trees effort or various other global programs, is unlikely.

The trends may change with use of different SSPs, and Nepal et al. (2019) and Korhonen et al. (2021) make projections for five selected SSPs in more detail. In addition, changing climate will certainly alter the viability of plantations as analyzed by all four key approaches summarized here, and illustrated in Figure 6. Climate change could increase growth and precipitation in some regions, and decrease growth due to drier climates and increased biotic and abiotic pathogens and threats in others.

We do believe that the prospects for seeing the projected increases based on past trends from Korhonen et al. (2022), for a mix of commercial wood fiber and some fuel and forest carbon, are quite achievable. And some forest carbon production in forest restoration projects has quite reasonable incremental costs of less than $20 per t$CO_2$ increase over BAU at current planting and restoration scales per Shyamsundar et al. (2022).

A recent global analysis of the southern hemisphere provides more context about the extent and range of costs for planted and natural forest regeneration for forest carbon purposes (Busch et al. 2024). They reported a median abatement cost through natural regeneration of US$23.80 per t$CO_2$ (Interdecile Range, US$3.60-79.70 per t$CO_2$). The median abatement cost through plantations was similar at US$23.00 per t$CO_2$ (Interdecile Range, US$14.80-724 per t$CO_2$), revenue generated through the sale of wood products helped to lower overall costs (Busch et al. 2024). The large interdecile ranges indicate considerable spatial variation in forest carbon abatement costs for both natural regeneration and plantations. Thus, choosing the more cost-effective method at each site, or in some cases the only method that is feasible, results in an even lower median abatement cost (US$12.50 per tCO2) than only using one method everywhere.

These results about carbon storage costs from planted and restored forests from the previous references indicate that forests offer a reasonably low-cost, practical alternative for capturing carbon and ameliorating climate change. They also provide diverse nature-based solution co-benefits as well such as biodiversity, soil and erosion protection, water quality and quantity benefits, livestock health, and, indeed, wood products that also store carbon. For comparison, costs for experimental direct carbon capture systems are estimated to exceed $100 per tCO_2. So forests can be used efficiently; moderate areas of land and sufficient technical knowledge already exist; and landowners are quite often amenable to accepting incentives to include planted trees in degraded forest or farm landscapes.

Furthermore, planting trees surely has captured the almost unanimous support and goodwill for a broad diversity of voluntary or mandatory programs. For example, in a Pew Foundation survey in the U.S., Kennedy et al. (2023) found that of six major policy alternatives of ways to capture carbon, planting about a trillion trees ranked first, with 87% of Republicans and 91% of Democrats agreeing with that statement. This was by far viewed the most favorably by Republicans—better than sealing methane gas leaks (77%), providing tax credits (67%), or taxing corporations for emissions (50%). Democrats favored all carbon capture alternatives more than Republicans, but planting trees was liked the most by all survey respondents.

Analysts, investors, communities, governments, and nongovernment organizations could also make their own analyses drawing from our research approach or the results presented here. These results can help identify the biophysical prospects for industrial or commercial planted forests by other possible private sector firms, and for use in industry strategic planning considerations. They also can help inform the prospects and scale of investments needed for public tree planting programs for achieving broad forest carbon or industrial wood products goals. Certainly, massive tree planting for either wood fiber or forest carbon sequestration will be challenging not only because finding land suitable for tree growing is limited, but also because of the additional challenges in growing and managing trees under changing climate and socioeconomic circumstances. These analyses at least help identify countries where those opportunities are most realistic and be extended and applied for other tree planting or forest restoration programs and policies.

CONFLICTS OF INTEREST

The authors confirm there are no conflicts of interest.

REFERENCES CITED

1t.org. A platform for the trillion tree community. Initiative by WEF. 2020. Available from https://www.1t.org/. [accessed 19 April 2020].

Brancalion PHS, Chazdon RL. 2017. Beyond hectares: four principles to guide reforestation in the context of tropical forest and landscape restoration. Restoration Ecology 25 (4): 491-496. https://doi.org/10.1111/rec.12519

Busch J, Bukoski JJ, Cook-Patton SC, Griscom B, Kaczan D, Potts MD, Yi Y, Vincent JR. 2024. Cost-effectiveness of natural forest regeneration and plantations for climate mitigation. Nature Climate Change. https://doi.org/10.1038/s41558-024-02068-1

Buongiorno J, Zhu S. 2016. Using the Global Forest Products Model (GFPM version 2016 with BPMPD). Staff Paper Series # 85. Department of Forest and Wildlife Ecology, University of Wisconsin-Madison. 37 p.

Carle J, Holmgren P. 2008. Wood from planted forests: A global outlook 2005-2030. For. Prod. J. 58, 6-18. https://doi.org/10.1079/9781845935641.0047

Cobon DH, Baethgen WE, Landman W, Williams A, van Garderen EA, Johnston P, Malherbe J, Maluleke P, Kgakatsi IB, Davis P. 2017. Agroclimatology in grasslands. Chapter in: Agroclimatology in grasslands. https://doi.org/10.2134/agronmonogr60.2016.0013

Cubbage F, Rubilar, R, Mac Donagh, P, Kanieski Da Silva B, Bussoni A, Morales, V, Balmelli, G., Lord V, Hernández C, Zhang, P, Ha Tran Thi Thu, Yao, R, Hall, P., Korhonen J, Luis Díaz-Balteiro, Roque Rodríguez-Soalleiro, Davis R, Chudy, R, De La Torre R, Lopera G, Somvang Phimmavong, Garzón, S, and Cubas-Baez A. 2022. Comparative global timber investment costs, returns, and applications, 2020. Journal of Forest Business Research, 1(1), 90-121. Accessed on August 13, 2023. https://doi.org/10.62320/jfbr.v1i1.16

d'Annunzio R, Sandker M, Finegold Y, Min Z. 2015. Projecting global forest area towards 2030. For. Ecol. Manage. 352,124-133. https://doi.org/10.1016/j.foreco.2015.03.014

Fagan ME, Kim Do-Hyung, Settle W, Ferry L, Drew J, Carlson H, Slaughter J, Schaferbien J, Tyukavina A, Harris NL, Goldman E, Ordway EM. 2021. The expansion of tree plantations across tropical biomes. Nature Sustainability. https://doi.org/10.1038/s41893-022-00904-w

FAO. 2004. Global forest resources assessment update 2005: Terms and definitions. FAO working paper no. 83/E, Food and Agriculture Organization of the United Nations, Rome. Italy

FAO. 2023. Global Land Cover Types by Country, 2022. Available from: https://www.fao.org/faostat/en/#data/LC. Accessed 15 January 2023.

FAO. 2022. The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome, FAO. 166 p.

FAO. 2020. Global Forest Resources Assessment 2020, Main Report. Food and Agriculture Organization of the United Nations. Rome, Italy. https://www.fao.org/documents/card/en?details=ca9825en. Accessed on January 18, 2024. https://doi.org/10.4060/ca9825en

Forbes Ecology. 2022. Review of actual forest restoration costs, 2021. Contract Report prepared for Te Uru Rākau - New Zealand Forest Service. New Zealand. https://www.mpi.govt.nz/dmsdocument/50209-Review-of-actual-forest-restoration-costs-Contract-Report-Prepared-for-Te-Uru-Rakau-New-Zealand-Forest-Service-November-2021. Accessed on September 3, 2024.

Forest Trends' Ecosystem Marketplace. 2022. The art of integrity: state of voluntary carbon markets, Q3 Insights Briefing. Washington DC: Forest Trends Association.

Hol KD, Brancalion PH. 2020. Tree planting is not a simple solution. Science, 368(6491), 580-581. https://doi.org/10.1126/science.aba8232

International Tropical Timber Organization (ITTO). 2020. Guidelines for forest landscape restoration in the tropics. Policy Development series no. 24. International Tropical Timber Organization. Japan. https://www.itto.int/direct/topics/topics_pdf_download/topics_id=6511&no=1&disp=inline. Accessed on September 3, 2024.

IUCN (International Union for the Conservation of Nature). 2015. Forest landscape restoration. https:// www.iucn.org/about/work/programmes/forest/fp_our_work/fp_our_work_thematic/fp_our_work_ flr/. Accessed 4 Sept 2019.

Kennedy B, Funk C, Tyson A. 2023. Majorities of Americans prioritize renewable energy, back steps to address climate change: but many foresee problems ahead with transition to renewables and oppose breaking from fossil fuels altogether. Pew Research Center, 2023. http://www.jstor.org/stable/resrep57333. Accessed 9 September 2024.

Korhonen J, Nepal P, Prestemon JP, Cubbage FW. 2021. Projecting global and regional outlooks for planted forests under the shared socio-economic pathways. New Forests (2021) 52:197-216. https://doi.org/10.1007/s11056-020-09789-z

Lamb D. 2014. Large-scale forest restoration. Routledge. New York. https://doi.org/10.4324/9780203071649

Nepal P, Korhonen J, Prestemon P, Cubbage FW. 2019. Projecting global planted forest area developments and the associated impacts on global forest product markets. J. Environ. Manage. 240: 421-430. https://doi.org/10.1016/j.jenvman.2019.03.126

O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, van Ruijven BJ, van Vuuren DP, Birkmann J, Kok K, Levy M, Solecki W. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42: 169-180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

Payn T, Carnus J-M, Freer-Smith P, Kimberly M, Kollert W, Liu S, Orazio C, Rodriguez L, Sliva LN, Wingfield MJ. 2015. Changes in planted forests and future global implications. For. Ecol. Manage. 352, 57-67. https://doi.org/10.1016/j.foreco.2015.06.021

Shyamsundar P, Cohen F, Boucher TM, Kroeger T, Erbaugh JT, Waterfield G, Clarke C, Cook-Patton SC, Garcia E, Juma K, Kaur S, Leisher C, Miller DC, Oester K, Saigal S, Siikamaki J, Sills EO, Thaung T, Trihadmojo B, Veiga F, Vincent JR, Yi Y, Zhang XX. 2022. Scaling smallholder tree cover restoration across the tropics. Global Environmental Change 76 (2022) 102591. https://doi.org/10.1016/j.gloenvcha.2022.102591

United Nations (UN) Climate Summit. 2014. New York declaration on forests. UN Headquarters, New York, NY.

World Bank. 2023. State and Trends of Carbon Pricing 2023. © http://hdl.handle.net/10986/39796 License: CC BY 3.0 IGO."URI https://openknowledge.worldbank.org/handle/10986/39796. Accessed November 28, 2023.

World Economic Forum. 2020. One trillion trees - World Economic Forum launches plan to help nature and the climate. https://www.weforum.org/agenda/2020/01/one-trillion-trees-world-economic-forum-launches-plan-to-help-nature-and-the-climate/. Accessed September 5, 2024.

WRI. 2024. World Resources Institute. Retrieved on 9/5/2024. Accessed at: https://research.wri.org/gfr/latest-analysis-deforestation-trends. 5 September 2024.WRI, 2024.

APPENDIX A. RESEARCH METHODS SUMMARY FOR ESTIMATING POSSIBLE LAND AREAS FOR ADDITIONAL PLANTED FORESTS

In order to find areas that had substantial areas of degraded, brushy, or cutover forest lands, we used FAO (2023) land cover database that identifies all major land cover types in the world by country. Our process is summarized below.

1) Obtain and summarize the projections for planted forest area reported in Korhonen et al. (2021), as provided with details by country from Prakash Nepal, using the projections for SSP2 economic assumption levels—a continuation of current economic trends, with original data and projections from 2015 to 2100;
2) Use that base tab and then calculate the change in projected planted area from 2020 to 2030 for all countries in the world;
3) Sort that projected change in planted area by the change in projected area, from highest amount of planted forest increase to least, for all countries in the world;
4) Select the most promising and relevant countries in the world for potential further analyses and for benchmarking from that world list, e.g. major Latin America, Asia, and Northern Hemisphere countries that had major planted area increases and potential;
5) Reduce that set of countries to just include the best possible countries that could have increases in planting to Latin America, Asia, and Oceania;
6) Use that same set and sort alphabetically for ease of reference;
7) Use that same set, reduced to highest potential countries; and
8) Use that same set and sort them by countries with the most increase in planted area from 2020 to 2030 in absolute area increase.

Then the last component of our data screening followed the steps numbered below.

1) Copy the original source tab that had all the countries in world as new file for projections from 2015 to 2100.
2) Copy the columns with the Latin American and Asia and projections for 2020 to 2050 and changes from 2020 to 2030 and 2020 to 2040 as a second tab for the land cover analyses.
3) Use the FAO data on land cover and pull it down for the key types of land use that could be used for tree planting, or possibly forest restoration. These categories included:

- Shrub-covered areas
- Shrub &/or herbaceous vegetation
- All shrub covered, total of above two categories
- Grassland
- All shrub and grassland, total
- Herbaceous crops
- Tree covered areas
- All possible cover areas

SUPPLEMENTAL DATA SOURCES AND DERIVED FOREST AREA AND PROSPECTS IN EXCEL TABLES

1) Excel spreadsheet: Projected Planted Forest Area for SSP2, Based on Quadratic Model.
2) Excel spreadsheet: Projected Planted Forest Area (Korhonen et al. 2021) and Other Land Cover Types from FAO (2023) with Potential for Tree Planting.
3) Excel spreadsheet: Projected Planted Forest Area, Cover Types, Forest Area, and Land Area for the Best Countries for Tree Planting.