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Forest regrowth improves people's dietary quality in Nigeria

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Two billion people currently suffer from micronutrient deficiencies. Existing literature shows that forests can improve people's dietary quality—yet forests are often overlooked in food security policies, which focus primarily on the production of staple crops. The Bonn Challenge has set a goal of restoring 350 million ha of forest by 2030, but it remains unclear whether restored forests will exhibit the species diversity needed to improve diets in the same way as existing forests. Here, we report how forest regrowth in Nigeria has affected people's dietary quality. We combine a new map on forest regrowth with food consumption panel data from over 1100 households—and use a combination of regression and weighting analyses to generate quasi-experimental quantitative estimates of the impacts of forest regrowth on people's food intake. We find that people living in areas where forest regrowth has occurred have a higher intake of fruits and vegetables and thus higher dietary diversity.

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INTRODUCTION

Reforestation is promoted globally as a key strategy for mitigating climate change through the storage of carbon in woody growth, with many co-benefits such as enhancing ecosystem services including management of water supplies. The Bonn Challenge, 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 2030¹. The Bonn Challenge supports a multitude of approaches to 'reforestation' including tree plantations (45% of national commitments), agroforestry (21%), and natural forest regrowth (34%). Natural regrowth is promoted as the most cost-effective way to achieve forest restoration at scale². In contrast to the assumed negative effects of plantations on biodiversity and net carbon storage (if replacing other carbon-rich ecosystems)^{3,4}, it is hoped that natural forest regrowth can achieve higher biodiversity^{5,6}. Yet, natural regrowth areas are assumed to provide fewer direct economic benefits to local communities, although they do include non-timber forest products (NTFPs) that are used by rural people as a source of income and help to perpetuate and enhance cultural traditions, including the consumption of food products such as bushmeat, fruits, and vegetables⁷.

There has been a recent surge in research establishing that forests can provide considerable benefits to households, including improved dietary quality. Forests can improve people's diets along four key pathways^{8–10}. The most direct way is via the provision of wild foods, such as fruits, vegetables, and animal products (i.e., bushmeat and insects), all of which are high in essential micronutrients^{11,12}. The second pathway is through income gains from sales of NTFPs, which can facilitate the purchase of nutritious foods from markets¹³. The third pathway is via the flow of ecosystem services from forests into surrounding agricultural landscapes which can in turn increase and/or diversify production¹⁴. The fourth pathway is via the provision of fuelwood for cooking, which can improve nutrition by facilitating the preparation of a range of foods, particularly those with long cooking times^{15,16}, as well as making water that is boiled safe to drink. Whether such benefits are restored in natural regrowth initiatives

has not yet been studied—so it remains unclear whether restored forests in degraded landscapes will exhibit the productivity and species diversity needed to improve diets and overall well-being. Filling this research gap is a valuable step to better design restoration initiatives under the Bonn Challenge.

In this study, we examine how the regrowth of tropical forests from 2000 to 2012 has affected local people's dietary quality and living standards in Nigeria. We do so by combining a new map¹⁷ that estimates 'natural regrowth' (all increases in non-plantation forest cover, including both natural regrowth and closed-canopy agroforestry) over this period with georeferenced panel data from the World Bank's Living Standards Measurement Study (LSMS) on food consumption and multidimensional poverty measures from 1154 households. We use LSMS data that were collected in 2012–2013 and 2018–2019 in order to capture the long-term impacts of forest regrowth. Our approach is the first assessment investigating long-term dietary and living standard outcomes from forest regrowth. Previous studies have focused on tropical plantation monocultures instead of diverse forest regrowth, and have attended to single potential benefits from these plantations such as wage labor, the income gained from plantations¹⁸, or the number of people using tree plantations for collection of fodder or fuelwood¹⁹. Here, we assess the broader household benefits that can flow from non-plantation regrowth areas through critical ecosystem services, including the provision of food and the income gains from sales of products obtained from the regrowth areas. When measuring food consumption, most existing studies assessing relations between forests (or deforestation) and diets^{20–22} rely on measures such as dietary diversity scores and binary consumption metrics of nutritious food groups as proxies for overall diet quality. Here, we go beyond those simple metrics by also quantifying fruit and vegetable consumption per person per day to gain a better understanding of how regrowth can affect people's diets. We focus on long-term outcomes (i.e., 6 years after the final regrowth year) rather than short-term effects due to the time lag between the establishment of a regrowth area and the improvements in species diversity that allow people to source food from these areas.

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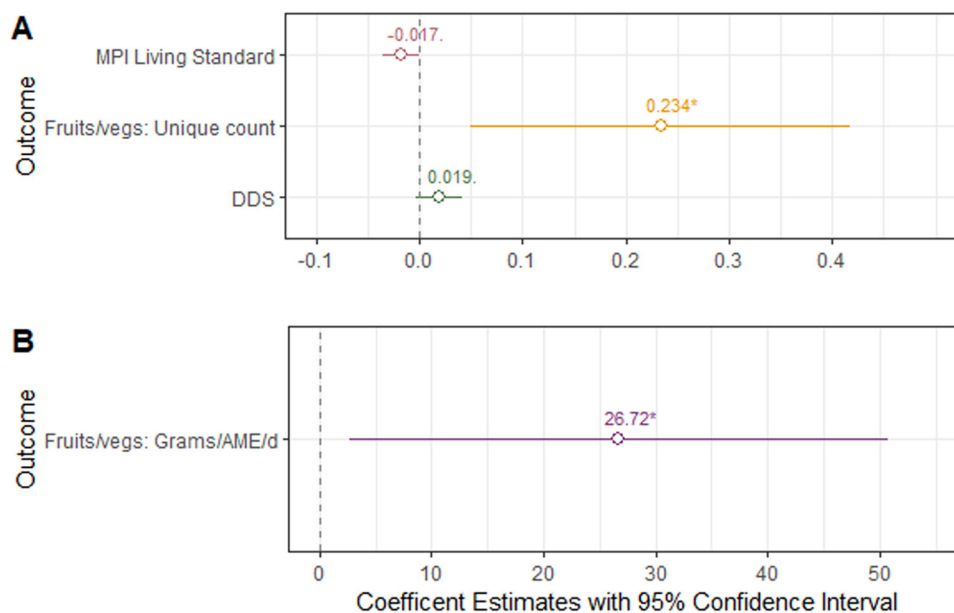


Fig. 1 Post-matching model results. **A** Negative coefficients indicate that forest regrowth from 2000 to 2012 is associated with a decrease (i.e., people being less deprived) in the Multidimensional Poverty Index (MPI) estimated for Living Standards, while positive coefficients indicate that regrowth is associated with an increase in the number of unique fruits and vegetables consumed over the past 7 days and an increase in the household Dietary Diversity Score (DDS). **B** The positive coefficient indicates that regrowth is associated with an increase in the amount of fruits and vegetables consumed per person per day. Note that coefficients are based on the log transformation of the natural regrowth variable. *p*-values: <0.1; *<0.05.

We run our models with data from Nigeria which is the most populous country on the African continent and the seventh largest in the world, home to over 200 million people—a number that is rapidly growing and expected to reach more than 500 million people by 2100²³. Sixty-three percent of people in Nigeria were living in multidimensional poverty in 2022²⁴. Moreover, at least 26 million Nigerians are undernourished, with 11 million children being stunted and 2 million affected by wasting²⁵. This ranks Nigeria as having the highest burden of malnutrition in Africa and the second highest in the world. Moreover, food insecurity is expected to rise sharply as the share of households experiencing the most severe forms of food insecurity (households reported going a whole day without food) increased from a level of about 14% in 2018 to 35% in 2020 during COVID-19²⁶. Also, from 2001 to 2021 Nigeria lost 1.14 Mha of tree cover (equivalent to an 11% decrease in tree cover), while the country gained 928 kha²⁷ (including both natural regrowth and plantations). Given the expected population increase, further tree cover loss primarily due to agricultural expansion is likely to take place, including in regenerating forests²⁸. In the early 2000s, natural regrowth was allegedly preferred over plantations because of insufficient funds to establish plantations as well as a wish to regenerate rainforest²⁹. Taken together, the very high rates of poverty and malnutrition, and the sheer scale of forest loss as well as reforestation efforts²⁹, justifies our focus on Nigeria—and makes it paramount to identify actions to improve nutrition and poverty.

In summary, our paper makes several contributions to the literature on the outcomes of reforestation through its focus on natural regrowth areas instead of plantations, the use of rigorous, quasi-experimental methods, and the use of detailed dietary quality metrics instead of simple dietary diversity scores. Specifically, our analysis advances the literature in three main ways:

1. We examine whether forest regrowth, which has higher ecological value than plantations but is seldom assessed for its socio-economic outcomes, can make positive contributions to dietary quality and multidimensional poverty.
2. Our panel data and matching methods allow us to isolate the causal relationship between people living in areas with

different amounts of regrowth from 2000 to 2012 and their dietary quality and living standards—which no studies, to our knowledge, have done.

3. Our study improves on previous studies of forests and nutrition by including both general dietary diversity and fruit and vegetable consumption.

RESULTS

We found that people living in areas with regrowth from 2000 to 2012 consumed significantly ($p = 0.0294$) more fruits and vegetables in 2018 than households with no regrowth in their surroundings. Specifically, after controlling for confounding variables we found that a 1% higher regrowth area was associated with 0.27 additional grams of fruits and vegetables consumed per person per day (Fig. 1)—or a 50% greater regrowth area was associated with 4.7 additional grams of fruits and vegetables. This is a notable increase given that fruit and vegetable consumption was just 129 and 234 grams per person per day in 2012 and 2018, respectively (Table 1)—which corresponds to 4.9% and 16.0% of household members meeting the recommended amount of 400 g per capita per day³⁰. Also, the mean regrowth area across the 10 km radius circles was 3.1 ha (corresponding to only 0.01% of the buffer area), meaning that many areas could have a high potential for further increases in regrowth area. As such, from an absolute perspective, a 50% increase constitutes a relatively small area. With the largest regrowth area across buffers being 127 ha, an increase from the mean (3.1 ha) to this maximum would translate into an increase in vegetable and fruit intake of 70 g per adult male equivalent (AME) per day—assuming a linear relationship.

A second key finding was that regrowth was significantly ($p = 0.01$) related to higher fruit and vegetable diversity (Fig. 1). This suggests that the regrowth areas exhibited the species diversity needed to facilitate the consumption of a wider variety of both fruits and vegetables. Tree species common in natural regrowth initiatives in Nigeria include the rapidly growing *Antiaris*

Table 1. Summary statistics for the key dependent and independent variables in each wave of the panel data.

		Mean (SD)		
		2012/2013	2018/2019	Baseline period
Outcome variables	Fruit and vegetable consumption (g/AME/day)	129.17 (168.94)	234.40 (300.60)	Baseline is 2012/2013
	Fruit and vegetable count (number of unique items)	3.99 (2.00)	5.05 (2.28)	Baseline is 2012/2013
	Dietary Diversity Score (DDS)	5.24 (1.61)	6.28 (1.79)	Baseline is 2012/2013
	MPI Living Standard (lower is better)	0.51 (0.24)	0.48 (0.26)	Baseline is 2012/2013
	Households meeting fruit and vegetable recommendations (%)	4.9%	16.0%	Baseline is 2012/2013
Control variables	MPI Education level	0.29 (0.41)	Controlled for 2012/2013 level in model	
	Distance to the nearest road (km)	5.56 (7.90)	Controlled for 2012/2013 level in model	
	Population density	781.23 (1718.41)	Controlled for 2012/2013 level in model	
	Rural (% of households)	67.5%	Controlled for 2012/2013 level in model	
	Elevation	229.66 (183.35)	Controlled for 2012/2013 level in model	
	Slope	4.31 (2.13)	Controlled for 2012/2013 level in model	
	Forest cover in 2000 (ha)		4735.2 (7698.6) [corresponding to 15% forest cover]	
	Forest change 2000–2012 (%)		−12.36 (24.55)	
	Regrowth area 2000–2012 (ha)		3.10 (10.68)	

For regrowth areas as well as forest variables, the period of interest is 2000–2012. $N = 1154$ households.
AME adult male equivalent.

toxicaria and *Lecaniodiscus cupanioides*³¹—both species yielding edible fruits.

Along with fruit and vegetable diversity, we also examined the effects on people's overall dietary diversity. We found that regrowth area had a marginal ($p = 0.0907$) positive effect on household dietary diversity score (DDS)—although the effect was small with a 1% increase in regrowth area translating into a 0.0002 increase in DDS. Because we also observed that the household dietary diversity increased from 5.2 in 2012 to 6.3 in 2018, the small effect suggests that there are likely other more efficient ways to increase overall dietary diversity than promoting regrowth (such as increasing market access or improving agricultural diversity).

Finally, we found that regrowth led to higher living standards (i.e., lower Multidimensional Poverty Index (MPI) value). Specifically, we found statistically significant ($p = 0.05$) effect sizes of regrowth area on MPI living standards, equating to an average improvement (i.e., index decline) in living standards of 0.0002 as regrowth areas increased by 1%. In other words, an increase in regrowth area from the mean of 3.1 ha (corresponding to only 0.01% of the buffer area) to the observed maximum of 127 ha would translate into a 0.03 improvement in living standards (seen by lower MPI values). This is a notable change given the level of poverty across the sample (mean living standard of 0.51, ± 0.24 , Table 1). One reason that regrowth areas can decrease poverty is likely due to the presence of early succession species such as *Funtumia elastica* (also known as “bush rubber”) which is economically and medicinally important for rural households³¹, with Nigeria producing more than 150,000 tons of natural rubber in 2021^{32,32}.

DISCUSSION AND CONCLUSION

Our results provide empirical evidence that forest regrowth has led to better dietary quality and higher living standards in Nigeria. We suggest that there are at least five interacting pathways through which this could be occurring.

First, forest regrowth has likely improved household dietary quality through the direct provision of wild fruits and vegetables,

such as dark leafy greens, which are high in essential micro-nutrients^{11,12}. Unfortunately, the LSMS datasets do not allow us to ascertain which foods were sourced from regrowth areas, but we can observe that the consumption of food items likely to be sourced from the wild, such as mango (*Mangifera indica* which is introduced), other fruits, and leaves, account for a substantial part of the total fruit and vegetable intake (Table S2). Second, income gains from sales of NTFPs have likely facilitated the purchase of nutritious foods, including fruits and vegetables, from markets¹³. Income gains from sales of NTFPs may also have contributed to the observed improvement in people's living standards. Bush mango (*Irvingia gabonensis*) is an example of a species used frequently for both local consumption and trade in Nigeria²⁶. The LSMS data would benefit from more detailed recordings of the income that people can gain from the sale of NTFPs. The current data only allows for coarser estimates of income-generating activities (with mean values higher for those households living in areas with regrowth as compared to those without regrowth, Table S3). Also, the survey allows for estimates of time spent collecting wild foods or firewood (with mean values lower for those households living in areas with regrowth as compared to those without)—but neither the data on income-generating activities nor the data on time spent are comparable across waves due to differences in the survey questions (Table S3). While there is vast empirical evidence showing how harvesting of NTFPs from forests can reduce poverty²⁶, our study shows that although such benefits are lost when deforestation occurs, the benefits can return when forests regrow. Third, assuming that the first pathway is occurring, the direct provision of ‘free’ fruits and vegetables from regrowth areas allows people to reduce the amount of money spent on food, thereby freeing up money that in turn can be invested in assets and accordingly improve living standards. Fourth, the flow of ecosystem services from regrowth areas into surrounding agricultural landscapes can increase and/or diversify crop production¹⁴ which in turn could have facilitated a) the observed higher consumption of fruits and vegetables, and b) income gains resulting in higher living standards. Finally, the

regrowth areas have likely provided fuelwood for cooking, which may have improved nutrition by facilitating the preparation of foods such as cooked green vegetables^{15,16}. The provision of fuelwood from regrowth areas might also be a source of income which in turn could have led to the observed improvements in living standards.

Varying effects of different tree species

The effects of regrowth on people's dietary quality and living standards are highly dependent on the tree species in question, and the types of ecosystems that they replace (e.g., intensive maize abandoned for regrowth versus grassland to regrowth). Yet, the newly produced regrowth map by Fagan et al.¹⁷ does not distinguish between tree species nor attend to the land cover types being replaced. However, we know that regrowth initiatives in Nigeria have taken various forms, including (a) clearing vegetation around desired 'mother' trees to promote natural regrowth through the emergence of seedlings from the soil seed pool, (b) poisoning of large undesirable tree species to open the canopy and facilitate natural generation of desirable species—although this method had limited uptake as it was costly and cumbersome, and (c) enrichment planting by which desirable species are planted alongside the growing tree stock²⁹. What is mapped as natural forest regrowth in Fagan et al.¹⁷ likely also includes areas of closed-canopy agroforestry, which are hard to distinguish using broad-scale remote sensing approaches given that both are characterized by diverse, mixed-species tree cover.

The observed positive effects of regrowth on dietary quality indicators suggest that the areas of regrowth sufficiently exhibit the species diversity needed to improve diets in the same way as existing forests. Likewise, the positive effects that we observe on people's living standards can be explained by the regrowth areas hosting high-value species allowing for income gains from sales of these forest products²⁶. Yet, further research is required to establish whether the positive relationship we have observed between regrowth and dietary quality/living standards holds true for different tree species within regrowth areas and different types of existing land cover that is replaced with regrowth. Moreover, further work is needed to disentangle the presence of cultivated agroforestry systems as compared to natural regrowth areas. As such, our findings also highlight the need for rethinking the political bias towards financing reforestation initiatives focused on the planting of highly visible, fast-growing, often introduced, tree species³³ instead of natural regrowth, given that 45% of national commitments under the Bonn Challenge are focused on monoculture tree plantations, whereas only 34% are natural regrowth initiatives.

Forest regrowth is a win-win strategy for social and ecological outcomes

Our study responds to recent calls for measuring the success of restoration initiatives in metrics related to improved human well-being and health^{33,34}. While one major advancement of existing knowledge is our focus on forest regrowth rather than plantations, we also use a comprehensive measurement of living standards, whereas previous studies have measured 'well-being' benefits through simple indicators such as the number of people using plantations for fuelwood, fodder and grazing¹⁹. Likewise, our analysis is the first to go beyond simplistic measures of dietary quality such as dietary diversity scores, instead using quantities and counts of fruit and vegetable consumption. As it is already well established that restored forest has ecological benefits^{5,6}, our study shows for the first time how regrowth is a promising strategy toward achieving win-win outcomes for both people and the environment in the long-term. Because we have used a rigorous, quasi-experimental estimation method that combined CBGPS weighting with regression analyses, we can ascertain that regrowth from 2000 to 2012 in people's surroundings has led to

better dietary quality and living standards—which no studies, to our knowledge, have yet done. Yet, we note that whether the regrowth areas and their benefits to people will persist depends on government effectiveness and land-use pressures³⁵—which are likely to be high in Nigeria given the expectation of reaching more than 500 million people by 2100²³.

Directions for future research

We identify four main directions for future studies on this topic. First, while we have established a positive effect of regrowth on people's diets and living standards in Nigeria, further work is required to test whether this relationship holds true in different countries and study settings. Attention to how different restoration initiatives affect people, not just the environment, is key and will complement recent research showing how land tenure security is essential to deliver forest restoration³⁶. Also, the harvesting of wild foods and products from regrowth areas can be limited by whether people have access to collect these and/or the traditional knowledge to know where to find them, their toxicity, and seasonal abundance. For example, a recent paper from Nigeria shows that Indigenous institutions and systems of controlled utilization and selective harvesting complement each other³⁷. More generally, it is increasingly recognized that those people who benefit the most from access to diverse food sources, mostly Indigenous Peoples and other local communities, are the best stewards of that land³⁸. Second, future studies should seek to identify the tree species within regrowth areas that are utilized by people in order to understand whether certain tree species within regrowth areas are more valuable than others for people's diets and living standards (e.g., are fruit-bearing trees more utilized and beneficial than trees that do not produce edible products?). Third, it is critical to understand the land-use type prior to regrowth in order to assess whether this impacts the potential benefits of regrowth. Lastly, while this study has found that regrowth improves people's diets and living standards, we are not able to ascertain the specific mechanisms by which this occurs. Future studies should seek to elucidate the causal pathways in order that strategies to expand forest regrowth can maximize benefits for both people and the environment.

METHODS

Household-level data

We extracted data for households that were included in both data collection waves two (2012–2013) and four (2018–2019) of the LSMS for Nigeria. This resulted in a sample size of 1154 households distributed across 204 clusters (most often corresponding to a village) (Fig. S1). Geolocations were provided at the cluster level. To spatially link household-level data with regrowth area (and other variables such as baseline forest cover), we used 10-km radii circles around LSMS clusters. We chose 10 km because while 99% of LSMS clusters are randomly displaced by 0–5 km (for confidentiality purposes), the remaining 1% are displaced up to a maximum of 10 km.

Outcome variables: measures of dietary quality and living standards. In each of the LSMS waves, surveyed households were asked to recall their food consumption over the past 7 days from a predetermined list of 142 food and drink items. We used this food consumption data to estimate three measures of dietary quality: (1) a household Dietary Diversity Score (DDS), (2) consumption of fruits and vegetables measured in grams per AME per day, and (3) the diversity of fruit and vegetable consumption measured by the number of unique items consumed over the past 7 days at the household level.

Dietary diversity is defined as the number of food groups consumed over a fixed time period, generally ranging from 24 h to

7 days. At the individual level, dietary diversity is a proxy for micronutrient adequacy of the diet³⁹ which is considered one aspect of diet quality. However, individual data are not available from the LSMS as all data are collected at the household level. We therefore constructed a modified household dietary diversity score (DDS) using the ten food groups recommended to construct the Minimum Dietary Diversity Score for Women (MDD-W)⁴⁰ but based on a dietary recall of the past 7 days at the household level. While the original MDD-W was designed to be used on 24-h dietary recall data for women of reproductive age (15–49 years), it has now become accepted to apply it at the household level for 7-day dietary recall data^{21,41}. It should be noted that our modified version of the MDD-W does not account for issues relating to the intra-household distribution of food and it should not be used for statements concerning particular population groups, such as women⁴². Nevertheless, the DDS can still be interpreted as a proxy for dietary quality as household and individual diets are highly correlated. We used the Food and Agriculture Organization (FAO) guide for measurement⁴⁰ to allocate the LSMS food items into ten food groups; (1) grains, white roots and tubers, plantains; (2) pulses; (3) nuts and seeds; (4) dairy; (5) meat, poultry, and fish; (6) eggs; (7) dark green leafy vegetables; (8) other vitamin A-rich fruits and vegetables; (9) other vegetables; and (10) other fruits. Households scored one point if they had consumed at least one food item from each group. The specific allocation of LSMS items into the ten food groups is provided in Table S1. We allocated 108 out of the 142 items, as items such as tea, coffee, or beer were not included in the analysis (in line with the FAO guide for measurement).

Our second measure of dietary quality was fruit and vegetable intake given that the consumption of these foods is strongly associated with positive health outcomes^{43,44}. We estimated the total fruit and vegetable intake in grams at the household level, and then at the individual level using the AME approach in line with Hall et al.⁴¹ and as outlined by Weissel and Dop⁴⁵. The AME approach is preferred over an estimation at the household level because it accounts for how food is allocated within a household based on the food requirements of the individuals constituting the household (based on the age and sex of individuals). As such, using AME values allows for the comparison of households of differing sizes and compositions. Importantly, it also allows us to compare the estimated consumption at the individual level with the WHO recommendation of 400 grams of fruit and vegetables per person per day³⁰. Our third measure of dietary quality was a simple count of the number of individual fruit and vegetable items consumed by each household over the past 7 days, to reflect the diversity of fruit and vegetable consumption within the household.

Finally, we used the living standards dimension of the MPI⁴⁶ as an outcome variable. The index varies from 0 to 1, with 1 being the most deprived. We calculated the index according to six indicators: (1) assets (TV, telephone, computer, animal cart, bicycle, motorbike, refrigerator, car/truck), (2) electricity, (3) sanitation, (4) cooking fuel, (5) water source, and (6) housing.

For all four outcome variables, we used the values in 2018/2019 as our dependent variable, but we controlled for the values in 2012/2013 (baseline year).

Data on natural regrowth and forest cover

We used a newly published map of natural regrowth from Fagan et al.¹⁷. While the map includes both tree plantations and natural regrowth areas, we focused on the natural regrowth areas because plantations are not as beneficial for ecological outcomes, especially biodiversity³. The dataset includes natural regrowth area patches >0.45 ha that were detected between 2000 and 2012 and persisted throughout 2015. We note that the natural regrowth areas likely also include agroforestry systems with greater than 50% tree cover, particularly in the humid forest zone. We summed

the natural regrowth patches to get the total area of regrowth within a 10 km radius circle surrounding households.

Control variables

We controlled for a number of variables that were hypothesized to affect people's dietary quality and poverty levels and thus confound the relationship with the natural regrowth area. That is, we controlled for household characteristics that have been shown, in other studies, to be significant predictors of dietary quality or poverty levels, including household size (in 2012)^{47,48} and the MPI education level of the household (in 2012)⁴⁹. The education dimension considers a household deprived if (1) no eligible household member has completed 6 years of schooling, or (2) any school-aged child is not attending school up to the age at which they would complete class eight⁴⁶. As with the living standards dimension of the MPI, the index range is 0–1 (with 0 being not deprived, and 1 being the most deprived).

We note that when using dietary quality metrics as the outcome variable, we also controlled for people's MPI living standard (in 2012) as a proxy for economic status as (off-farm) income has been shown to positively affect people's nutrition in Nigeria⁵⁰.

Moreover, we identified various important geographical variables shown to affect diet quality or poverty levels: distance to the nearest major road in 2012 as a proxy for market access, which is known to influence people's diets¹³, elevation and slope (all three variables were produced by the LSMS team), population density in 2010 (gridded population of the world (GPW), version 4)⁵¹, forest cover in the 'baseline' year 2000 (i.e., before regrowth), and forest cover change during the regrowth period 2000–2012. All geographic variables were estimated as the mean in a 10 km radius circle surrounding households. Finally, we included whether the area was classified as urban or rural in the LSMS survey.

To assess forest cover, we extracted data in the 'baseline' year (2000) before the regrowth happened. We used the publicly available 30-m-resolution global tree cover dataset²⁷. Using Google Earth Engine, we downloaded the tree cover tiles covering the spatial extent of Nigeria and imported these into R. The imported data showed the percentage of tree cover (ranging from 0 to 100) in each pixel, with trees defined as vegetation taller than 5 m. In 10 km radius circles surrounding each LSMS cluster, we then extracted a percentage of forest (which was accordingly transformed into hectares of forest cover). To create a forest loss variable for the regrowth period 2000–2012, we calculated tree cover in 2012 as tree cover in 2000 minus the pixels that experienced a loss until 2012.

Statistical approach

We tested whether changes in natural regrowth area (hectares) between 2000–2012 affected changes in dietary diversity, fruit and vegetable consumption, and MPI poverty levels over the 6-year period from 2012/2013 to 2018/2019. Note that the regrowth area was our "treatment" variable.

Natural regrowth does not occur randomly across landscapes but rather tends to occur in more isolated, less productive areas^{52,53}. To address this problem, we use a quasi-experimental matching technique (Covariate Balancing Generalized Propensity Scores; CBGPS^{54,55}) to adjust for the nonrandom distribution (selection bias) of natural regrowth, our treatment variable of interest. We use CBGPS because this method has been shown to be robust to model misspecifications and applicable in the case of continuous treatment⁵⁴. The weights minimize the correlation between treatment and observable pre-treatment covariates when included in regression models. Doing so reduces the dependence (endogeneity) between treatment assignment and outcome given covariates. If left untreated, it can bias the estimated effects of regrowth on people's dietary quality or poverty levels. The CBGPS builds on the conventional propensity

score methods for binary treatments in creating inverse propensity score weights⁵⁴. To generate the CBGPS weights, we use the control variables mentioned previously as pre-treatment variables: A 'baseline' dietary metric in 2012 (included either as grams of fruits and vegetables/person/day, a count of unique fruit and vegetable items consumed per day, or dietary diversity score—depending on the outcome variable), household size, MPI household education level in 2012, MPI household living standards in 2012, distance to the nearest road, population density, elevation, slope, forest cover in the baseline year 2000, and forest cover change during the regrowth period 2000–2012.

We used the CBPS package⁵⁴ in R (version 4.1.2) to perform the matching analyses. Correlations between treatment (natural regrowth area) and covariates were sufficiently reduced after matching (Fig. S2). After matching, we performed four regression analyses to correct for any remaining imbalances in covariates. For the outcome variable related to the quantity of peoples' fruit and vegetable intake in 2018 (g/person/day), we fitted a linear model, with natural regrowth area as a key predictor of interest. When using the MPI Living Standard in 2018 as the outcome variable, we used the same model specification without including the 'baseline' fruit and vegetable consumption levels—yet, still controlling for 'baseline' household living standards in 2012. Finally, we conducted quasi-poisson regression analyses to estimate the effect of regrowth on the count of unique fruit and vegetable items consumed over the past 7 days as well as household DDS. All four models were fitted with log-transformed natural regrowth areas due to highly skewed data (Fig. S3). We used both a pairwise correlation matrix as well as the variance inflation factor (VIF) to assess potential collinearity among the independent variables included in our models after fitting regressions. All correlation coefficients were <0.5 and VIF did not exceed a value of 5. For all four models, we used the sandwich package in R to calculate heteroskedasticity-robust (type "HC1") clustered standard errors⁵⁵.

DATA AVAILABILITY

Food consumption and all other socio-economic data are publicly available from the World Bank's microdata library (<https://microdata.worldbank.org/index.php/catalog>). Tree cover data are publicly available on Global Forest Watch's Open Data Portal (<http://data.globalforestwatch.org/>). Regrowth data are available in Fagan et al. (2022). All other relevant data are available in the article and/or SI Appendix. The codes used for this analysis are available upon request.

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AUTHOR CONTRIBUTIONS

L.V.R. and B.d.B. designed the research; L.V.R. performed the analysis with input from B.d.B. M.E.F. and B.d.B. prepared the regrowth data. All authors contributed to the interpretation of results and paper writing.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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