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Scaling smallholder tree cover restoration across the tropics

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ABSTRACT

Restoring tree cover in tropical countries has the potential to benefit millions of smallholders through improvements in income and environmental services. However, despite their dominant landholding shares in many countries, smallholders' role in restoration has not been addressed in prior global or pan-tropical restoration studies. We fill this lacuna by using global spatial data on trees and people, national indicators of enabling conditions, and micro-level expert information. We find that by 2050, low-cost restoration is feasible within 280, 200, and 60 million hectares of tropical croplands, pasturelands, and degraded forestlands, respectively. Such restoration could affect 210 million people in croplands, 59 million people in pasturelands and 22 million people in degraded forestlands. This predominance of low-cost restoration opportunity in populated agricultural lands has not been revealed by prior analyses of tree cover restoration potential. 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 21st 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. Furthermore, our analyses show that countries with low-cost restoration potential largely lack policy commitments or smallholder supportive institutional and market conditions. Discussions among practitioners and researchers suggest that four principles – partnering with farmers

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and prioritizing their preferences, reducing uncertainty, strengthening markets, and mobilizing innovative financing – can help scale smallholder-driven restoration in the face of these challenges.

1. Introduction

Large-scale tree planting in agricultural and degraded lands is envisaged by international initiatives such as the UN Decade on Ecosystem Restoration (UN Decade on Restoration [WWW Document], n.d), the Bonn Challenge to restore 350 million hectares of degraded landscapes by 2030 (The Bonn Challenge | Bonn Challenge," n.d), and nationally determined contributions (NDC) to the Paris Agreement. Yet, persistent concerns remain about the feasibility and social desirability of substantive increases in tree cover. These concerns relate to implementation challenges (Coleman et al., 2021; Mansourian et al., 2021), potential threats to food security (Fleischman et al., 2020; Peña-Lévano et al., 2019), water supplies (Jackson et al., 2005) and biodiversity from large-scale tree planting, especially in non-forest biomes (Bond et al., 2019; Fleischman et al., 2020), market risks (Binkley et al., 2020), and possible exacerbation of inequities from ignoring local socio-economic realities (Elias et al., 2021a). Misgivings about whether large-scale tree cover increases can deliver global climate and biodiversity (Coleman et al., 2021; Gopalakrishna et al., 2021; Lewis et al., 2019), or local socio-economic, benefits (Adams et al., 2016; Hofflinger et al., 2021; Malkamäki et al., 2018; Nilson et al., 2021; Valencia, 2021) and whether they can be sustained when not driven by local priorities (Coleman et al., 2021; Pritchard, 2021), suggest the need for a more inclusive approach to tree cover restoration. Such an approach would promote a portfolio of activities (e.g., woodlots, agroforestry, natural regeneration, industrial plantations) in different land classes and tenure systems through deliberate engagement with diverse actors, including rural smallholders.

Prior forest restoration studies at global or tropical scales (Bastin et al., 2019; Brancalion et al., 2019; Busch et al., 2019; Griscom et al., 2020, 2017; Strassburg et al., 2020) have not distinguished and evaluated the potential importance of restoration by smallholders. While much is known about what motivates investments in tree planting by institutional investors, corporations and governments (Binkley et al., 2020; Cubbage et al., 2020; Nepal et al., 2019) and the factors that influence tree planting by individual smallholders (Amare and Darr, 2020), the combination of conditions necessary to achieve large increases in smallholder tree planting is poorly understood (Castle et al., 2021; Miller et al., 2020; Ota et al., 2020). This gap in the literature is all the more important because 94 percent of farms (572 million) globally that support crop and livestock production have landholdings that are 5 ha or smaller, accounting for 18 % of farmland (Lowder et al., 2021). Smallholdings (5 ha or less) are a particularly significant component of the landscape in low- and lower middle-income countries (LLMICs), accounting for approximately 72 % and 60 % of farmland, respectively (Lowder et al., 2021). In tropical regions of the world, which are the focus of this study, smallholders operate an estimated 30 % of agricultural land, producing more than 70 % of regional food calories (Samberg et al., 2016). In addition to private lands, smallholders also utilize sizable tracts of communal and Indigenous lands. Indigenous Peoples hold rights to and use nearly 4 billion ha of agricultural and forest land (Garnett et al., 2018).

Here we address the relative neglect of smallholder restoration strategies by bringing together three types of data: global, spatially explicit data on trees and people, national data on indicators of enabling conditions, and expert knowledge on farmer needs at the local level. We use the term *smallholder tree cover restoration* to refer to intentional actions performed by smallholder households or communities to grow trees on land that was originally forested but currently lacks tree cover. Smallholder tree cover restoration includes agroforestry (incorporating trees into cropland (i.e., agrosilviculture) or pastureland (i.e., silvopasture)), woodlot and plantation development, and other means of restoring tree cover on private, communal, or public lands (Nair, 2005) (Fig. 1). We focus on tropical countries because of their great biophysical potential for restoration and their large numbers of smallholders.

Smallholder tree cover restoration provides a vital opportunity to combine climate change mitigation with the pursuit of other sustainable development goals. Smallholders live in highly biodiverse and threatened landscapes (Erbaugh et al., 2020; Samberg et al., 2016) and are exposed to multiple hazards, including climate change (Cohn et al., 2017), with women farmers being particularly vulnerable because of prevailing discriminatory norms and institutions (Isgren et al., 2020; Jost et al., 2016). Their demographic strength, role in rural land-use decisions, and exposure to poverty and food insecurity make smallholders key stakeholders in determining where and how to restore tree cover. Knowing the geographies where relatively low-cost incentives could promote smallholder tree cover restoration and the populations of these lands will help clarify where and how many smallholders could engage in, potentially gain from, or need assistance with tree cover restoration.

In this article, we broadly identify the locations, land use distribution, and populations in tropical areas where tree cover restoration may be feasible at low cost, defined here as requiring incentives to smallholders that do not exceed US\$20 tCO_2^{-1}. This threshold reflects the high end of prices on California and European carbon markets at the end of 2019 (Busch et al., 2019). Due to various data limitations, including a lack of subnational data on smallholder presence, the locations we identify should not be treated as specific targets for restoration interventions. Nevertheless, our analysis points to the potential scale and importance of engaging with smallholders, and it paves the way for more careful participatory targeting and design of smallholder-based restoration.

In addition to needing to be attractive to smallholders, restoration will require a set of enabling policies and institutions that can support and incentivize smallholders to restore tree cover (Arvola et al., 2020). Given the consequential role of national governance systems, we examine governance, regulatory, and market conditions in countries with tropical restoration potential to assess how they may shape smallholder restoration. This analysis seeks to identify constraints that are often not reflected in spatial analyses of potential restorable areas. Our examination of indicators for twenty countries with the most low-cost tree cover restoration potential points to critical gaps in enabling conditions, for instance tenure security, which may act as deterrents to restoration if left unaddressed.

While restoration can benefit smallholders, especially farmer-driven investments in tree planting that align design elements and benefits with community needs (Binam et al., 2017; Reyes-García et al., 2019; Seghieri et al., 2021), there are instances of tree planting projects diminishing land use rights and increasing economic hardships (Andersson et al., 2016; Hofflinger et al., 2021; Valencia, 2021). However, some counter examples also showcase how plantations may alleviate poverty (Afonso and Miller, 2021). Recognizing such diverse local realities, we complement our cross-national analysis with information drawn from deliberations among a group of researchers and practitioners related to on-the-ground restoration challenges and solutions in LLMICs. These discussions, together with a review of the literature on restoration practice, offer four broad principles – partnering with smallholders, reducing uncertainty, strengthening markets, and mobilizing innovative financing – that can help increase the scale of smallholder tree cover restoration in the tropics.

2. Material and methods

We first assess the extent of different land use types and the number of people living on lands with potential for low-cost tree cover restoration in the tropics. We then compare countries' performance on indicators of national conditions that can enable smallholder tree cover restoration. Finally, drawing on data from consensus-building expert discussions and literature reviews, we identify local and sub-national implementation challenges and potential solutions.

2.1. Estimating land use and populations in potential restoration areas

To identify dominant land cover and population in areas with potential for low-cost tree cover restoration in the tropics and smallholder land shares, we combine several published and publicly available datasets. These include projections of where low-cost tropical forest restoration is potentially feasible under a US\$20 tCO_2^{-1} financial incentive for forest regrowth (Busch et al., 2019; Erbaugh et al., 2020); agricultural land use (Fritz et al., 2015; Ramankutty et al., 2008); farm size distributions (Lowder et al., 2021); and population ((CIESIN, 2018) in (Erbaugh et al., 2020)).

The data we draw upon to identify areas with potential for low-cost tree cover restoration, henceforth the Busch-Erbaugh data, represent the intersection of spatial datasets that contain information on forest cover change, estimated agricultural revenues, and populations. This dataset identifies ~5.5 km^2 (3 arcmins) grid cells across the tropics that under business as usual and a US\$20 tCO_2^{-1} financial incentive are projected to contain an increase in forest cover between 2020 and 2050 (Busch et al., 2019). The grid cells further contained at least 30 % forest cover in 2000 and population densities below 100 people km^{-2} in 2010 (Erbaugh et al., 2020). Tree cover gain data within the grid cells are based on a predictive model that assumes land operators are as responsive to carbon payments as they are to changes in agricultural revenues but does not account for private costs of active tree cover restoration (e.g., agroforestry, woodlots). Our analysis thus assumes that any such costs are approximately offset by income gains from tree cover (see, for instance, Castle et al., 2021; Tschora and Cherubini, 2020; Sánchez et al., 2022).

The Busch-Erbaugh data contain ~5.5 km^2 grid cells with at least 30 % forest cover in 2000 and low population densities to attempt to exclude urban areas and non-forest ecosystems like native grasslands. While these data represent some of the best available peer reviewed maps of efforts to identify areas with potential for low-cost tree-cover restoration opportunity, they remain limited by the use of a single cost point (US\$20 tCO_2^{-1}), modeling assumptions, such as income gains as the main driver of land cover change, which may not hold true under different conditions (Jones et al., 2020; Kesicki and Ekins, 2012), and a coarse spatial resolution of ~5.5 km^2 grid cells that contain some amount of potential tree-cover restoration. Further, the data do not distinguish the extent to which forest restoration within a grid cell is predicted to occur through "business as usual" regrowth or additional regrowth from the US\$20 tCO_2^{-1} incentive (Busch et al., 2019).

To estimate area and population totals on low-cost restorable lands in crops, pasture, or degraded forest, we intersect the Busch-Erbaugh data with data on the extent of croplands (Fritz et al., 2015) and pasturelands (Ramankutty et al., 2008), which are both 1-km resolution resampled to ~5.5 km^2 grid cells. We avoid double-counting by excluding cropland from the resampled pastureland data, which are less recent and have lower resolution than the cropland data. We identify degraded forestland as areas in the Busch-Erbaugh data that are potentially restorable and are not used for crops or pasture, noting that our definition of degraded forestland excludes grid cells that lost forest cover prior to 2000, i.e., forest areas that were already degraded below 30 % forest cover by 2000. While we refer to this area as degraded forestland, we recognize that it might include smaller mosaics of land uses (e.g., small habitations, or small tracts of cropland, pastureland, recovering forests, or shifting cultivation) in addition to degraded forestland. Within countries, we calculate zonal statistics for the areas

Fig. 1. 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.

and populations within potentially restorable croplands, pasturelands, and degraded forestlands.

To assess the conjunction of low-cost tree cover restoration opportunities and agricultural smallholdings at the national level, we use World Census of Agriculture data (Table S3; Lowder et al., 2021) on average landholding size and land under smallholdings (defined as 5 ha or smaller). We identify smallholder population sizes, average size of land holdings, share of agricultural area in smallholdings, and communally managed lands for the twenty countries with the most low-cost restoration potential (Table S4). Table S4 includes information on communally managed lands because they make up large portions of agricultural lands in many regions, particularly Africa (Wily, 2011a, 2011b), yet available global data on farmlands (Lowder et al., 2021, 2016) do not, generally, include communal lands. Forest-dependent Indigenous Peoples and local communities (IPLC), who undertake agriculture and manage an estimated 15.3 % of global forest land (Rights and Resources Initiative, 2018), are one example of an important demographic group who operate on communal lands.

2.2. Assessing national policy and market conditions

To assess if macro-level conditions are conducive to smallholder restoration, we examine national indicators in the twenty countries with the largest low-cost tree cover restoration potential. The national-level indicators were selected based on a review of the literature and discussions with experts (as described in the next section) about policies and institutions that facilitate smallholder tree cover restoration. They reflect a set of country-level factors that are largely not reflected in the spatial analysis of potentially available low-cost reforestable areas.

Effective promotion of smallholder tree cover restoration depends on enabling conditions such as policy and extension support for tree planting (Arvola et al., 2020; Bragança et al., 2022; Rahman et al., 2017; Sandewall et al., 2015). Moreover, without good governance protecting land-based investments, smallholders may not risk planting trees. Hence, tenure security is an important precondition for catalyzing tree planting investments (Aggarwal et al., 2021; Arvola et al., 2020; Borelli et al., 2019; Rahman et al., 2017; Sandewall et al., 2015; Yi et al., 2014). Not only are formal tenure rules vital, but their perceived legitimacy and tenure security are also important (Larson et al., 2012; Sunderlin et al., 2018). In addition, market institutions that facilitate access to information, credit and market transactions (Arvola et al., 2020; Bettles et al., 2021; Rahman et al., 2017; Vincent et al., 2021) are strong enablers of smallholder restoration. Smallholder tree cover restoration is more likely to increase in countries where smallholders have access to inputs (Lillesø et al., 2021; Miller et al., 2020), technical knowledge (Arvola et al., 2019), output markets (Arvola et al., 2019; Bettles et al., 2021) and capital, particularly rural credit (Nepal et al., 2019; Sikor, 2011), as trees are a long-term investment (Sikor, 2011) that require multiple inputs for processing and sale (Luan, 2019). Areas where smallholders have become a major force in tree planting, such as China and Vietnam, fulfill all or most of the above conditions (Sandewall et al., 2015; Sikor, 2011).

We assess policy commitments to restoration using Nationally Determined Contributions (NDCs) to the Paris Climate Agreement. Although NDCs are non-binding, they can signal a real intention to pursue forest restoration (Arvola et al., 2019). We use data from (IUCN, 2020), which identifies countries with quantitative and/or qualitative forest landscape restoration-aligned mitigation or adaptation-related NDC commitments.

For governance, we use two indicators that represent institutional conditions conducive to smallholder tree cover restoration: the World Bank's World Governance Index (WGI) and PRINDEX, a global index that tracks perceived tenure security across countries. WGI aggregates six dimensions of governance using data from 200 countries: voice and accountability; political stability and absence of violence; government effectiveness; regulatory quality; rule of law; and control of corruption (https://datacatalog.worldbank.org/dataset/worldwide-governance-indicators). The indicators are expressed in units of a standard normal distribution, with mean zero, standard deviation of one, and range from approximately −2.5 to 2.5, with higher values corresponding to better governance. We use the mean of the values of all six indicators as a measure of governance. PRINDEX tracks how an individual feels about the security of their home and their land and property, based on a survey of a nationally representative sample of individual adults (18+) in 140 countries around the world. The tenure security index shows the percentage of people who believe it is very unlikely or unlikely that they will lose the right to use their property or part of it against their will in the next five years (source: PRINDEX https://www.prindex.net/data/, downloaded on 28th August 2021).

We treat markets for agriculture as a proxy for tree-product related markets. We use the World Bank's Enabling the Business of Agriculture (https://eba.worldbank.org/en/eba) index to identify countries with conditions conducive to developing agricultural businesses. We report the average 2019 country score calculated by the World Bank based on eight core indicators: supplying seed; registering fertilizer; securing water; registering machinery; sustaining livestock; protecting plant health; trading food; and accessing finance. We also provide the score on accessing finance separately in the SI.

We use median travel time to markets from restorable areas as an indicator of market access. We calculate the median travel time from low-cost restoration areas to the closest town or city (in minutes) using travel time data from (Nelson et al., 2019). We use the data product that includes all town sizes (Nelson et al., 2019) – from smallest villages to largest cities – to capture all possible markets. Using the spatial extent from the restoration data (in Fig. 2), we calculate travel time to the closest city for each restoration cell, then calculate the median travel time for all low-cost restoration cells in each country.

Some of the data sources underlying the national indicators (EBA, WGI, and PRINDEX) are more recent than the land use data on restorable areas (Busch et al., 2019; Erbaugh et al., 2020; Fritz et al., 2015; Ramankutty et al., 2008) and travel time data (Nelson et al., 2019). Each dataset is subject to methodological limitations and more recent and higher resolution data would improve the accuracy of our results.

2.3. Identifying local challenges and solutions

Even where macro conditions align to enable reforestation, smallholder tree-planting can face many micro-level impediments. Success in tree cover restoration will, in part, depend on subnational realities (Elias et al., 2021a), program design elements (Reyes-García et al., 2019), coalitions and non-state actors supporting restoration (Bettles et al., 2021), and strategies that can surmount prevailing governance hurdles.

To identify sub-national considerations based on transdisciplinary co-produced knowledge (Chambers et al., 2022) that is grounded in local realities (Langston et al., 2019), we draw on information from a group of restoration practitioners and academics. We implemented a survey and organized a two-day in-person workshop with 23 experts (Table S6) in February 2020. We followed this up with a literature review to corroborate and clarify workshop conclusions. Workshop participants, including several authors of this article, are conservation practitioners and researchers working on agroforestry, reforestation, and forest restoration and management in tropical regions. They represent non-governmental and academic institutions, with experience in a range of countries in the Asia-Pacific region (e.g., India, Myanmar, China), South America (e.g., Brazil and Colombia), and Africa (particularly, Kenya, Tanzania, and Zambia).

We combined elements of a standard Delphi survey-based approach and Nominal Group techniques to strengthen participant dialogue and build consensus on critical considerations for smallholder restoration (Landeta et al., 2011). The expert group first responded to a survey on their restoration activities, key challenges, and solutions. The survey

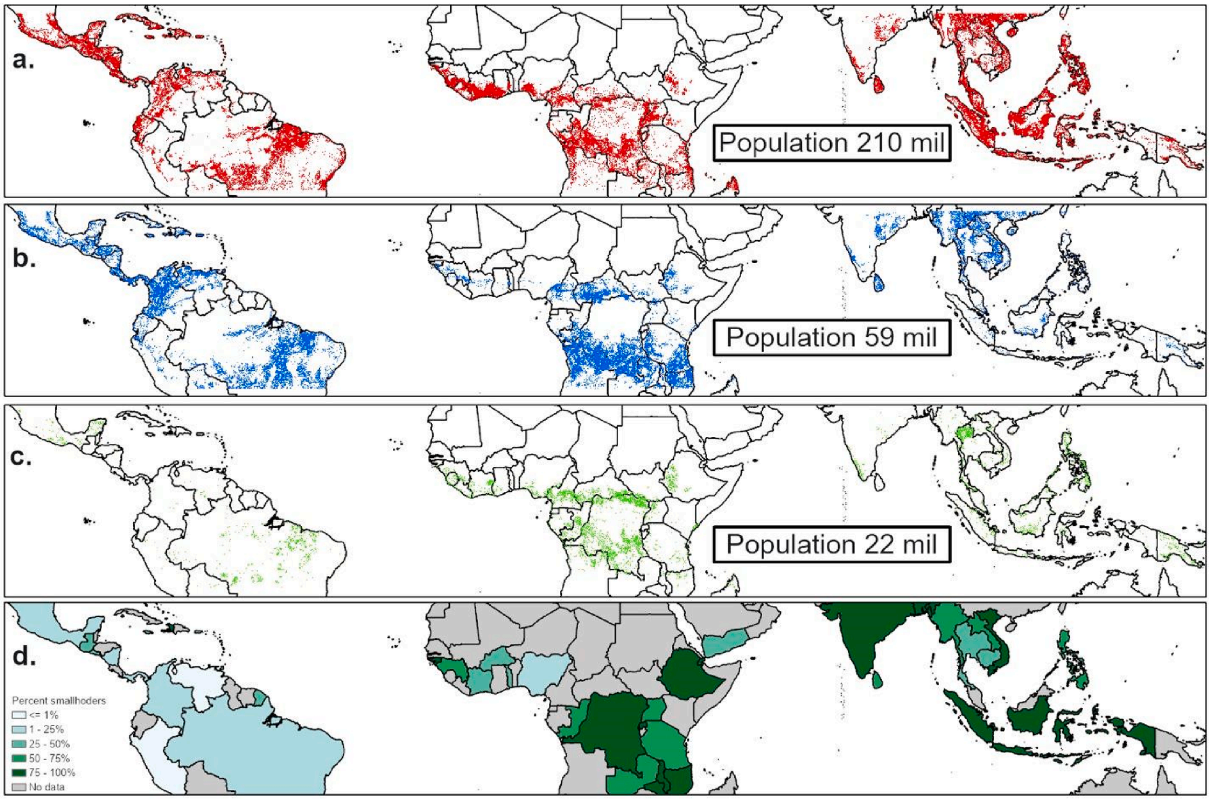

Fig. 2. Panels a-c: Tropical areas with tree cover restoration potential between 2020 and 2050 at an incentive of \$20 tCO_2^{-1} following (Busch et al., 2019) and (Erbaugh et al., 2020), classified according to dominant land use: cropland based on (Fritz et al., 2015), (a), pastureland based on (Ramankutty et al., 2008), (b), and degraded forestland as the residual (c), with population size based on (CIESIN, 2018). Panel d: National percentages of smallholdings in agricultural land area, based on (Lowder et al., 2021).

was based on a literature review of tree cover restoration and agroforestry. During the in-person workshop, the group reviewed survey responses and deliberated on priority concerns for restoration project implementation. Deeper discussions focused on four themes: economic and financial considerations; technical and informational needs; management and extension challenges; and norms, institutions, and policy environments. During day two, participants examined enabling conditions for scaling-up restoration activities and research and learning requirements.

These expert group discussions helped in cataloging key local challenges and solutions for effective restoration. Additionally, we reviewed literature with practical examples of restoration activities and examined data to assess national enabling conditions. Combining expert knowledge with publicly available information enabled us to develop a coherent framework for implementing smallholder tree-cover restoration.

3. Results and discussion

3.1. Prospects for smallholder tropical tree cover restoration

Strategies pursuing tree cover restoration must identify current land uses in areas with the greatest potential for restoration. Fig. 2 panels a-c show tropical areas that lost tree cover between 2000 and 2010 and contain potentially restorable area between 2020 and 2050 with incentive payments up to \$20 tCO_2^{-1}.

Following tree cover loss, most low-cost, potentially restorable lands (89 %) in the tropics were used as cropland (panel a) or pastureland (panel b), but regional patterns differ. Low-cost, potentially restorable areas in cropland comprise 280 million hectares (Mha) globally and are distributed fairly evenly among Asia, Africa, and the Americas (details in Supplementary Information Tables S1 and S2). In South and Southeast Asia, low-cost and potentially restorable areas are predominantly (>70 %) in cropland. Pastureland comprises 200 Mha of potentially restorable lands and accounts for 45 % and 40 % of restorable lands in Africa and the Americas, respectively. Potentially restorable degraded forestland is much less extensive (60 Mha, only 11 % of the total) than restorable cropland and pastureland, and is concentrated in Africa (Table S1). These findings echo other research (Curtis et al., 2018) showing that recently deforested lands (2000–2015) in the tropics are overwhelmingly used for commodity or shifting agriculture.

It is important to note that Fig. 2 does not identify specific areas where low-cost tree cover restoration is likely to occur or be feasible within a 5.5 km grid cell, due to the resolution at which the data were available and the various assumptions made in modeling predicted tree cover restoration. The figure also does not differentiate between gross (i.e., business as usual and \$20 tCO_2e^{-1} incentives) and net (i.e., \$20 tCO_2e^{-1} incentives) restoration potential.

Our estimates indicate that croplands constitute about half of the area that contains the greatest potential for low-cost tree cover restoration in the tropics. Some previous studies (Bastin et al., 2019; Griscom et al., 2017) have excluded cropland from their estimates of potentially restorable land, out of concern for food security. Food security is clearly important, as reflected for example by Sustainable Development Goal 2, which calls for zero hunger by 2030. Information on locations where carbon pricing could cause farmers to convert cropland is essential for determining if risks to food security are substantial. Moreover, the croplands that we identify as having potential for low-cost tree restoration are lands with low agricultural opportunity costs (Busch et al., 2019). These may be low-productivity areas and relatively less essential for overall food security. Additionally, some tree restoration practices, such as agroforestry, in particular, can enhance soil health (Cardinael et al., 2020; Muchane et al., 2020) and increase and diversify food production (Castle et al., 2021; Mbow et al., 2014; Rosenstock et al., 2019; Tschora and Cherubini, 2020). Still, given limited systematic evidence of the human well-being benefits of agroforestry investments (Miller et al., 2020) and potential general equilibrium effects of large-scale tree planting on prices or labor markets (Andersson et al., 2016; Peña-Lévano et al., 2019), any tree cover restoration in crop lands would necessarily have to take food consumption and livelihood considerations into account. Our analysis points to opportunities for forest-agriculture mosaics as sites for tree cover restoration and the potential for smallholders to become partners in restoration activities that enhance food security and rural wellbeing.

(Erbaugh et al., 2020) estimate that some 291 million people live in or near areas with potential for low-cost forest restoration. Combining their population data with the land-use data in Fig. 2, we estimate that 210, 59, and 22 million people live in areas that we identified as potentially restorable cropland, pastureland, and degraded forestland, respectively (Table S1). These different land-use types contain average population densities of 74, 29 and 38 people per km^2, respectively, which highlights the demographic significance of restorable cropland. Thus, restorable agricultural land has a far larger demographic footprint than restorable degraded forestland, in addition to accounting for more of the total restorable area.

At present, no global spatial dataset identifies smallholder agricultural areas. Thus, in panel d of Fig. 2, we instead show the likely importance of smallholdings within potentially restorable areas based on the share of a country's agricultural areas they operate, drawing on national data from Lowder et al. (2021). In the twenty countries with the greatest potential for low-cost tropical tree cover restoration by area (Table 1), average farm size ranges from 1.2 ha (India) to 3.1 ha (Thailand) in Asia, 0.5 ha (DRC) to 3.9 ha (Ivory Coast) in Africa, and 25 ha (Colombia) to 65 ha (Brazil) in the Americas (Table S4).

Smallholdings dominate tropical agricultural lands in most countries in Asia and Africa but not the Americas, reflecting variation in average farm sizes across regions (1.5 ha, East Asia and the Pacific; 1.6 ha, Sub-Saharan Africa (excluding S. Africa); 39.8 ha, Latin America and the Caribbean: Table 2,(Lowder et al., 2021)). In countries with low-cost restorable areas, smallholdings represent 76 % of agricultural landholdings in tropical Asia (excluding China, which is mainly in the temperate zone), 60 % in Sub-Saharan Africa, but only 3 % in the tropical Americas (Table S3). National percentages vary from 44 % to 100 % in Asia, 9 % to 100 % in Sub-Saharan Africa, and ~1 % to 93 % in the Americas. Given that the Americas account for approximately half of all 21st century tropical deforestation to date (Curtis et al., 2018; Parsons et al., 2021), this striking regional difference suggests that high-priority countries for reducing or reversing recent deforestation are not necessarily the same as high-priority countries for promoting low-cost tree cover restoration on the smallest (<5 ha) landholdings.

Spatial datasets are lacking for the tenure arrangements under which potentially restorable land is held. The majority of global farmland is in family farms, most of it held by individual households or businesses rather than communities (Eastwood et al., 2010; Lowder et al., 2016). However, these global estimates (including Fig. 2d) generally exclude communal areas. In the tropics, many individual landholdings are held under customary tenure, which may be officially recorded as public lands. Additional areas are managed or owned by communities, including Indigenous communities, as communal lands. Some 65 % of global land area (Wily, 2011a) and possibly 69 % of land area in Africa (Wily, 2011b) is under some form of common property. Several countries with the greatest low-cost restoration potential (Table 1) have large areas under community-based tenure systems (e.g., 75 % and 52 % of land area in Tanzania and Mexico, respectively; Table S4). The top three countries with low-cost restoration potential in the tropical Americas also have significant amounts of land under community-based tenure systems (Brazil, Mexico and Colombia, Table S4), which may partly explain the low average percentage of smallholdings in this region in official agricultural statistics. Additionally, the distinction between individual and community land may not be sharp, with large proportions of communal lands subject to overlapping customary and statutory rights (Wily, 2011a). Thus, while individually managed smallholdings are an important target for restoration efforts, the presence of large areas of land held by communities in some tropical countries points to the possibility of smallholders having an even larger rural footprint than indicated by published data on agricultural smallholdings. IPLC have been observed to undertake tree cover restoration on croplands (Miller et al., 2020), woodlots (Kimambo et al., 2020), and plantations (Frey et al., 2018), including through assisted natural regeneration (Murugan and Israel, 2017; Reij and Garrity, 2016) on public and communal lands as well as private smallholdings. This makes it important to recognize and seek the participation of smallholders and Indigenous communities operating on communal lands in tree cover restoration.

Our global analysis of land uses in areas with potential for low-cost tree cover restoration was only possible by making assumptions that limit contextual and temporal variation. The Busch-Erbaugh data represent ~5.5 km-wide grid cells where business as usual scenarios predict forest regrowth or where opportunity costs of forgoing agriculture could be offset by a US$20 tCO_2^{-1} payment. However, the spatial resolution of this dataset does not allow us to determine where land cover is projected to change within a ~5.5 km-wide grid cell, as its coarse resolution does not reveal local variation in opportunity costs. Furthermore, our estimates have opposing biases, by not accounting for transaction and tree planting costs, which bias our area estimates upwards, or returns to agroforestry or woodlots, which bias them downward. Similarly, implementing any carbon payment programs would entail sizeable additional costs, some of which would fall on land operators, with the remainder borne by the actors who implement interventions aimed at removing feasibility barriers and facilitating payments. Temporal changes in underlying economic drivers of global tree cover change since 2010 may also affect estimates of areas available for low-cost restoration. For instance, any increases in returns to agriculture from rising crop prices, caused by general equilibrium effects if large areas of land are removed from crop production, or by expansion of transport networks or irrigation, may reduce areas available for restoration. The lack of spatial data at finer resolutions on smallholder farmlands and absence of the information on smallholder-farmed communal areas are additional limitations. These limitations necessitate further examination of policy, governance, and market constraints to smallholder restoration.

3.2. Policy, governance, and market constraints

Table 1 shows how the 20 countries with the most potential for low-cost tree cover restoration perform on a set of indicators of enabling conditions: government policy commitments to restoration, good governance, secure land tenure, and market institutions that facilitate transactions in tree products (for all tropical countries, see Supplementary Information Table S5). Strengthening these conditions can make tree planting less costly and increase private benefits to smallholders, incentivizing them to grow trees on cropland and pastureland to obtain cash income, support subsistence, and meet longer-term economic needs.

Overall, the national indicators point to the presence of constraints that may deter smallholders from undertaking restoration and to the need for reforms that can relax these constraints. None of the twenty countries in Table 1 ranks high globally on institutional or market conditions conducive to smallholder tree-cover restoration: none is in the top (4th) quartile (i.e., the highest values for WGI, EBA, and PRINDEX, and the lowest values for time to market) of all countries in the world for any of the selected indicators. Only seven of the twenty countries have a quantitative policy target for tree restoration as part of their NDC to the Paris Agreement, and these countries vary in terms of governance and market opportunities. For instance, of the seven

Table 1
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.

	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 4 th (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^2) in a country that could be reforested with a US\$20 tCO_2^{-1} incentive in Fig. 2 (Busch-Erbaugh dataset). **Quantified 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).

countries, only India is in the third quarter of countries worldwide on the governance index. Only five of the twenty countries are in the third quarter of countries for perceived tenure security.

Regarding market conditions, only five of the 20 countries have an EBA score in the third quarter. In Supplementary Information Table S5, we present another indicator, the inclusive finance index, which identifies the availability of financial instruments for smallholders and is one of the indicators used to compute the EBA score. Only two of the countries, the Democratic Republic of the Congo and Mexico, rank high on this index. The median time to market from low-cost tree cover restoration areas ranges from 28 to 187 min and is less than one hour in only seven countries. Thus, smallholders are likely to face substantive transaction costs in accessing markets, goods, and services required for restoration. This is not surprising given that areas with low agricultural opportunity costs are likely to be less accessible.

More generally, while the national indicators aim to identify constraints that are generally not reflected in the spatial analyses and assess broad features of countries to enable cross-country comparisons and time trends, the design of country-specific policy reforms requires more detailed diagnostic data. As noted by the World Bank with regards to the WGI, such indicators are too coarse for evaluating or informing policies in any particular country (https://info.worldbank.org/governance/wgi/Home/FAQ consulted on 15th April 2022). Likewise, while the EBA indicators seek to identify conditions that facilitate the growth of agricultural businesses, including for smallholders, these indicators may not be effective in assessing opportunities for subsistence-based smallholders (Spann, 2017). Thus, comprehensive national and sub-national information would be needed to assess and strengthen markets that work for smallholders in countries with restoration potential.

3.3. Responding to local implementation challenges

Enabling conditions for smallholder tree cover restoration manifest in different ways at sub-national levels where restoration activities are implemented. While opportunity costs of land are critical to tree-planting decisions, smallholders and local community decisions are also influenced by other factors, including access to inputs and credit (Bettles et al., 2021; Jara-Rojas et al., 2020; Jones et al., 2020; Rahman et al., 2017), socio-cultural considerations (Jara-Rojas et al., 2020; Reyes-García et al., 2019; Zinngrebe et al., 2020) and governance constraints (Arvola et al., 2020; Binam et al., 2017; Borelli et al., 2019). Fig. 3 presents a typology of implementation constraints on smallholder tree restoration programs and emerging and demonstrated solutions based on expert discussions and the available literature.

Technical and biophysical challenges. Increasing the quality and quantity of germplasm is an important first step for scaling restoration. To address this challenge, non-state actors such as the World Agroforestry Center have created tree gene banks that contribute to germplasm supply chains focused on enhancing food security (Kitonga et al., 2020). Technical constraints are also being addressed through development of seed quality standards (Bettles et al., 2021), contract farming (Väth et al., 2019), and interventions that build farmer capacity through demonstration and training (Miller et al., 2020) and use of local knowledge to match sites and species (Reyes-García et al., 2019; Schmidt et al., 2019). Tree species maps at the sub-national level are improving the understanding of environmental and socio-economic potential of smallholder reforestation in specific countries, while platforms such as RESTOR (Restor, n.d.) bring the possibility of global “connectivity and ecological insights” to land managers. Almost

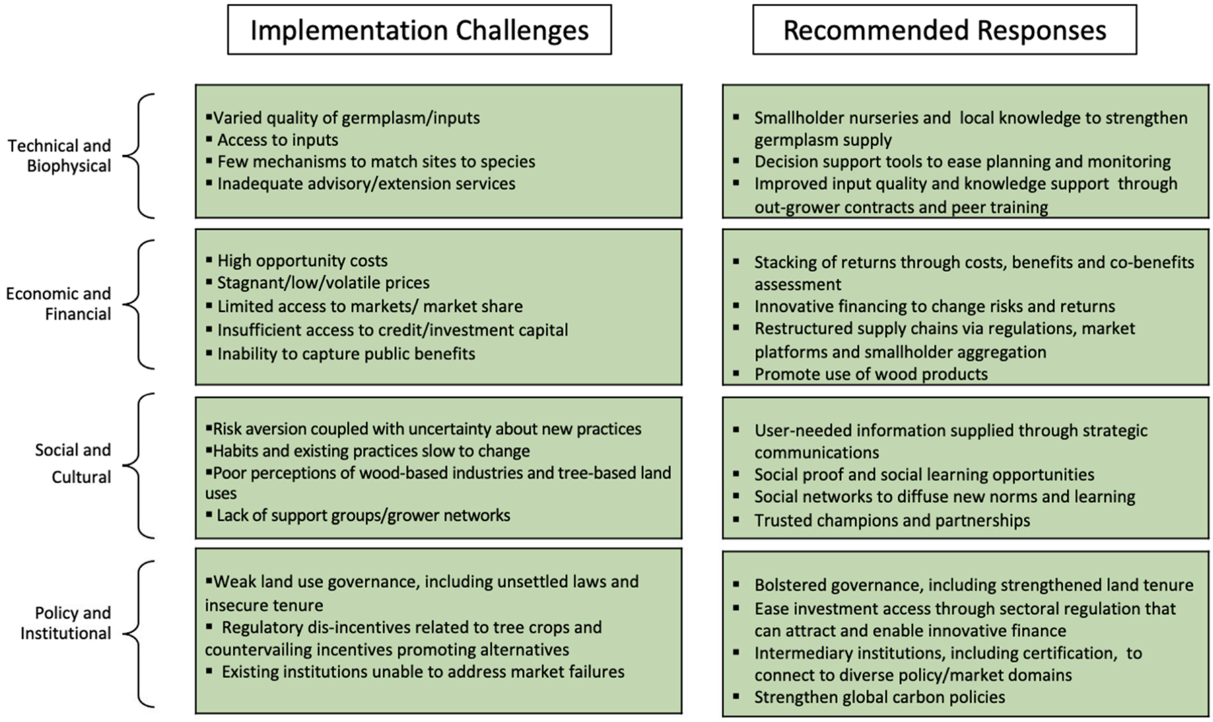

Fig. 3. A typology of challenges and potential and demonstrated solutions associated with implementing smallholder tree cover restoration projects based on discussions with experts.

universal access to mobile phones is changing the scale of outreach and advisory services. For instance, over 44,000 smallholder farmers in Kenya are enrolled in mobile-based monitoring and information services in the watershed supplying water to Nairobi, with several thousand growing trees on their land (IFAD, 2021).

Economic and financial challenges. Assessing benefits, costs, and risks to smallholders from tree planting and identifying financing options is essential for motivating restoration. Ex-ante assessments, including choice experiments, randomized controlled trials (RCTs), and return-on-investment analyses allow for better planning based on smallholder preferences (Richards et al., 2020; Vincent et al., 2021). Gaps in financing are being addressed through innovative payment schemes and supply chain improvements. Payments for ecosystem services, which can increase the competitiveness of restoration with alternative land uses, are becoming available to 'stack' into a bundle of revenue streams for smallholders (Duguma et al., 2020) through multiple financing mechanisms. These pathways include climate-related public funds, forest carbon offset markets, institutional investors such as pension funds, and impact investments (Binkley et al., 2020; Shyamsundar et al., 2021; Vincent et al., 2021). Modifications in market supply chains, for instance through out-grower schemes, whereby companies offer technical advice, financing, or guaranteed market access to smallholders (Väth et al., 2019; Vincent et al., 2021), or producer associations that help increase smallholder knowledge and political and market power (Bettles et al., 2021; FAO, AgriCord, 2016), can also make tree planting more attractive to smallholders. Essential to these market-based strategies is a steady demand for wood and tree products, including for carbon offsets, which as discussed below requires policy and institutional reforms.

Social and cultural challenges. Communicating restoration-related benefits, including from local environmental services, and risks can enhance smallholders' value perception of trees (Marais et al., 2019) and help them make informed decisions (Arvola et al., 2019; Place et al., 2012). Strategies that encourage farmers to learn from peers, offer timely information, and ensure that information flows through trusted messengers, can serve as important social levers (Bujold et al., 2020; Miller et al., 2020; Seghieri et al., 2021). Building social capital and networks is essential for expanding farmer participation and landscape-level diffusion of information and practices (Jara-Rojas et al., 2020; Zinngrebe et al., 2020). Given gender differences in cropping patterns, labor, and rights, women smallholders may require additional resources to ensure effective and equitable restoration (Broeckhoven and Cliquet, 2015; Isgren et al., 2020). Non-government organizations can act as trusted partners (Gupta et al., 2020), working with community-based organizations and communities-of-practice to build capacity and provide multi-layered assistance (Bettles et al., 2021; Winowiecki and Sinclair, 2020).

Policy and institutional challenges. Policies that incentivize smallholders and strengthen rights, including tenure, will bolster restoration. Global platforms, such as the Rights and Resources Initiative (Forest and Land Tenure, n.d), provide evidence on the importance of tenure reform, even though there is uncertainty around the circumstances under which tenure reform encourages tree growing (Vincent et al., 2021). On-the-ground efforts, such as government-NGO partnerships in Brazil that help rural property holders register lands in order to meet environmental regulations (Rasmussen et al., 2016; Roitman et al., 2018) are crucial for promoting tree planting and survival (Duguma et al., 2020) and avoiding displacement of informal landholders by government reforestation projects (Fleischman et al., 2020). Finance and banking sector reform is another critical lever, as illustrated in Vietnam's smallholder reforestation efforts (Sikor, 2011). Reforms that enable forest carbon pricing, ease harvesting and wood transport restrictions (Keerthika et al., 2015), and facilitate forest product tracing (Arts et al., 2021), would provide additional incentives. Institutional changes such as certification schemes that enable group certification (Erbaugh et al., 2017), make certified product purchases more reliable (Hutz-Adams et al., 2016), and offer rigorous evaluation of outcomes (DeFries et al., 2017) can also support smallholder efforts. Addressing these multiple challenges may require jointly implemented solutions (Schulte et al., 2022; Shyamsundar et al., 2020).

Building on real-world experience, the expert group discussions among practitioners and researchers point to four general principles for scaling up smallholder tree cover restoration:

1. Partner with smallholders: The design of restoration programs needs to align with farmer preferences, build on social norms, and address capacity needs (Seghieri et al., 2021). Doing so will require engaging with smallholders upfront, building trusted partnerships and prioritizing smallholder preferences where there are differences between global restoration and smallholder goals. Given the significant presence of women smallholders in many parts of the world, restoration strategies need to be particularly cognizant of social and institutional barriers faced by women farmers (Broeckhoven and Cliquet, 2015; Isgren et al., 2020; Jost et al., 2016). Decisions on how to engage smallholders in tree planting can be informed by analytical approaches such as choice experiments and RCTs and should incorporate social strategies such as peer-to-peer learning.
2. Reduce uncertainty: Uncertainty regarding inputs and outcomes associated with tree planting needs to be reduced. A set of stock coefficients or lookup tables on appropriate species, tree survival and carbon accumulation rates, management practices, carbon prices, indicators on ease of forestry business, and land and tree rights would reduce the transaction costs of reforestation investments. New platforms such as the Africa Tree Finder App ("Africa Tree Finder," n.d) are beginning to fill some of these gaps. Tenure reform is an overarching policy consideration that can reduce smallholder uncertainty about reaping future benefits from investing in tree growing.
3. Strengthen markets: Policy reforms that increase revenues from tree products and make market transactions less costly and more widespread are essential. Low prices are perhaps the single greatest impediment to global tree cover restoration: prices received by landholders for growing wood have been stagnant for decades, and carbon prices are far below levels required to achieve the Paris targets (Hänsel et al., 2020; Strefler et al., 2021; Vincent et al., 2021). Policies that boost demand for wood products and take more aggressive action on climate change are needed. Technological enhancements that strengthen traceability of sustainably harvested timber or market platforms will need to become smallholder friendly. Also needed are institutional reforms that facilitate aggregation (producer organizations or virtual platforms), ensure technical assistance and guaranteed buyers (for instance, through outgrower schemes), and encourage sustainability (local auditors or group certified tree products).
4. Mobilize innovative financing: Financing from public and private resources will need to meet smallholder needs by reducing transaction costs for loans and grants, expanding rural credit access, accepting varied forms of collateral, and offering new insurance products or loans with longer payback periods to allow for tree growth. Intermediaries that seek to grow the supply of 'investment ready' smallholder reforestation projects such as the Africa Forest Carbon Catalyst (Mongabay, 2021) can help smallholders access global finance.

The above principles add to existing proposed principles (Holl and Brancalion, 2022; UN Decade on Restoration et al., n.d.) that provide guidelines on ecological (Brancalion et al., 2020; Committee, 2022; Di Sacco et al., 2021; Gann et al., 2019) and people-centered restoration (Dick Frederiksen et al., 2021; Elias et al., 2021b; Osborne et al., 2021). These papers all emphasize the importance of stakeholder engagement, with the people-centered literature further unpacking what this means and highlighting the need to privilege equity and justice considerations. Our four principles lay out a set of requirements for scaling restoration driven by smallholder needs. In the absence of systematic empirical evidence on what facilitates the scaling of restoration, these principles, which draw on practitioner experience and the published literature, represent a set of overarching ideas that should be verified and adapted to local conditions.

4. Conclusions and recommendations

We argue that low-cost tree cover restoration may be feasible in large areas of cropland, pastureland, and degraded forestland in the tropics. Additionally, we show that agricultural lands in many tropical countries with low-cost restoration potential are dominated by smallholdings, offering opportunities for smallholder-driven restoration. Given uncertainties in the spatial datasets we have used, however, any restoration interventions targeting smallholders in the areas identified by our analysis would require additional verification.

Smallholders, including large numbers of women farmers, are among the most vulnerable people in the world. Thus, smallholder-driven restoration, particularly agroforestry, could advance sustainable development goals by improving farmer well-being while addressing global ambitions to mitigate climate and biodiversity challenges. Our analysis identifies national policy, regulatory and implementation hurdles that would need to be addressed to clear the path for smallholder restoration.

Our spatial analysis calls for reassessing how and where nature-based investments should be made. The dominance of agricultural lands over degraded forestlands and the large presence of smallholders in low-cost restorable areas suggest the need for restoration efforts to strengthen their focus on profitable farm-level tree systems (woodlots, small plantations, agroforestry etc.) relative to other options. While such investments, particularly agroforestry, may result in higher private benefits per unit land area relative to public climate or biodiversity benefits from natural forest restoration, they may be a more feasible option on many lands (e.g., Gopalakrishna et al., 2021).

Smallholder-based reforestation may play a larger role in efforts to reverse recent forest loss in Asia and Africa than in the Americas. Our investigation suggests that smallholder dominated areas with significant low-cost restoration opportunity may not overlap with regions with the highest recent deforestation rates, i.e., the tropical Americas. However, it is important to note that official data on smallholdings generally exclude areas under communal management systems, which are widespread in the Americas and often managed by smallholders. In addition, our analysis focuses on holdings that are less than 5 ha. However, understandings of smallholdings differ across countries, with definitions varying based on inputs and outputs, market linkages, social organization etc. (Buainain and Garcia, 2018; Cohn et al., 2017). In Brazil, for instance, what accounts as a smallholding may vary by municipality (Rasmussen et al., 2016), and farm type (family run versus alternatives) rather than farm size characterizes policy discussions (Buainain and Garcia, 2018). Such differences point to the need for careful assessments of the potential for smallholder-driven restoration in any particular country.

Restoration efforts do not always result in net benefits, either locally or globally (Coleman et al., 2021; Reyes-García et al., 2019). Tree planting, whether driven by global agreements, national policies or market needs, can, under varied circumstances, contribute to conflicting visions of land use, power grabs and authoritarian actions (Fleischman et al., 2020; Reyes-García et al., 2019; Shyamsundar et al., 2021; Valencia, 2021). Additionally, depending on how it impacts crop composition, large-scale tree planting could have general equilibrium effects that may impose costs by raising food prices (Fujimori et al., 2022; Peña-Lévano et al., 2019) or create conditions that increase poverty, as evidenced in Chile (Andersson et al., 2016; Hofflinger et al., 2021; Nilson et al., 2021). Scientific enquiry and global restoration efforts must invest in understanding and reducing any such negative outcomes of restoration.

Discussions among restoration practitioners and researchers suggest that the adoption of four principles – partner with smallholders in planning projects, reduce uncertainty for smallholders and other investors, strengthen markets to increase private benefits, and mobilize innovative finance to enable smallholders to invest in tree planting – could facilitate an expansion of smallholder tree cover restoration. Where there are mismatches between global and local land use needs, policymakers and non-state actors should acknowledge local needs in negotiated agreements and prioritize them as they put these principles into practice. Non-state actors have an important role to play in partnering with smallholders and advocating for policy and institutional reforms. Collaboration between state and non-state actors will be necessary to mobilize the information, investments, and institutions necessary to enable smallholders to benefit from ambitious global forest restoration efforts.

International aspirations regarding tree planting risk failing and exacerbating pre-existing inequalities in LLMICs if they overlook the potential role and preferences of smallholders and local communities. Increasing tree cover on smallholdings at scale has the potential to yield livelihood, biodiversity and climate change benefits, outcomes that need not be in conflict. Making people central to a quest to restore tree cover would make implementation more politically feasible, more equitable, and more likely to succeed over time and at large scales.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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