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Establishment success of Brazil nut trees in smallholder Amazon forest restoration depends on site conditions and management

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ABSTRACT

1. Forest landscape restoration (FLR) has gained momentum globally and guidance is needed to identify those species, sites and planting methods that increase restoration success. Incorporating native Non-Timber Forest Product (NTFP) species in FLR approaches provides an opportunity to simultaneously deliver ecological and economic benefits. The Brazil nut tree is one of the most valuable Amazonian NTFP species and could fulfil a cornerstone role in Amazon FLR. However, the factors defining establishment success within Brazil nut restoration activities remain unknown.

2. Here, we evaluate the effect of management practices, restoration site (pastures, agroforestry, secondary forest and canopy gaps in old growth forest) and environmental conditions on the establishment success (tree growth, survival and fruit production) of Brazil nut restoration projects implemented by smallholders in the Peruvian Amazon. We performed a field study at 25 restoration sites of 1–38 years in age, where we conducted measurements on 481 trees and interviewed 21 smallholders. We used mixed effect models to identify drivers of performance.

3. Twenty years after planting, diameter growth in secondary forests was 38%, 34%, and 24% higher than in canopy gaps, pastures, and agroforestry sites, respectively. Survival rate was similar for trees planted in pastures and secondary forests, but 15–20% higher there than trees planted in agroforestry sites, and 7–12% higher than in canopy gaps. Fruit production was 262% higher for reproductive trees in secondary forest sites compared to pastures, but production probability did not differ between restoration sites. These results show that secondary forests are the most suitable sites for planting Brazil nut trees.

4. In addition to restoration site effects, we also found significant effects of management practices. Survival rate increased with application of fire for clearing and weeding and economic investments and decreased with potentially inefficient herbivore protection. Fruit production was lower for trees planted further away from smallholders' homes. These results show that smallholders' management has a substantial effect on establishment success.

5. Our findings suggest a significant importance of post-planting maintenance of trees to increase success of FLR projects. Further, our study shows that evaluation of past restoration activities can guide future forest restoration in tropical landscapes.

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1. Introduction

Forest and landscape restoration (FLR) has gained momentum in tropical forest regions as over 140 Mha of restoration commitments have been pledged across the global tropics through multiple initiatives such as the Bonn Challenge, AFR100, and the 20x20 initiative (Brancalion et al., 2019). Now that commitments are turning into actions on the ground (Dave et al., 2019), guidance is needed to identify those species, sites, and planting methods that ensure sustained restoration success (Brancalion & Holl, 2020; Fischer et al., 2020). FLR is more than increasing tree cover, and can vary from ecological restoration with a large diversity of species, to tree planting with only one or a few valuable species, or other activities that restore a landscape. In general, FLR includes activities and land uses that besides increasing tree cover in human-modified landscapes, promote landscape functionality and conservation of native habitat (Brancalion & Chazdon, 2017). The planting of native species that produce non-timber forest products (NTFPs), such as fruits, resins, ornamental flowers, and seeds, is often seen as a way to combine ecological with socio-economic restoration objectives, which can lead to improved rural livelihoods while promoting smallholder participation in the restoration process (Lamb, 2018). However, very little is known about the factors that define the success – in terms of establishment and productivity – of native NTFP species planting as a FLR strategy.

FLR includes restoring sites with very different environmental conditions, varying from degraded old-growth forests to pastures and from agroforestry systems to secondary forests (Chazdon et al., 2016; Lamprecht, 1989). Light and soil conditions, and species interactions, differ largely across such sites, with implications for the biophysical dimension of restoration success (Rodrigues et al., 2009). Further, trees planted in a restoration setting may suffer from high mortality rates and reduced growth due to, for example, insect attacks, fires, or increased weed cover (Schroth et al., 2000; Sileshi et al., 2008), which can require application of management methods such as removing competing vegetation through tending and weeding and establishing protection against herbivores to increase tree performance (Lamprecht, 1989). So far, the contributions of these three groups of critical factors (species, sites, and planting methods) for NTFP species establishment success in FLR practices appear to have been insufficiently evaluated in tropical FLR projects. Most measurements of restoration success to date have involved assessments of hectares covered or seedling survival in a short timeframe, neither of which is an indicator of ecosystem establishment in the long term (Mansourian et al., 2017). Evaluation of establishment success may provide important input to produce evidence-based restoration guidelines (Brancalion et al., 2020).

One of the most important NTFP- species in South American tropical forests is the Brazil nut tree (*Bertholletia excelsa*). It is considered a cornerstone of Amazon forest conservation (Guariguata et al., 2017; Thomas et al., 2018) and one of the major carbon sink species across the Amazon (Galia Selaya et al., 2017). The nutritious nuts are traded locally and globally. International demand for Brazil nuts has increased substantially over the last two decades (UN FAO, 2020) and is likely to continue to rise. Enrichment planting of Brazil nut trees within FLR initiatives may be a lucrative activity in managed fallows (Bongiolo et al., 2020), providing an opportunity to simultaneously deliver important ecological and economic services (Jansen et al., 2020). There has been a resurgence in interest to plant Brazil nut trees since the 1980′s, which has led to many planting initiatives. These initiatives, often led by local NGOs, governments, and communities, have involved hundreds of thousands of Brazil nut seedlings, planted by smallholders and other actors over thousands of hectares (see e.g. Homma et al., 2014; IIAP, 2018; Mori, 1992). It remains however unclear, which factors determine the success of such small-scale Brazil nut planting efforts.

Some indications are provided by field experiments that have been conducted. Such experiments revealed that planting can be successful in canopy gaps in old growth forests (Moll-Rocek et al., 2014), in secondary forests (Peña-Claros et al., 2002), and on (fallow) agroforestry plantation systems (Corvera-Gomringer et al., 2010; Costa et al., 2009). Among these sites, fallow fields have been shown to provide more favourable conditions for Brazil nut recruitment and regeneration than forest gaps and pastures (Bongiolo et al., 2020; Cotta et al., 2008; Kainer et al., 1998; Paiva et al., 2011), likely due to intermediate light conditions that favour growth but prevent negative effects related to excess radiation (Myers et al., 2000; Peña-Claros et al., 2002). In addition, fruit production has been studied extensively for natural populations (e.g. Jansen et al., 2021; Kainer et al., 2007; Rockwell et al., 2015; Staudhammer et al., 2021; Thomas et al., 2021), but as far as we are aware, not for planted populations.

Although these experimental studies provide clear indications on the importance of planting site for establishment success, they do not provide information on other factors that might be relevant. Possibly other management activities that are applied by smallholders that alter biotic and abiotic factors in favour of the planted trees (e.g. tending, light regime, and herbivory protection) significantly contribute to establishment success as well.

With this study, we aim to evaluate current Brazil nut tree planting practices and relate these to establishment success, in terms of growth, survival and fruit production. We did this through a combination of field measurements and farmer interviews in Madre de Dios, in the Peruvian Amazon. We surveyed 25 sites, which included agroforestry systems, abandoned pastures, secondary forests, and canopy gaps in old growth forest, where Brazil nut trees were planted 1–38 years ago. We documented the methods smallholders currently employ to plant Brazil nut trees and evaluated the effect of these methods and of environmental conditions on establishment success.

2. Methodology

2.1. Study species and area

The Brazil nut tree (*Bertholletia excelsa*), also known as Amazon nut tree or locally as *Castaña*, is one of the most prominent NTFP tree species across the Amazon basin (Guariguata et al., 2017). The nuts of this species have been historically popular thanks to their nutritional attributes. Due to this characteristic, the nuts are an important economic resource for thousands of families in the study region: Madre de Dios, Peru (Fig. 1) (Guariguata et al., 2017). Some households in this region acquire up to 71% of their total household income from forest products and 45–65% of this is income is derived from Brazil nuts (Garrish et al., 2014). Madre de Dios is a highly biodiverse rainforest area with a hot and humid tropical climate, and an average annual temperature of 31 °C and up to 38 °C during the dry season (June – August). Annual precipitation varies from 1600 to 2400 mm and the 5 to 6-month-long rainy season usually begins around December. Multiple rivers dissect the area, which is characterized by nutrient poor alluvial soils. The majority of Madre de Dios' rural population are smallholders within diversified production and land use systems consisting of farming, logging, Brazil nut harvesting, other NTFP collection, small-scale mining and livestock farming (Robiglio et al., 2015). Planting of Brazil nut trees in degraded areas, active and abandoned agricultural fields and in primary forest by smallholders has recently been actively promoted by government and non-governmental programs to improve local livelihoods and to restore degraded areas (IIAP, 2018).

2.2. Quantification of management practices

A total of 21 smallholders were interviewed using semi-structured interviews. By asking questions about management and planting methods we sought insights into the methods that smallholders applied and to quantify these (see Table A1 of the supplementary material for the employed interview format). From the interviews we were able to derive 33 planting and management related variables, which included

variables such as the application of herbivory protection, weeding frequency, plant spacing, and management costs (see Table A2 of the supplementary material for a complete list).

2.3. Site conditions

The 21 smallholders together managed 25 sites, which we categorized based on the restoration site at time of planting and which we classified as: pastures (P, n = 6), agroforestry systems (AF, n = 7),

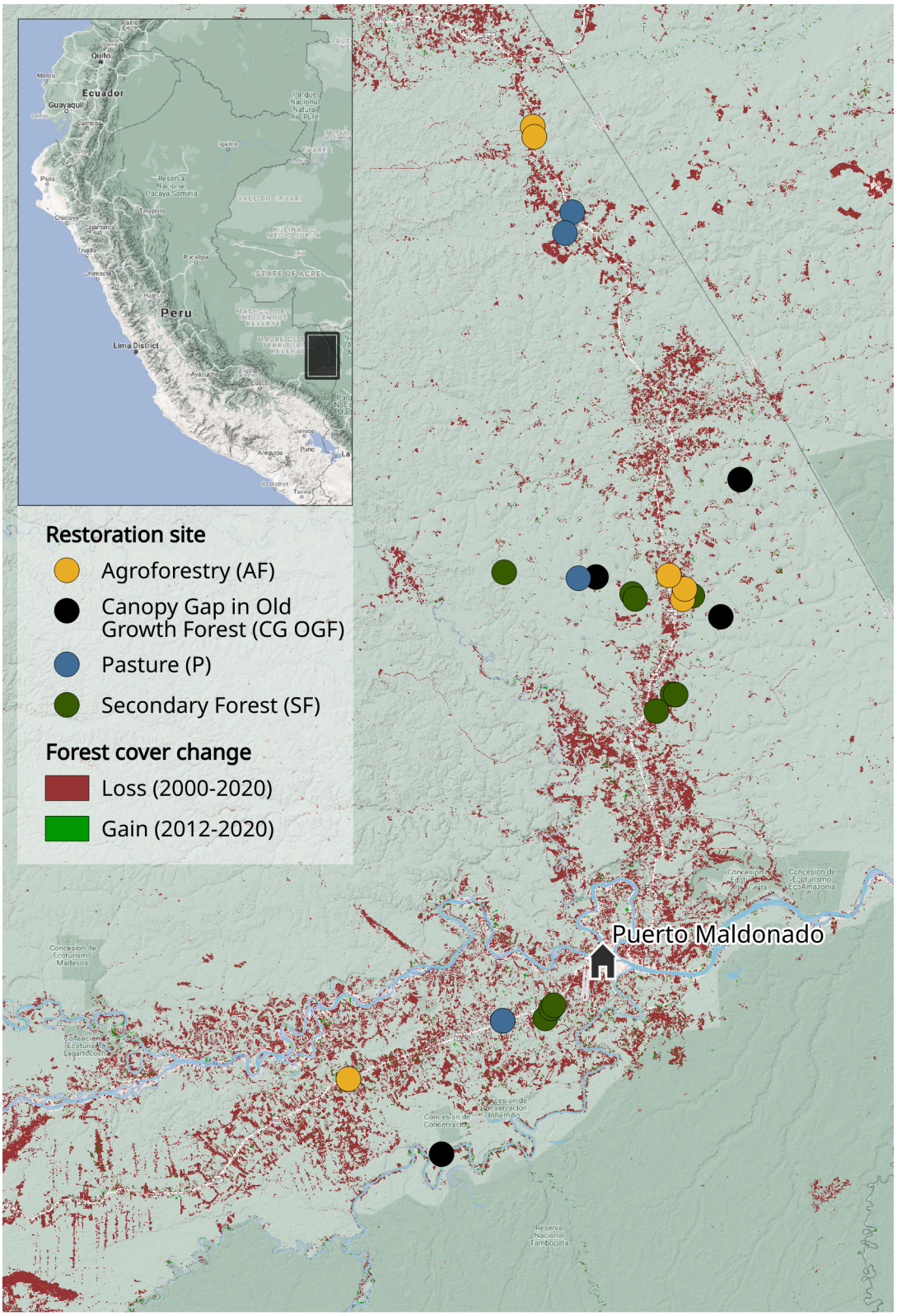

Fig. 1. Geographic distribution of study sites in Madre de Dios, Peru. Study sites are indicated with dots and colour-coded to represent the four types of restoration sites. Forest cover loss and gain is based on the annually updated data set of Hansen et al. (2013).

secondary forest (SF, n = 9) and canopy gaps in old growth forests (CG-OGF, n = 3, Figs. 1 and 2). Trees that were planted in abandoned agroforestry systems, fallows, or young forests were broadly categorised as planted in secondary forests. Sites classified as canopy gaps in old growth forests were either naturally occurring or resulting from selective logging. In our study setup, restoration site was defined as the type of the site at the moment the Brazil nut trees were planted. However, sites may undergo successional changes over time. Trees that were planted in for example pasture, may grow in secondary forest after a number of years if newly grown vegetation is not regularly cleared. Therefore, we also documented the current site vegetation type. At the time of our census we determined whether the site had transitioned to another type (e.g. from agroforestry system to secondary forest), or if it remained in the same type (e.g. agroforestry system that remained an agroforestry system). From this we constructed the following site transition combinations: AF-AF; P-AF, SF-SF; CG-OGF, other combinations were not present or in our dataset or had only 1 replicate and were removed from further analysis.

Tree age, defined as the time since planting of Brazil nut trees on a particular site, ranged from 1 to 38 years, with an average of 12.85 years. In total n = 481 trees were measured within the 25 sites. The number of trees initially planted per site ranged from 25 to 1000. In addition, we measured dominant vegetation height and canopy cover at five randomly selected points within our sites, and estimated the Crown Position Index (CPI) (Clark & Clark, 1992) for each of the measured Brazil nut trees within the sites.

2.4. Establishment success

Establishment success was measured in terms of survival, growth and fruit production. Survival was calculated per site as the ratio between planted and surviving individuals within that site. Growth was defined at the individual tree level as diameter at breast height (DBH) and tree height for up to 20 randomly chosen individuals per restoration site using the random compass method and selecting the nearest Brazil nut tree. For the same 20 trees, productivity (yes/no productive) was determined based on visual inspection, which was confirmed by the smallholders in the field. Estimations of nut production in kg per tree were provided by smallholders based on their memory (which have been shown to be relatively accurate in the case of Brazil nut gatherers, Thomas et al., 2017).

2.5. Data analysis

To test the effect of restoration site on establishment success over time, we use mixed effect regression analysis (for DBH, height and nut production in kg) and regression analysis (for survival rate). Trees that were not producing were not included in the nut production model. In all models, age, restoration site, and an interaction between age and restoration site were included as fixed effects; and site was included as a random effect in the mixed effect models. To evaluate the effect of succession within restoration sites on establishment success, we performed an additional analysis in which the transitions from one restoration to another vegetation site type were included. All models were fitted in R (R Core Development Team, 2011) using the lme4 package (Bates et al., 2014).

Further, we applied orthogonal transformation to discover patterns in currently applied management methods. All enrichment planting and management variables applied by 21 smallholders were analysed using Factor Analysis for Mixed Data (FAMD), which is a principal component method to explore data comprising both continuous and categorical variables (Pagès, 2004), to detect patterns in management. Lastly, we used mixed effect regression analysis to determine the effect of management and environmental variables on establishment success (i.e. DBH growth, height growth and production chance), and linear regression analysis for survival rate. We included the five highest correlated management variables of the first three axes of the FAMD analysis as fixed effects in these models. A more detailed description of the methodology and data analysis is given in the supplementary material.

3. Results

3.1. Effect of restoration site and age on establishment success

We found that trees planted in secondary forests (SF) reached significantly larger DBH over time compared to trees planted in canopy gaps in old growth forest (CG) and pastures (P) ($p = 0.040$; $p = 0.018$ respectively; $R^2_m = 0.66$, $R^2_c = 0.81$, Fig. 3a, and Table A4), and non-significantly in agroforestry systems (AF, $p = 0.056$). There were no significant differences between the other restoration sites. To illustrate, at age 20, the DBH of trees planted in secondary forest, was estimated to be a factor 1.39 higher than trees planted canopy gaps in old growth forest (DBH after 20 years was CG = 25.3 cm; AF = 28.2 cm; P = 26.1 cm and SF = 35.0 cm). In terms of height growth trees planted in secondary forest, and pasture performed significantly better than the trees planted in canopy gaps in old growth forest during the initial years after planting (SF $p = 0.002$; P $p = 0.024$, $R^{2m} = 0.68$, $R^{2c} = 0.89$, Fig. 3b, and Table A4). Trees planted in secondary forest also performed better than trees in planted in agroforestry systems ($p = 0.043$). We also found a significant interaction effect between age and site, with trees planted in canopy gaps in old growth forest performing better when they grow older compared to trees planted in secondary forest and pasture (SF $p = 0.002$; P $p = 0.001$). No significant interaction effect was found between agroforestry and age. To illustrate, at age 20, the height of trees planted in secondary forest and canopy gaps in old growth forest were estimated to be factor 1.35 and 1.46 higher than that of trees planted in pasture (height after 20 years was CG = 20.1 m; AF = 17.5 m; P = 13.8 m and SF

Fig. 2. Illustrations of the four types of restoration sites included in the study. From left to right: abandoned pastures (P), agroforestry systems (AF), secondary forests (SF), and (gaps in) old growth forests (CG-OGF).

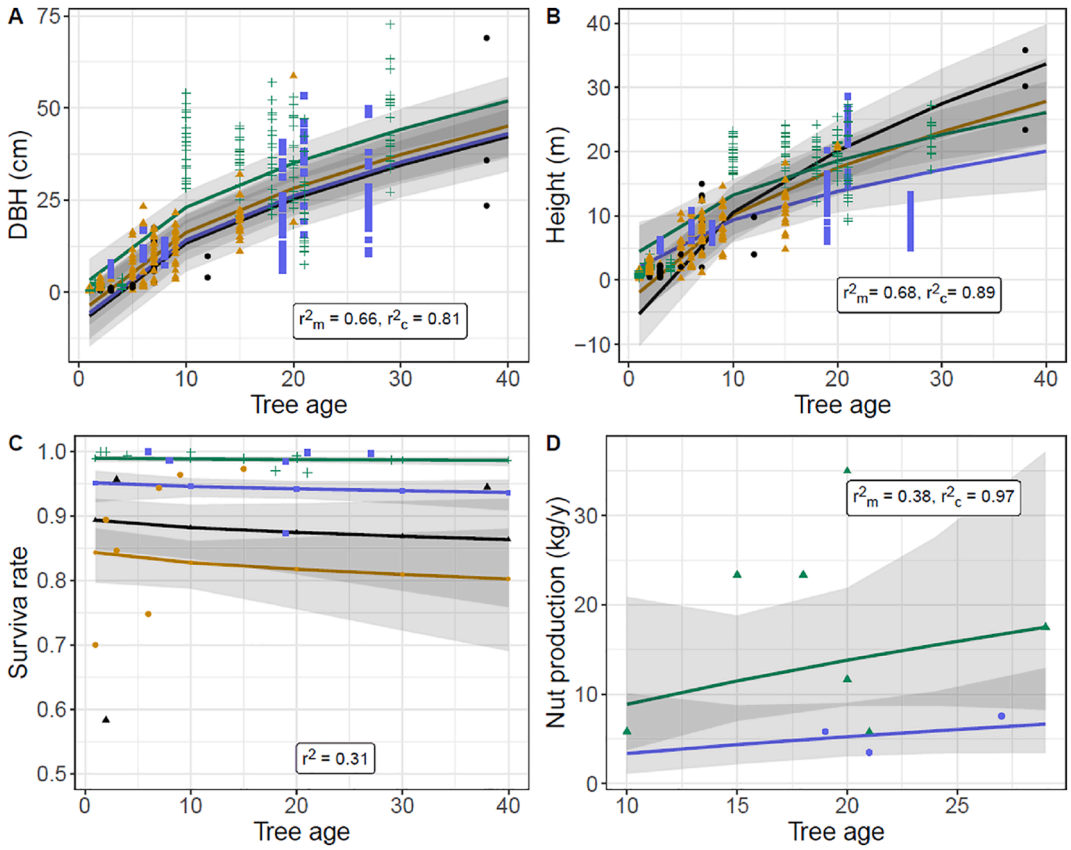

Fig. 3. Results of mixed effect models for DBH **(A),** Height **(B)**, Survival rate **(C)**, and Brazil nut production in kg **(D)**, as a function of tree age (i.e., time since start of restoration). Points and lines are colour-coded by restoration site (green = secondary forest SF, black = canopy gaps in old growth forests CG, yellow = agroforestry systems AF, and blue is pastures P). Regression lines for AF and CG-OGF are missing in the nut production figure because no trees were producing here at the time of our census Ribbons show 95% confidence intervals; R^2m indicates the variance explained by the fixed effects; R^2c indicates the variance explained including the random effect. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

= 18.6 m). Further, survival was highest for trees planted in pasture and secondary forest sites, and lowest in trees planted in agroforestry systems (SF p = <0.001; P p= <0.001, R^2 = 0.31, Fig. 3c and Table A4) and canopy gaps in old growth forest (SF p=<0.001; PF p = 0.002). At age 20 years, the survival of trees in secondary forest and pasture was estimated to be a factor 1.21 and 1.15 respectively higher than trees planted in agroforestry systems. Survival rates did not significantly differ between trees planted in canopy gaps in old growth forest and those planted in agroforestry systems (p = 0.051).

We found that 90 of 481 trees were producing nuts. Nut production only occurred in trees planted in canopy gaps in old growth forest, secondary forest and pasture. Canopy gaps in old growth forest was removed from our model because there were too few producing trees planted within canopy gaps to include in the model. The youngest reproductive tree we found was 9 years old, while the smallest DBH for a reproductive tree was 10.4 cm, and the shortest height was 5 m. We found that nut production in kg per tree was higher in trees planted in secondary forests sites compared to trees planted in abandoned pastures (p = 0.037 R^{2m} = 0.38, R^{2c} = 0.97, Fig. 3d and Table A4). At age 20, the nut production of trees planted in secondary forest was estimated to be factor 2.62 higher than trees planted in pasture (nut production in kg per tree after 20 years was P-SF = 5.26 kg; and SF-SF = 13.82 kg). In all models we also tested for interactions between restoration site and tree age. Interactions only remained in the final selected best model for tree height.

The results of the analysis in which we evaluated the effect of site transitions (i.e successional changes within sites) on establishment success were similar to the results for the restoration site models described above (see supplementary material, Fig. A2 and Table A5).

3.2. Currently applied management methods

We were able to quantify 33 planting and management related variables from our semi-structured interviews. A complete list of these variables with their units or category levels can be found in the supplementary material (Table A2). FAMD analysis over these 33 management variables yielded 3 axes that were retained. These axes respectively explained 16.5%, 12.2%, and 11.7% and cumulatively 40.49% of variation in tree establishment measures. The first axis was mostly associated with geographical and environmental location of a restoration site, the second axis with restoration site and site preparation measures, and the third axis with herbivory measures, seed origin, and management costs (which mostly consisted of labour costs). The first and second axes are shown in Fig. A1 and describe differences in applied management in Brazil nut enrichment planting. Some variables contributed above average (>3.03%) to an axis and thus explained variation in enrichment plantings better (top 5 of the most contributing variables per axis is shown in Table 1).

3.3. Effect of management and environmental conditions on establishment success variables

3.3.1. Survival

We found significant effects of eight explanatory variables on survival rate (Fig. 4A and Table A6 in the supplementary material). Survival rates of the planted trees were positively related to per hectare economic investments in management and occurrence of fire damage (p = 0.007 and p = 0.033 respectively). Additionally, trees planted in secondary forest and pasture sites had higher survival rates, compared to

Table 1
FAMD Top five above average contributing variables per axis.

Variable description	Axis 1	Axis 2	Axis 3
Current site type: secondary forest, agroforestry system, old growth forest	9.0%	13.4%	
Restoration site: the site type during planting; Agriculture, canopy gap, pasture, secondary forest	8.9%	14.5%	
Distance from site to community in km's	7.7%		
Area (m^2) available per individual plant	6.2%		
Fire damage to plants y/n	6.3%		
Herbivore protection type		11.6%	13.5%
Herbivore protection y/n			12.5%
Duration of protection measures			12.4%
Type of area cleared before planting (clear-cut, strip etc.)		9.2%	
Line planting, random planting		9.0%	
Origin of seeds/seedlings			11.4%
management costs/ha			6.6%

All management practices were divided into three rough categories based on the axes derived from the FAMD analysis (axis 1 = geographical and environmental location, axis 2: restoration site and site preparation measures, axis 3 = Herbivory measures, seed origin and management costs). Contribution of variables to each axis are shown in the table as percentages, which excludes the variables that contributed below average to all three axes.

trees that were planted in agroforestry systems or canopy gaps in old growth forest sites ($p = <0.001$). On the other hand, establishing herbivore protection to protect seedlings negatively affected survival rates ($p = 0.003$).

3.3.2. DBH growth rates

The model that best explained DBH growth rate contained nine of the thirteen explanatory variables, explained 38.74% of the variance when only fixed effects are considered and 72.48% including the random effect of site. DBH growth rate was significantly higher for trees planted in secondary forest compared to agroforestry systems and canopy gaps in old growth forest sites ($p = 0.009$). Trees with a higher CPI, which are receiving more light, also had significantly higher DBH growth rates (CPI 5 $p = 0.001$; CPI 4 $p = <0.001$; CPI 2L $p = 0.033$; and CPI 3 $p = 0.004$). Management variables did not have a significant effect on DBH growth rate (Fig. 4B and Table A7 in the supplementary material).

3.3.3. Height growth rates

The model that best explained height growth rate contained eleven of the thirteen explanatory variables, explained 34.41% of the variance (only fixed effects) and explained 64.95% of the variance including the random effect of site. Trees with a higher CPI, which are receiving more light, also had significantly higher height growth rates ($p = <0.001$), while too much light is unfavourable since our model showed that canopy cover also has a small positive effect on height growth rate ($p = 0.026$). Height growth rate decreased with tree age ($p = <0.001$). No significant differences in height growth rate between restoration sites were predicted in our model (Fig. 4C and Table A8 in the supplementary

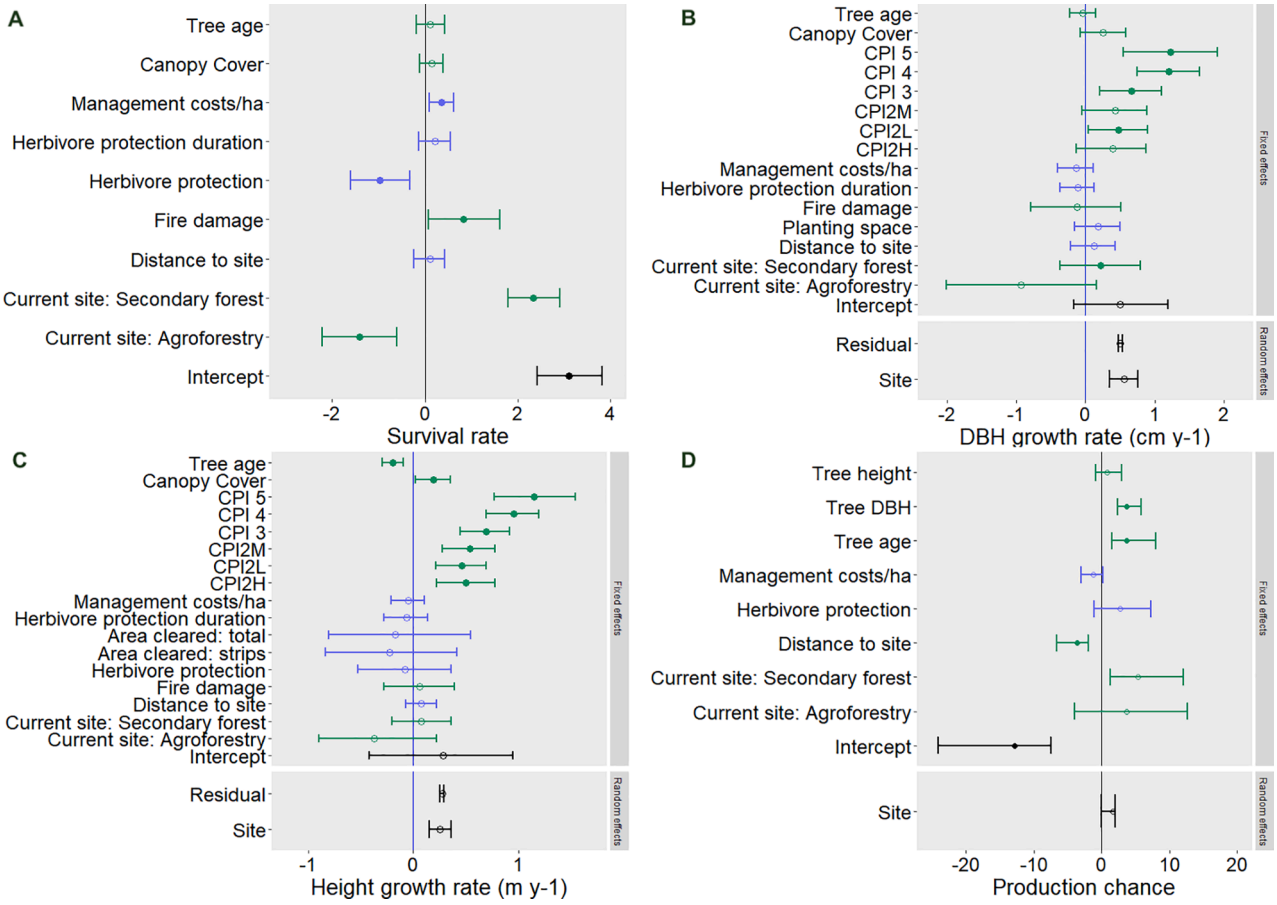

Fig. 4. Results of mixed effect models for survival **(A)**, DBH growth rate **(B),** height growth rate **(C)**, and production chance **(D)** showing the estimates of normalized predictor variables of the best fitted models with 95% bootstrap confidence intervals. Variables relate to the current state (green) of the restoration site, or to the management (blue) applied on the plantation. Significant predictors are indicated by the filled dots, fixed and random effect (site) are shown separately for B, C and D. CPI = Crown Position Index. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

material).

3.3.4. Nut production

The nut production (in kg) model, including management variables, did not retain any significant predictors after refitting with REML. We also modelled production chance (producing yes/no). The model that best explained production chance contained eight of the fifteen explanatory variables, including tree height and DBH. The variance explained by the production chance model was 93.27% (only fixed effects) and 96.31% including the random effect of site. Trees that were older and had larger DBH had a higher production chance ($p = 0.007$, and $p = <0.001$ respectively), while trees that were located further from the owner's home (distance to site) had a lower production chance ($p = <0.001$) (Fig. 4D and Table A9 in the supplementary material).

4. Discussion

In this study, we evaluated the drivers of establishment success of Brazil nut trees planted within restoration initiatives, including the importance of restoration site and management. Our study is the first to simultaneously evaluate how environmental and management factors drive establishment success and productivity of NTFP enrichment planting in a restoration setting, conducted by local smallholders.

4.1. Effect of restoration site, management and biophysical conditions on establishment success

Our results clearly show that establishment success of Brazil nut trees was higher in secondary forest compared to other restoration sites, in terms of survival, growth and fruit production. Twenty years after planting, diameter growth in secondary forests was 24–38% higher than in the other restoration sites, while height growth was initially highest in secondary forests and pastures. Yet, over time this trend changed to higher height growth in canopy gaps in old growth forests and after 20 years trees planted in agroforestry systems, secondary forest and canopy gaps were 26–45% taller than those planted in pastures. It should be noted though that the relatively high performance of trees planted in canopy gaps at later ages could be the result of a small sample size at these ages biased towards those trees that were planted in canopy gaps years ago. Fruit production of trees planted in secondary forest was 2.62 times higher than in that of trees planted in pastures. Survival rate was 15–20% higher for trees planted in secondary forests (and pastures) compared to those planted in canopy gaps in old growth forest and agroforestry sites. Further, we found that, apart from restoration site, establishment success was associated with herbivore protection (negative effect on survival), managements costs per hectare (positive effect on survival) and distance to site (negative effect on production chance).

The highest establishment success in secondary forest compared to other restoration sites is in line with experimental studies on Brazil nut planting. Such studies have shown that Brazil nut trees regenerate better under disturbance (including secondary forests (Bongiolo et al., 2020), degraded areas (Porcher et al., 2018), crop fields (Scoles & Gribel, 2021), and canopy gaps (Garate-quispe et al., 2020)), compared to the understories of mature forests; although Kainer et al. (1998) did not find any significant difference in two-year seedling survival among forest gaps, agroforestry systems, and pastures. Several studies have shown that growth rate of (planted) Brazil nut seedlings is higher in partly cleared areas compared to untouched vegetation and within total clearings (Myers et al., 2000; Peña-Claros et al., 2002; Zuidema, 2003).

Previous studies have suggested that the higher establishment success of Brazil nut seedlings in secondary forest compared to other restoration sites is related to the intermediate light conditions in these sites (Garate-quispe et al., 2020; Peña-Claros et al., 2002). However, a recent study found that survival was highest in crop fields with nearly 100% light exposure (Scoles & Gribel, 2021). An explanation for our low survival rates in agroforestry systems could be that excess radiation has an negative effect on soil water content of exposed soils, which can lead to increased drought stress of the seedlings (Hall & Ashton, 2016). Indeed, our field observations indicated a higher fraction of bare soil in agroforestry sites compared to secondary and old growth forest sites. The positive effects of CPI on growth and survival, also suggest improved performance at higher light availability (i.e. high CPIs). The positive effect of canopy cover on growth and survival on the other hand suggests the opposite, however this is likely to be the result of established Brazil nut trees that are part of the canopy layer (and therefore have a high CPI).

Other explanations for the observed differences in Brazil nut performance among restoration sites could be differences in level of herbivory, and climate. According to interviews with smallholders in our study, tapirs and agoutis are the main cause of herbivory of Brazil nut seedlings, of which the former is more likely to occur in old growth forests and the latter in agroforestry systems. Herbivore pressure by insects has also been shown to be higher in old growth forests than in fallows (Cotta et al., 2008). Several of the smallholders in our study used protection against herbivores. Herbivore protection was however negatively related to seedling survival (possibly due to inefficient measures). The studied sites were planted at different moments in time and were thus subject to different climatic conditions over time, which could have affected tree growth rates (Toledo et al., 2011). Further, the relatively higher fruit production at secondary forest sites could be related to a higher abundance of pollinators in secondary forests compared to landscapes that are under more anthropogenic influence such as pastures (Campbell et al., 2018), consistent with negative effects of forest degradation on Brazil nut production (Jansen et al., 2021) and suggestions of pollinator limitation in Brazil nut plantations (Cavalcante et al., 2018).

A small proportion of the large number of tested management factors had a significant effect on establishment success. Apart from the negative effect of herbivore protection (discussed above), we found a positive effect of management costs on seedling survival, which could be related to a combination of more frequent weeding (and thus higher labour costs) and the application of fertilizers, herbicides and pesticides. However, individually these management factors did not reach the top five of most contributing variables, and were therefore not included in the final analysis. This suggests that these management activities may be more effective when combined, than when applied separately.

The positive effect of the presence of fire damage on seedling survival seems to be counterintuitive, but is consistent with studies showing positive fire effects on Brazil nut regeneration and re-sprouting (Paiva et al., 2011; Porcher et al., 2018). Nevertheless, fires likely reduce pollination and together with other processes of forest degradation, this could have a negative effect on Brazil nut reproductive capacity (Chiriboga-Arroyo et al., 2020) and productivity (Corvera-Gomringer et al., 2010) and should certainly not be promoted as weeding or clearing practice.

4.2. Implications for FLR practices

Our evaluation of the long-term success of tree planting activities suggests a pivotal role of restoration site in determining Brazil nut survival, growth, and reproduction. Further, our results revealed that planted Brazil nut trees were quite intensively managed (including herbivore protection, tending, and the application of fertilizer), suggesting that restoration success can be improved by enhanced post-planting maintenance that extends for many years after planting. In this regard, the NTFP-based forest restoration activities that we investigated here differ markedly from the common practice of short-term (typically 1–3 year) of post planting maintenance in restoration sites (Vieira et al., 2009). For Brazil nut planting by smallholders, we found tending to continue up to decades after planting. For other planted tree species, intensive management such as anti-herbivory measures, weed control and applying fertilizer was shown to increase seedling growth

and survival (Devine et al., 2007; Sweeney et al., 2002) and lead to rapid forest canopy closure on abandoned agricultural lands (Campoe et al., 2010). When restoration sites are heavily degraded, more intensive interventions might be necessary to achieve establishment success (Chazdon, 2008), and this may also apply to the more degraded sites in our study (pastures and agricultural fields). Manuals for planting and managing Brazil nut trees exist (e.g. Corvera-Gomringer et al., 2010), but these are largely based on experimental studies (although some NGOs have started to get in-practice experience in collaboration with smallholders). Smallholders-based restoration activities differ in three important respects.

First, smallholders' reality often does not match such experimental settings, largely because smallholders lack the means to implement suggested costly management activities. This implies that in smallholder-based restoration activities, more focus should be given to restoration site and less to cost-intensive management practices. Second, in smallholder-based restoration activities, it is crucial to understand the motivation. Our interviews showed that the main motivation to plant Brazil nuts was to improve livelihoods. This implies that the long-term success of smallholder-based restoration projects importantly depends on the economic rewards for landowners and land users, and not on the recovery of ecosystem functions and processes. Thus, increased income and food security may help incentivise smallholders to restore forests if planted species are economically valuable tree species (Lagneaux et al., 2021; Vieira et al., 2009), a tactic that is applied in many restoration initiatives (Bosshard et al., 2021). Therefore, planting Brazil nut trees in secondary forest or planting NTFP species like Brazil nut trees in combination with other species by smallholders can fulfil both socio-economic and ecological restoration goals (Jansen et al., 2020). Third, a likely additional benefit of smallholder NTFP-based restoration projects is that more labour-intensive post-planting management can be applied, which supports tree performance and establishment success. The current decade on ecosystem restoration, declared by the United Nations, provides an excellent opportunity to consider FLR in the tropics from a social-ecological perspective and evaluate past restoration activities (Fischer et al., 2020). Fortunately, the many initiatives, like the one studied here, allow us to learn from past successes and failures, and will help to improve FLR projects during this and following decades.

CRediT authorship contribution statement

Rens G. Brouwer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization. **Pieter A. Zuidema:** Supervision, Conceptualization, Formal analysis. **Fidel Chiriboga-Arroyo:** Supervision, Conceptualization. **Manuel R. Guariguata:** Validation. **Chris J. Kettle:** Validation. **Francisco Ehrenberg-Azcárate:** Data curation. **Julia Quaedvlieg:** Methodology. **Mishari R. García Roca:** . **Ronald Corvera-Gomringer:** . **Flor Vargas Quispe:** Data curation. **Merel Jansen:** Supervision, Conceptualization, Formal analysis.

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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Data availability statement

Data will be made available on the Dryad Digital Repository.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119575.

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