communications earth & environment | Article

https://doi.org/10.1038/s43247-024-01845-2

Tree plantations and forest regrowth are linked to poverty reduction in Africa

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Numerous countries have adopted large-scale tree planting programs as a climate mitigation strategy and to improve local livelihoods. However, it remains poorly documented how the surge in tree plantations has altered local livelihoods. Here, we assess whether tropical tree plantation expansion and forest regrowth across 18 African countries are associated with local people's living standards. By combining a recent map that distinguishes tree plantations from regrowth from 2000 to 2012 with multidimensional poverty measures from more than 200,000 households, we find a positive association between people's living standards and areas where tree plantations have expanded or, to a lesser extent, forest regrowth has occurred. Because tree plantations make up a large proportion of recent increases in tropical tree cover – and controversy remains about their potential impacts on both biodiversity and local people – our study provides broad empirical support for the idea that tree plantations and forest regrowth can be linked with reduced poverty in the short term.

In recent years, there has been a surge of interest worldwide in promoting rapid and widespread reforestation. The Bonn Challenge[1], launched in 2011 and extended in 2014 by the New York Declaration on Forests, has set a goal of restoring 350 million hectares of degraded and deforested lands across the planet by 2030. Although 'reforestation' typically evokes the idea of restoring fully functioning forest ecosystems, the Bonn Challenge supports a range of approaches including tree plantations (45% of national commitments), agroforestry (21%), and natural regeneration (34%). These different approaches are anticipated to have distinct costs and benefits for local communities, but there is limited empirical data on their actual socio-economic impacts.

Tree plantations (including both afforestation and tree crops) and agroforestry are often the interventions of choice for national governments, corporations, organizations, and funders for a wide range of environmental and economic challenges[2,3]. Recent work assessing the socio-economic outcomes of tree planting includes a case-study from India[4] which focuses on selected indicators of socio-economic sustainability, such as fuelwood and fodder collection, as well as case-studies from Brazil and Indonesia on the income gains obtained from oil palm plantations[5,6]. A review by Adams et al.[7] synthesized 46 articles on large-scale forest reforestation and livelihoods—finding that 89% of these were local case studies—with mixed socio-economic effects on local livelihoods. Similarly, Malkamäki et al.[8] conducted a systematic review of 92 case studies on the socio-economic impacts of large-scale plantations—finding predominantly negative impacts, yet with only 23% reported in Africa. Importantly, the authors noted that only 22 studies presented a comparator and accounted for confounding factors, resulting in limited robust evidence on the socio-economic impacts of large-scale plantations and a lack of clear theories to explain why certain outcomes occur.

Despite their widespread use in reforestation, plantations have been critiqued as ineffective for addressing biodiversity loss[9], especially if they replace intact forest and grassland ecosystems[10–12]. On the other hand, forest regrowth is promoted as the most cost-effective way to achieve forest restoration at scale with greater biodiversity benefits[13,14], but is often assumed to provide fewer economic benefits to local communities[15]. Yet, a recent study from Nigeria shows positive effects of forest regrowth on people's dietary quality and living standards[16]. Intact forests can provide considerable benefits to households, including directly through the collection of food, fuel, medicines and construction materials, and indirectly via the provision of important ecosystem services[17,18]. Yet, linkages between such benefits and forest restoration initiatives have not yet been studied at scale, and would be valuable in guiding the design and choice of restoration initiatives globally under the Bonn Challenge.

In this study, we examine whether the expansion of tropical tree plantations and forest regrowth patches (that were established between 2000 and 2012 and persisted for at least four years after, until

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the end of 2015) are associated with local people's living standards across 18 African countries. We do so by combining a recent map[19] that distinguishes tree plantations from 'natural regrowth' (i.e., any non-plantation forest cover, including both natural regrowth and closed-canopy agroforestry) with georeferenced data from livelihood surveys collected by the Demographic Health Survey (DHS) in 2012–2015 (i.e. after the establishment of plantations and regrowth). The DHS surveys provide data to assess multidimensional poverty across more than 200,000 households (Fig. 1). We note that our data only comes from one single time point. Therefore, the effects of plantations and forest regrowth patches refer to associations in real-world settings and we cannot make claims about causality. As such, it is plausible that poverty reduction can lead to the establishment of plantations and/or forest regrowth as opposed to the reverse of this: plantations and regrowth leading to poverty reduction. For example, recent work from Indonesia[20] has shown how cash transfers to alleviate poverty have reduced deforestation, as market-purchased goods can substitute for deforestation-sourced goods (e.g., cooking with gas can substitute wood fuel). Alternatively, it might be due to an external (unobservable) factor such as the broader 'investment climate', for example in the form of political stability, leading to both poverty reduction and increased opportunities for capital investors to invest in tree planting activities for economic gain[21]. Although cross-sectional data does not allow for causal inference, it is still useful to explore the potential linkages between plantations, forest regrowth and poverty in order to better understand the socio-economic impacts of global restoration initiatives.

Here, we assess the multiple household benefits that can flow from tree plantations and regrowth areas, both directly (sales and employment) and indirectly (secondary economic effects)[22]. To capture diverse potential revenue streams, we examine how tree plantations and regrowth areas are associated with people's multidimensional poverty index (MPI[23]), a composite index that includes indicators on living standards, education and health. Our approach is the first broad-scale, multi-country assessment investigating the associations between widespread tree planting and regrowth, and poverty.

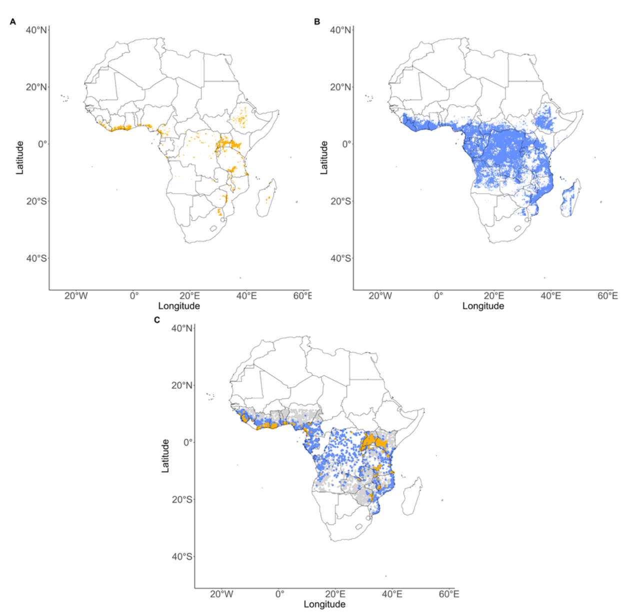

Fig. 1 | Distribution of plantations, forest regrowth and DHS clusters. Maps of tree plantation expansion (**a**), forest regrowth (**b**) and DHS household clusters in Africa (**c**). Blue points indicate clusters overlapping a plantation expansion area, orange points indicate clusters overlapping an area of forest regrowth, and gray points indicate clusters that do not overlap with plantations or forest regrowth.

We focus on Africa because African governments have committed to restoring more than 120 million ha through AFR100 (which contributes to the Bonn Challenge), 100 million ha through the Great Green Wall for the Sahara and Sahel Initiative, and 200 million ha through the Pan-African Agenda on Ecosystem Restoration[24]. Taken together, these initiatives illustrate the extent of the political will for forest restoration, but they also point to the need for evidence on the impact of tree planting and regrowth on local livelihoods. Such evidence is urgently needed because of the risk of large-scale tree plantations expanding onto cropland owned by smallholders, causing displacement of local people[3,25]. Similarly, restoration ecologists have cautioned that tree planting should not be equated with forest restoration if it is in the form of plantations[26,27].

In our analysis, we acknowledge that plantations and regrowth areas are not situated randomly in landscapes, and that people living near plantations or regrowth areas may systematically differ in socio-economic attributes from those who do not, thus confounding any assessment of poverty. For example, regrowth tends to occur in more isolated, less agriculturally productive areas[28]. We therefore used quasi-experimental matching techniques to create two "control" groups of households located >5 km from plantations and regrowth areas, respectively, but that were similar to people living close to plantations or regrowth areas in terms of important socio-economic variables. Because the DHS data is not panel data, we could not control for baseline poverty levels (i.e., before the plantation and regrowth expansion). Instead, we controlled for baseline nightlight activity, which is a proxy for economic activity[29] and baseline population density. We also controlled for baseline forest cover before the plantation and regrowth expansion. In addition, we controlled for travel time to the nearest densely populated area, percentage of area covered by water, and average slope. Finally, we also controlled for the following variables collected by the DHS at the household level, which may influence poverty levels: age of the household head, number of household members, and number of children under 5 years (see Supplementary Table 1 for summary statistics on control variables).

We first assessed the associations between plantations and regrowth and the living standards dimension of the MPI (MPI-LS), which uses criteria to assess whether a household is deprived across six indicators: 1) assets, 2) electricity, 3) sanitation, 4) cooking fuel, 5) water source, and 6) housing. Secondly, we computed the associations between plantations and regrowth and three alternative poverty metrics: 1) the DHS relative wealth index (RWI), which classifies households into five categories (from least to most wealthy) based on the ownership of fifteen different assets; 2) the overall MPI, which also includes education and health as dimensions (see Supplementary Table 6 for a list of all the indicators); and 3) nightlight activity in 2012 after the expansion of tree plantations and forest regrowth. Finally, we checked whether a) non-matching (naïve) regressions, or b) using 10 km instead of 5 km as a threshold, altered our findings. Our findings were robust and consistent across countries.

Results

Heterogeneous effects of tree plantations

In our matched statistical analysis, we found that on average, people living in areas where plantations have expanded from 2000–2012 were less deprived than people living in areas without plantation expansion. Specifically, after controlling for confounding variables (Supplementary Table 1), we found that the MPI-LS value of households was 7.4% ($P = 0.010$) lower in areas with plantations compared to areas without plantations (Fig. 2). Our results translate into an average reduction of the number of MPI-LS indicators a household is deprived in from 4.28 to 4.17 (Supplementary Table 2) across the entire dataset, though the magnitude of change differs by country. For the seven countries with sufficient plantation expansion to estimate effects (≥ 30 DHS clusters with plantation patches (mean: 35, se: 3)), we observed reductions in the number of deprived indicators for households in Côte d'Ivoire (30.8% reduction, $P = 0.075$), Uganda (24.9% reduction, $P < 0.001$), Benin (19.9% reduction, $P = 0.032$) and Kenya (10.4% reduction, $P = 0.062$). The largest effect sizes were observed in Côte d'Ivoire where plantation

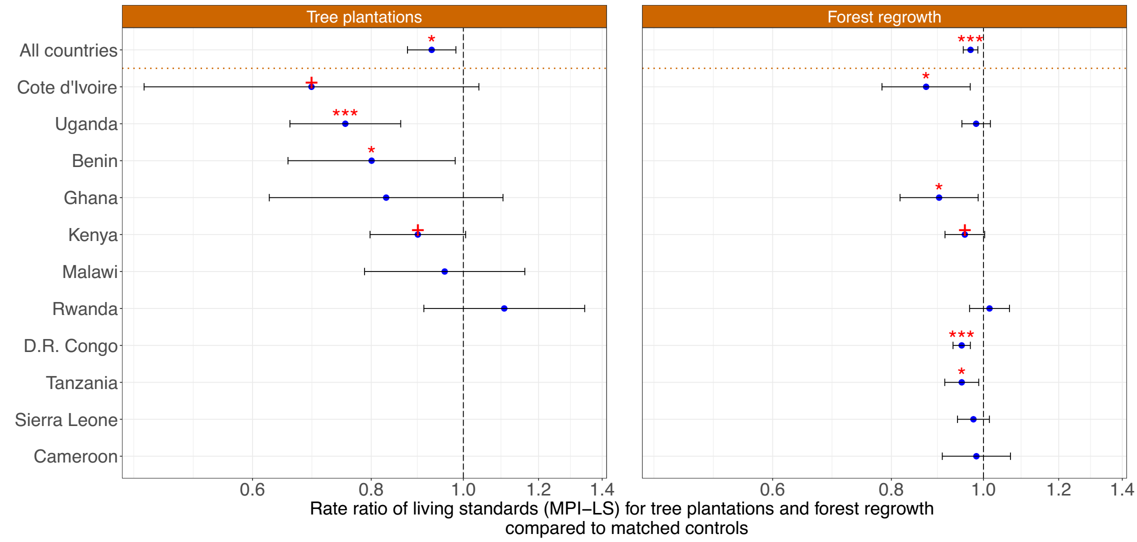

Fig. 2 | Post-matching model results. Rate ratios higher than 1 indicate countries in which increases in plantations (left) or regrowth areas (right) from 2000–2012 were associated with increases (i.e., people being more deprived) in the Multidimensional Poverty Index estimated for Living Standards (MPI-LS), while rate ratios lower than 1 indicate countries in which plantations or regrowth areas were associated with lower MPI-LS (i.e., people being less deprived). Analyses of individual countries include countries with at least 30 clusters overlapping a plantation patch and 40 clusters overlapping a regrowth patch. Analysis of all countries includes those with at least one patch of plantation or regrowth. Full model results are presented in Supplementary Tables 2-3. Significance levels: +<0.1; *<0.05; **<0.01; ***<0.001.

expansion was associated with an average predicted reduction of deprived indicators from 3.80 to 3.36 (Supplementary Table 2). Importantly, there was no evidence of a negative association between plantations and poverty in any of the seven countries, but three countries showed no significant relationship between plantations and MPI living standards.

We then re-ran our matching models using three alternative metrics, the DHS relative wealth index (RWI), the overall MPI (living standards, education, and health) and nightlight activity. Effects on the DHS RWI were comparable to our main analysis (Supplementary Fig. 1). Across all countries, we observed similar results with the RWI, with plantations being associated with lower poverty. Indeed, households near plantations were 32% more likely to be classified in a higher wealth category than households in control areas without any plantation expansion (odds ratio (OR) = 1.32, $P < 0.001$). Compared to the effects measured for MPI-LS, plantations in Ghana shifted from having neutral to marginally positive effects on livelihoods (OR = 2.39, $P = 0.078$), while Côte d'Ivoire (OR = 2.00, $P = 0.132$) shifted from marginally positive to neutral (Supplementary Fig. 1).

Using the overall MPI (with a threshold of 0.33 to distinguish poor and not poor) as a third alternative outcome variable, our results show that the associations between plantations and poverty are maintained when taking into account other poverty dimensions (Supplementary Fig. 2). Across all countries, the percentage of poor people living near a plantation expansion patch was lower ($P = 0.035$) compared to control households (54% and 61%, respectively). Consistent with the MPI-LS results, we did not find any poverty exacerbation effects. In contrast to MPI-LS, plantations in Benin and Kenya shifted from having positive effects to insignificant effects on livelihoods. However, when we measure effects on overall MPI as a continuous measure (without using a poverty threshold) we see the same effects for overall MPI as for MPI-LS.

Finally, we used nightlight activity after the tree plantation expansion as an outcome variable. Because we could not measure nightlight activity for individual households, we conducted this analysis at the level of the household clusters (similar to a village). Our results (Supplementary Fig. 3) showed no significant difference ($P = 0.264$) between household clusters overlapping a plantation and control clusters. Yet, in Benin ($P < 0.001$) and Uganda ($P < 0.001$), nightlight activity was higher in clusters overlapping a plantation, but in Malawi ($P = 0.064$) we found marginally significant evidence that nightlight activity was lower in plantation clusters.

Heterogeneous effects of forest regrowth

Our matched statistical analysis revealed that, on average, households living in areas with forest regrowth had higher living standards (MPI-LS) compared to control areas without forest regrowth (Fig. 2). Thus, across all countries the direction of the effect of regrowth expansion is similar to that of plantation expansion. Yet, the effect size of forest regrowth was smaller. We found that the number of indicators that households were deprived in was on average 3.1% ($P = 0.006$) lower in areas with forest regrowth (compared to 7.4% for plantations), translating into an average reduction from 4.48 to 4.40 deprived indicators (Supplementary Table 3). For the 9 countries with sufficient regrowth to estimate effects (≥ 40 regrowth patches (mean: 212, se: 59)), reductions in the number of deprived indicators were observed in Côte d'Ivoire (12.8% reduction, $P = 0.011$), D. R. of Congo (5.1% reduction, $P < 0.001$), Tanzania (5.1% reduction, $P = 0.012$) and Kenya (4.4% reduction, $P = 0.066$). We observed the largest effect sizes in Côte d'Ivoire where regrowth equated to an average predicted reduction of deprived indicators from 4.5 to 3.7 living standards indicators. We did not observe evidence of poverty exacerbation associated with forest regrowth in any country.

Analysis of the DHS RWI confirmed that regrowth is also associated with increases in living standards (Supplementary Fig. 1). Across all countries, households in areas with forest regrowth were 44% ($P < 0.001$) more likely to be classified in a higher asset-based wealth category than households in control areas without any forest regrowth. Three countries shifted in their estimated effect on DHS RWI compared to MPI-LS. In Uganda, the effect shifted from neutral to a marginally positive increase in DHS RWI ($P = 0.064$), while D.R. Congo and Ghana shifted from positive to neutral. For the overall MPI, we also observed lower poverty in areas with higher forest regrowth across countries (Supplementary Fig. 2). However, we did not find a consistent effect in the countries that displayed significantly lower poverty measured by MPI-LS (Côte d'Ivoire, D.R. Congo, Tanzania and Kenya). We only found significantly lower poverty in Tanzania (binary measure of regrowth ($P = 0.069$); continuous measure of regrowth ($P = 0.024$)), D.R. Congo (only significant using a continuous measure ($P = 0.005$), insignificant when using a binary measure), and Benin (binary measure ($P = 0.033$); continuous ($P = 0.005$)). Yet, a significant increase in poverty was observed in Ghana (binary measure ($P = 0.028$); continuous measure ($P < 0.001$)).

Finally, we used nightlight activity after the regrowth as an outcome variable to proxy economic growth. Our results showed that across all countries, clusters overlapping a regrowth area had slightly lower nightlight activity ($P = 0.014$) than control clusters (Supplementary Fig. 3). When analyzing individual countries we only observed marginally significant higher nightlight activity in Rwanda ($P = 0.053$).

Robustness checks

Finally, we ran three main robustness checks to ensure the validity of our approach. First, we checked whether the extent of tree plantation or regrowth area influenced our results. For this sub-analysis we only selected households overlapping a tree plantation or regrowth area and removed households without a tree plantation or regrowth patch nearby. We then split this group in two by the median area of tree plantations or regrowth within a 5 km buffer circle. We then compared these two groups for both tree plantations and forest regrowth (Supplementary Fig. 4). For tree plantations, we found that across all countries, households overlapping with higher plantation areas had lower MPI-LS poverty levels than comparable households with smaller plantation areas ($P < 0.001$). We found the same pattern in Kenya ($P < 0.001$), but not in other countries. For forest regrowth, we found no significant differences for most countries, except Tanzania (indicating that a larger regrowth area resulted in higher poverty than a smaller regrowth area). Secondly, we checked whether using a larger buffer size (10 km instead of 5 km) influenced our results on MPI-LS. Our analyses across countries revealed similar patterns, but we observed different results for some countries (Supplementary Fig. 5). For tree plantations, Benin switched from having positive to neutral effects on MPI-LS. For regrowth, Cote d'Ivoire and Tanzania switched from positive to neutral. Uganda switched from neutral to marginally positive ($P = 0.070$). Rwanda switched from neutral to marginally negative ($P = 0.056$). These results suggest that in some countries, tree plantations and regrowth patches nearby might be more important than regrowth patches further away (except for regrowth in Uganda). Finally, we ran an ordinary least squares (OLS) regression with the same model specification as the main analysis using MPI-LS as the outcome variable but without matching (Supplementary Fig. 6). We found similar results across countries for both plantations and regrowth, but found some difference for specific countries. In Ghana, MPI-LS effects shifted from neutral to positive ($P = 0.046$), while in Benin and Cote d'Ivoire the effect shifted from positive to neutral, and in Rwanda the effect shifted from neutral to marginally negative ($P = 0.091$). Effects of regrowth shifted from neutral to positive in Uganda ($P = 0.003$), but shifted from positive to neutral in Cote d'Ivoire and D.R. Congo, and from neutral to marginally negative in Ghana ($P = 0.073$).

Discussion

Our results demonstrate that for our extensive dataset, which goes far beyond the spatial scope of previous studies, there is empirical evidence that plantations and forest regrowth are associated with lower poverty levels in Africa.

We propose at least three possible pathways or mechanisms through which plantation expansion or regrowth can lead to poverty reduction. First, plantations may improve household living standards by generating income or other material benefits via the sale of plantation products such as rubber or palm oil that can then be spent on household assets[30]. This pathway could also be true for regrowth areas if they take the form of agroforestry. Second, paid employment in the plantations can likewise generate income that can be spent on household assets[6]. Given the nature of the DHS dataset, which does not include information on plantation or regrowth products, we cannot determine whether these two pathways are present. We observed that in two countries (Uganda and Benin) economic activity (proxied by nightlights) was higher in areas with plantations as compared to those without. In contrast, economic activity appeared lower in areas where regrowth had occurred as compared to areas without regrowth (Supplementary Fig. 3). This might be because regrowth is likely to take place in more remote areas or in land that is abandoned—or that nightlight data are too coarse in resolution (2.7 km) to capture individual-level economic gains from plantations or regrowth. Third, regrowth areas can lead to improved environmental conditions for nearby households, allowing people to benefit from a greater abundance of useful plants and animals which can be sold at markets, resulting in income that can be spent on household assets[31]. Although there is a vast literature demonstrating how these pathways or mechanisms occur in standing forests[17], our study indicates that where these benefits may have been lost due to deforestation, they can return when forests regrow. Yet, as mentioned earlier, there is an additional explanation for our findings in which the pathway is reversed, whereby poverty reduction can lead to regrowth. Finally, external (unobservable) factors could cause both plantation expansion or forest regrowth and poverty reduction. For example, remittances from outmigration could improve living standards and outmigration could likewise lead to forest recovery when people leave rural areas to work elsewhere[32]. We do not have empirical evidence for or against these explanations as the DHS dataset does not include information on the tree products people use—or potentially substitute when poverty levels are reduced, nor is there data available on migration patterns. With data on people's actual use of products from plantations or regrowth areas, as well as data on income gains from these, future studies may better distinguish these competing explanations and identify the causal linkages between plantations and regrowth, and poverty.

Insights from multidimensional analysis

Our analysis responds to recent calls for measuring the success of forest restoration in metrics that are linked to improved human well-being and health[33]. Most previous studies (e.g., Coleman et al.[4]) use indirect measures of living standards such as the number of people using plantations for fuelwood, fodder and grazing. Our results indicate that it is important to broaden the focus beyond living standards to different dimensions of poverty. For example, we found that while forest regrowth was associated with a modest improvement in living standards, improvements in people's education and health were generally lower. This may reflect the conflicting effects of, on the one hand, increased forest resources available for harvesting, and on the other hand, local agricultural abandonment associated with regrowth.

Towards measuring long-term poverty effects

Our analysis shows for the first time how the expansion of plantations and regrowth areas are linked to local people's living standards. That we see the strongest positive associations in Côte d'Ivoire—a country known for rapid expansion of cocoa and rubber plantations—is likely due to foreign companies providing monetary compensation to landowners for clearing these areas to plant cash crops, as well as the jobs and income provided by such companies[34]. However, some of the observed short-term benefits might be outweighed over the longer-term by foregone land use and income opportunities caused by plantations and/or regrowth. It would thus be valuable to follow-up this work with longer-term assessments of the effects of plantations and regrowth on local livelihoods.

A more complete evaluation of how tree plantations and regrowth can impact poverty in the short and long-term would include additional dimensions that we could not capture in our analysis due to limitations in the availability of certain social indicators. These include, for example, social equity, dispossession, displacements and exclusions. Because plantations often need large areas of land, it can require conversion of customary or state land to privately titled land or land under long-term lease, resulting in the removal of former residents[3]. Yet, studies from Ghana and Zambia[35] have shown that plantations did not bring about land dispossession when they were established in areas with low population density, and where agricultural potential was limited. However, more attention is needed to other important social dimensions of plantations such as whether class, race, gender, or physical and mental ability might affect an individual's ability to engage in, decide on, and benefit from plantations. For example, another study from Ghana showed how women were negatively affected by a large-scale oil palm project as it restricted access to farmland and important forest products, with employment benefits for women being smaller than for men whose income rose after the plantation project[36]. Yet, a further study from Ghana showed that oil palm plantations were associated with increased women's empowerment and employment opportunities in processing palm fruits and marketing activities[37]. Tree plantations may also replace natural ecosystems, particularly forests[38]. Since plantations (especially monocultures) do not provide the same ecosystem services as natural forests, the reductions in ecosystem services might negate any positive effects in the longer term[39].

In summary, our findings illustrate that plantations can be associated with important benefits to people, but also emphasize the need for future research on the long-term economic benefits, as well as social considerations —as inattention to these dimensions may ultimately lead to reduced equity and effectiveness of restoration interventions.

Towards measuring effects across different species

Previous work has indicated that the effects of plantations on local livelihoods are highly dependent on the tree species being planted[4], and the types of ecosystems that they replace (e.g., intact forest to plantations vs intensive maize production to plantations[8]). The number of tree species is similarly important in the restoration of natural vegetation. Unfortunately, the map produced by Fagan et al.[19] does not distinguish between tree species nor attend to the land cover types being replaced. In addition, diverse poly-species plantations and agroforestry stands (such as cocoa) were for the most part omitted in the map even though they are important products in several countries, such as Côte d'Ivoire (2.7 Mha, Supplementary Table 9). On the other hand, tree-like herbaceous species that reach 3–5 m (e.g., bananas) were included, but do not fit in all definitions of tree plantations. However, the map did include common commercial tree plantation species in Africa (e.g. oil palm and cashews) which were recognizable and distinct in high-resolution imagery, as were many other plantation species in Africa. Future research that distinguishes species within plantations and quantifies land cover replacement is needed to fully understand the impacts of specific forest landscape restoration efforts on livelihoods and the environment.

In countries where we see positive associations between tree plantation expansion and MPI living standards, the plantation species that were covering the largest areas were cashew (Côte d'Ivoire—1.1 Mha), coffee (Kenya —0.11 Mha) and plantains (Uganda—0.98 Mha) (Supplementary Table 9). However, these species are also planted in other countries where we do not see positive associations (e.g. cashew in Benin—0.50 Mha), so the role of different species and land use remains unclear. Our continental-level study spanned numerous different planted species and a diversity of pre-existing land cover types being replaced by natural vegetation (e.g. savannas to forest vs. grassland to forest). Regardless, given the political bias in many countries towards financing the planting of highly visible fast growing tree species[33]— although different species are often preferred for local livelihoods[4]— understanding the causes of the variability in the poverty outcomes we observed is a research priority (e.g. in Rwanda we observe a neutral association between regrowth and MPI-LS using a 5 km buffer, but a marginally negative association when using a 10 km buffer).

Towards win-win strategies for reforestation

Our results are based on the location of plantation and regrowth areas during the period 2000–2012. Regrowth is likely concentrated in less productive, accessible, or valued land than plantations[19]. As such, tree planting schemes that incentivize passive restoration on more productive lands may yield different results than what we report here. Also, given DHS survey limitations, our analysis is largely cross-sectional. While preprocessing data by matching can perform well, it would be desirable, where data exist for particular plantations or regrowth areas and/or countries, to assess how household poverty impacts evolve over time after plantation or regrowth establishment. Finally, we are unable to distinguish the actors responsible for plantations and regrowth. In some countries, plantation expansion is mostly driven by foreign companies who acquire large tracts of land for cultivation. Yet, in Cote d'Ivoire, most of the production (cacao) is carried out by non-industrial producers who are familiar with local land tenure policies and thus are more capable of acquiring the necessary licenses for cultivation[40]. Who owns the plantation (or is responsible for the regrowth) is likely an important factor in determining effects on poverty and other social dimensions, but requires more research.

Despite these caveats, our results have important implications for global reforestation policies because we show that patterns of planted forests present across the 18 African countries are associated with lower levels of poverty. As such, our findings could inform reforestation efforts such as the Bonn Challenge. The provision of socio-economic benefits is a powerful incentive to engage and involve local communities in restoration initiatives —which is key for these initiatives to persist over longer time periods[33,41]. Reforestation can also have a multitude of ecological benefits, though tree species and forest configuration are important, with monoculture plantations typically having low biodiversity benefits while regrowth or planting of mixed species can result in better ecological outcomes[42]. Emerging research suggests that local communities value positive ecological outcomes, especially in combination with other benefits[43]. However, research is still needed to simultaneously assess the social and ecological benefits of restoration, thereby enabling a better understanding of whether and how benefits for people and nature can be harmonized in restoration initiatives, or where trade-offs will occur (e.g., more livelihood benefits at the expense of ecological outcomes).

Finally, the variation that we have found at the national level across our 18 study countries supports earlier work (e.g., Malkamäki et al.[8]) showing heterogeneous outcomes of tree plantations—likely because particular patterns of land use and land tenure will lead to different outcomes. With the key contribution of this paper being the coverage of a larger spatial extent than what has been done previously, we have also been limited in teasing apart the plantation or regrowth types or characteristics associated with poverty reduction. As such, future research should move beyond assessing socio-economic outcomes of plantations in general and attend to potential differences of, for example, smallholder driven agroforestry which is likely widespread in African countries, as compared to large-scale timber plantations.

Methods

Data

Our analysis uses publicly available data from the Demographic Health Survey (DHS) from 18 sub-Saharan countries (Supplementary Table 4). Data were collected at the household-level between late 2011 and 2016. A total of 208,591 households were surveyed from 7738 clusters (a sampling unit normally corresponding to a village). Geolocations are provided for each cluster, but are displaced up to 5 km for 99% of the clusters, and up to 10 km for the remaining 1% of clusters. In this study we used a 5 km buffer around each geolocation to integrate the household survey data with data on plantations and regrowth and other spatial data. We used this buffer to account for the spatial displacements of geolocations. We also tested whether a larger buffer of 10 km affected our results, but we found mostly similar patterns. We only focused on households in rural areas and excluded dry biomes because of potential inaccuracies in the tree cover data[44]. The DHS uses survey weights to ensure that the selected villages are nationally representative. Although we did not include these survey weights in our main analysis, we repeated our main analysis including these survey weights (following Solon et al.[45]) and found that including survey weights did not influence our findings (Supplementary Fig. 7).

Poverty

Our main outcome variable is the living standards dimension of the multidimensional poverty index (MPI). The living standards dimension is composed of six indicators: 1) assets, 2) electricity, 3) sanitation, 4) cooking fuel, 5) water source, and 6) housing and is measured as a count of the number of indicators a households is deprived in. In addition, we use the overall MPI (ranges from 0 to 1), which also includes education and health. To distinguish poor and non-poor households, we use a cutoff point of 0.33 following Alkire and Foster[23]. When we do not use a cut-off point, we find similar results (Supplementary Fig. 2). To ensure that our poverty findings are robust, we also use the DHS RWI. The DHS calculates the RWI for each country separately and classifies households into five categories (from least to most wealthy) following ownership of fifteen assets: electricity in household, telephone, automobile, motorcycle, refrigerator, TV, radio, water supply, cooking fuel, trash disposal, toilet facilities, floor material, wall material, roof material, and number of rooms in the house.

Tree plantations and natural regrowth

We used the map on tree plantations and natural regrowth from Fagan et al.[19] Tree plantations were defined as monocultures of agricultural or industrial arborescent species established and managed by humans for fruit, wood, fibre and other products. Fagan et al. used a machine learning approach to reclassify gain patches from the Global Forest Change product[46] into tree plantations (90.7% user's accuracy) and forest regrowth (84.5% user's accuracy). The dataset only includes (tree plantation and forest regrowth) patches >0.45 ha that were detected between 2000 and 2012 and persisted until the end of 2015. We used a binary coding to indicate whether any plantation or forest regrowth patch was present within 5 km of the geolocated household.

Covariates

We controlled for biophysical and socioeconomic covariates that are likely to influence the relationship between trees and poverty. First, we controlled for forest cover in 2000 before the detection of plantations and regrowth. Second, we controlled for average nightlights at baseline in 2000. In the absence of available poverty data, we used nightlights as a substitute given that it correlates with asset-based poverty metrics such as the ones used in this study[29]. Third, we controlled for household characteristics that are significant predictors of household wealth: household size, age of the household head, number of children under 5 years old, and education level of the household[47,48]. Note that in our analysis using the overall MPI as the outcome variable, we do not include education as a covariate. Fourth, we control for geographical variables that influence land suitability and access: slope, percentage of area covered by water, population density and travel time to the nearest population center[49]. Geographical variables were calculated as the mean within 5 km of the geolocated household. Finally, for our analyses on the effects of tree plantations we included forest regrowth as a covariate, and we included tree plantations as a covariate in our analyses on effects of forest regrowth. Additional descriptions of the data and sources are available in Supplementary Table 5.

Analysis

We conducted a combined matching and regression analysis to assess the associations between tree plantations or forest regrowth and poverty. We analyzed all the countries together and each country separately. Due to the small sample sizes, we only included countries with at least 30 DHS clusters overlapping a plantation patch when analyzing plantations, and at least 40 DHS clusters overlapping a regrowth patch when analyzing effects of natural regrowth. We extracted all the geographic data on covariates using Google Earth Engine[50]. All statistical analyses were conducted in R (R Core Team, 2022). Matching is a preprocessing step used to optimize balance in covariates between treatment and control units, and is used when treatment and control could hinder causal inference. One of the benefits of matching is that it relaxes the functional form assumptions of subsequent regressions, and reduces the likelihood of predicting in areas without common support (i.e., the overlap in the propensity score distribution between the treatment and control groups; Supplementary Fig. 8). We used full matching in the Matchit package[51], which is a form of propensity score matching, but has been shown to perform better than nearest neighbor matching and retains a larger sample[52,53]. Full matching maximizes the data by matching each treatment unit to multiple control units, or a control unit to multiple treatment units. In our analysis covering all the countries, we performed an exact match on each country so that matches were confined within country borders. We used post-matching standardized mean differences of <0.25 as a threshold to define balance between treatment and control groups[53]. In our analyses spanning all the countries, we found acceptable balance (Supplementary Fig. 9). In our analyses on single countries, balance was not always reached after matching, but balance was improved for almost all covariates (Tables S7-8). After matching, we conducted regressions on the matched sample using weights produced by the matching algorithm, and the same set of covariates used to produce the weights (as recommended by Ho et al.[51]). For MPI-LS, our primary outcome variable, we conducted quasi-poisson regressions because MPI-LS is a count measure of the number of indicators a household is deprived in. We used binomial regressions to model overall MPI when using the cut-off value to distinguish poor and non-poor, because this is a binary outcome. We used OLS regressions when using MPI as a continuous outcome variable. We used DHS RWI represents a wealth class, and therefore we modelled RWI using ordinal regressions to take into account the order of wealth classes in the RWI. We conducted a robustness check to test whether our findings would differ if we did not use the matched weights. For our analyses across all countries, we included country as a fixed effect in subsequent regressions. We used the sandwich package to compute cluster-robust standard errors at the cluster level to adjust for the lack of independence of households within the same cluster[54]. Finally, we calculated Oster's regression coefficient stability estimates[55] (δ values) using the "robomit" package in R[56]. δ values represent the effect relative to the treatment allocation that an unmeasured confounder would need to have to flip the regression coefficient to zero. For our statistically significant findings we found relatively high absolute δ values (Tables S1 and S2), indicating that the unobserved variable would need to be much stronger to counter the observed effect.

Data availability

All data needed to replicate our results are available online. Survey data can be downloaded from the Demographic Health Survey (DHS) at https://dhsprogram.com/. Maps on tree plantations and forest regrowth are available at https://data.globalforestwatch.org/content/pantropical-tree-plantation-expansion-2000-2012/about.

Code availability

All code to replicate our results have been deposited in the Harvard Dataverse, https://doi.org/10.7910/DVN/FXSBYG.

Received: 14 March 2024; Accepted: 25 October 2024;
Published online: 20 November 2024

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Acknowledgements
B.d.B., C.M.H. and L.V.R. were funded by the European Research Council under the European Union's Horizon 2020 Research and Innovation Programme (Grant Agreement 853222 FORESTDIET. L.V.R. gratefully acknowledges support from the Independent Research Fund Denmark (DFF) via grant no. DFF 0241-00003B.

Author contributions
B.d.B. conceived and designed the objectives and methodology, conducted the analysis and wrote the manuscript. C.M.H. conceived and designed the objectives and methodology, supported with the analyses and wrote the manuscript. J.R. conceived and designed the objectives and methodology, supported with the analyses and supported in writing the manuscript. M.F. contributed data on tree plantations and forest regrowth and supported in writing the manuscript. L.V.R. conceived and designed the objectives and methodology, supported with the analyses and wrote the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43247-024-01845-2.

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Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editors: Martina Grecequet. A peer review file is available

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