Forest Ecology and Management 464 (2020) 118019

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Swidden fallow management to increase landscape-level Brazil nut productivity

Eduardo S. Bongiolo[a,*], Karen A. Kainer[a,b], Wendell Cropper[a], Christina L. Staudhammer[c], Lúcia Helena de Oliveira Wadt[d]

[a] University of Florida, School of Forest Resources and Conservation, Gainesville, FL 32611-0410, USA
[b] University of Florida, Center for Latin American Studies, Gainesville, FL 32611-0410, USA
[c] University of Alabama, Department of Biological Sciences, Tuscaloosa, AL 35487, USA
[d] Centro de Pesquisa Agroflorestal de Rondônia (Embrapa Rondônia), BR 364, km 5,5, Caixa Postal 127, CEP 76815-800 Porto Velho, Rondônia, Brazil

ABSTRACT

Brazil nut (*Bertholletia excelsa* Bonpl.) is considered the cornerstone non-timber species of Amazonian conservation. Nuts (or seeds) of this massive tree are harvested by local people living in and near old growth forests, supporting local livelihoods and regional economies. Secondary forests, however, particularly plots previously used for agriculture (swidden fallows), present better *B. excelsa* seedling and sapling recruitment than mature forest. This study examines the extent to which forest residents could increase nut productivity by allowing their fallows to grow into Brazil nut rich forests. We conducted *B. excelsa* inventories in the Brazilian state of Acre in abandoned swidden fallows of different ages. We also conducted interviews to determine landowner perspectives on the fallow potential for increasing nut production. An individual-based model, based on in-situ inventories and primary and secondary datasets from prior fieldwork, simulated growth, survivorship and production from the 250 inventoried trees in 18 fallows of varying sizes (from 0.41 to 4.18 ha) and different regrowth stages (12 to 60 years old). These simulation model predictions showed that after 10 years, 2.4% of existing trees would be productive, with an average of 68.6 ± 21.5 fruits per reproductively mature tree in the four fallows that most quickly yielded productive trees. By the final projected time interval (40 years), predictions suggest all fallows will produce fruits with cumulative production averaging 1475 ± 359 fruits ha^{-1}, suggesting an increase in landowner income of US$55.1 ± 13.4 per hectare of fallow. Our simulation model is the first to explore fruit productivity of Brazil nut in secondary forest. It likely underpredicts *B. excelsa* growth and nut production, considering that swidden fallows provide better resource availability than the forest-derived datasets we used to construct the model equations. In conclusion, our findings support previous research that suggests that higher *B. excelsa* recruitment rates observed in abandoned swidden fallows could indeed translate into greater adult densities and thus potentially, higher nut production – a conclusion mirrored by most participant landowners.

1. Introduction

Brazil nut (*Bertholletia excelsa Bonpl.*) has been identified as the ‘cornerstone of Amazonian conservation’ (Clay, 1997; Ortiz, 2002; Guariguata et al., 2017). It occurs across the entire Amazon basin (Mori and Prance, 1990). Almost all nut (seed) harvests are from old growth forests and collection appears to be sustainable (Zuidema and Boot, 2002; Wadt et al., 2008; Scoles and Gribel, 2011; Ribeiro et al., 2014; Bertwell et al., 2017, but also see Peres et al., 2003). Critically, the thriving Brazil nut market substantially supports local livelihoods and regional economies (Stoian, 2005; Cronkleton and Pacheco, 2010; Coslovsky, 2014; Kainer et al., 2018). Duchelle et al. (2011) determined that nut revenues correspond to up to 43% of small landholder incomes in the tri-frontier region of Madre de Dios, Peru, Acre, Brazil and Pando, Bolivia. Moreover, prices received by nut harvesters have doubled in Bolivia from 2009 to 2015 (Soriano et al., 2017). In Brazil, prices surged even more dramatically, increasing over 14-fold in the last 20 years (IBGE, 2018). These findings suggest that Brazil nuts are an extremely valuable forest commodity, motivating harvesters and policymakers alike to conserve Brazil nut-rich standing forests.

Studies have shown that disturbed or secondary forest, particularly plots previously used for agriculture (swidden fallows), present better *B. excelsa* seedling and sapling recruitment than mature forest (Kainer et al., 1998; Cotta et al., 2008; Paiva et al., 2011). Swidden agriculture is defined by Fearnside (1990) as the process by which small patches of forest are cleared, burned, planted for subsistence crop production, and once no longer suitable for agriculture, abandoned to fallow. These fallows (or secondary forests) can either grow into mature forest or be cleared again in a few years to initiate the swidden process all over again. Compared to old-growth forests, swidden fallows provide better light and soil conditions (Cotta et al., 2008) for more rapid growth of *B. excelsa* trees, which could translate into forests with higher densities of productive individuals. Therefore, abandoning fallows to grow into forest (versus clearing again for agriculture) could potentially enhance

* Corresponding author.
E-mail address: eduardosbongiolo@gmail.com (E.S. Bongiolo).

https://doi.org/10.1016/j.foreco.2020.118019
Received 1 August 2019; Received in revised form 16 January 2020; Accepted 22 February 2020
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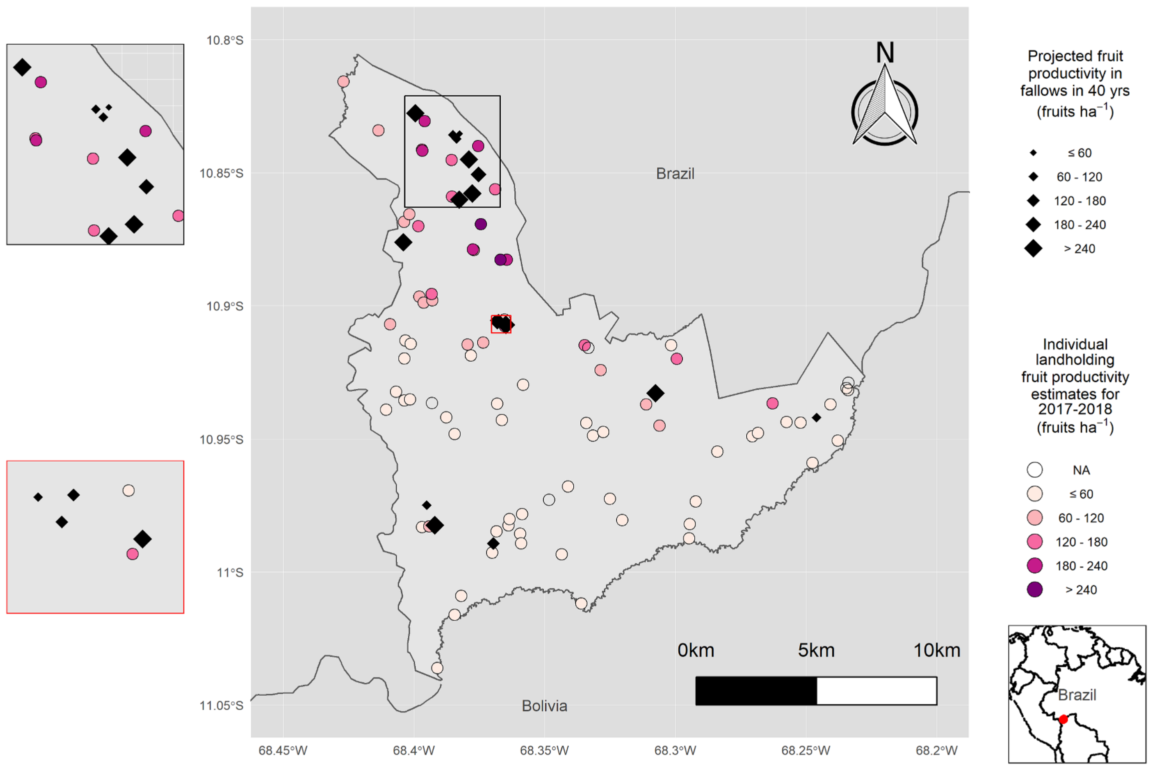

Fig. 1. Distribution of the 18 swidden fallows (in black diamonds) across the study site (PAE Chico Mendes) and their corresponding projected Brazil nut productivity (fruit ha^{-1}) at 40 years. Brazil nut fruit productivity (shades of pink dots) of individual landholdings are based on landowner-reported estimates of total nut production for 2017–18. Dot positions represent house locations at each landholding and GPS coordinates reported were obtained from the Instituto Nacional de Colonização e Reforma Agrária (INCRA).

B. excelsa densities and ultimately nut production, which could significantly increase forest resident incomes and contribute to the sustainability of Brazil nut extraction and forest conservation. Some local landowners also perceive the benefit of fallows to increase Brazil nut production. For example, one forest resident interviewed in the Brazilian Amazon stated that he intended to increase the production of Brazil nuts on his land by abandoning agriculture plots to fallow (Wadt and Kainer, personal communication). Like the more than 290,000 forest residents who live in sustainable use protected areas across the Brazilian Amazon (D'Antona et al., 2013), his family traditionally makes a living through subsistence swidden agriculture and extraction of timber and non-timber forest products, including Brazil nuts.

This research investigates to what extent forest residents could increase Brazil nut productivity by abandoning swidden fallows. Specifically, this study aims to quantify the long-term Brazil nut productivity potential of swidden fallows, addressing the following specific questions:

1. What are the densities and sizes of *B. excelsa* individuals in abandoned swidden fallows of different ages?
2. What are the perceptions of local landowners regarding abandonment of existing swidden fallows to increase Brazil nut production?
3. What is the projected productivity in these fallows into the future, given measured rates of *B. excelsa* growth, diameter at reproductive maturity, and production levels at different diameters?

These findings will be a first attempt to quantify the potential of abandoned swidden fallows to enhance future Brazil nut productivity. The study also reveals preliminary landowner perspectives on the promise of these fallows for potentially enriching Brazil nut production in their landholdings to generate future income.

2. Materials and methods

2.1. Study species

Bertholletia excelsa is a very large and emergent Amazonian tree, occurring throughout the Amazon basin in *terra firme* (non-flooded) forest (Mori and Prance, 1990). Adults can be long-lived; for example, one individual lifespan was estimated at 401 years by growth-ring analysis (Schöngart et al., 2015) and another tree had its age estimated as more than 1000 years by radio-carbon-dating (Vieira et al., 2005). They can reach up to 50 m in height and 3 m in diameter at breast height, measured at 1.3 m above ground level (DBH) (Zuidema, 2003). The species is considered gap-opportunistic (Myers et al., 2000), thriving in environments with higher light availability (Kainer et al., 1999; Cotta et al., 2008). According to Staudhammer et al. (2013), *B. excelsa* achieves canopy dominance and stable diameter growth rates in mature forest when DBH is between 40 and 50 cm.

Fruit production is variable at the population and individual tree levels (Kainer et al., 2007; Tonini and Pedrozo, 2014; Neves et al., 2015) and also between years (Zuidema, 2003; Tonini and Pedrozo, 2014; Rockwell et al., 2015). The reproductive maturity of *B. excelsa* is strongly correlated with DBH. For example, while 96% of 192 trees between 50 and 100 cm DBH had reached maturity in the state of Acre, Brazil (Wadt et al., 2005), only 3.5% of 364 individuals < 40 cm DBH were producing in two sites in the Bolivian Amazon (Zuidema, 2003). Fruits are spherical and large (10–16 cm), and take 14 months on average to reach maturity and fall from the tall, expansive crowns (Maués, 2002), trapping the nuts (which are botanically classified as seeds) inside until opened by scatterhoarding rodents or humans (Peres and Baider, 1997) Nuts per fruit can range from 19.4 ($\pm$ 2.9 SD) in a sample from Pando, Bolivia (Zuidema and Boot, 2002), 17.1 in Pará, Brazil (Peres and Baider, 1997) and 18.0 ($\pm$ 2.6 SD) in Acre, Brazil (Viana et al., 1998). Based on a sample of 60 seeds from each of 10 maternal families, Kainer et al. (1999) estimated that each unshelled nut weighs on average 9.8 (± 2.0 SD) g when fresh (undried).

2.2. Research site

Fieldwork was conducted in the state of Acre, Brazil, in the Chico Mendes Agro-Extractive Settlement Project. The settlement site known as Cachoeira, is located in the municipality of Xapuri, bordering Bolivia (Fig. 1). Vegetation of this region is classified as moist tropical forest, with undulating topography (Holdridge, 1978). It is dominated by open forest with bamboo and spots of dense forest and open forest with palm trees (Governo do estado do Acre, 2010), and has a dry-season that lasts 3 months, from June to August. Cachoeira was safeguarded as a settlement project in 1989 as a direct result of a non-violent social movement by rubber tappers to protect resident livelihoods and the forest on which they depend (Stone-Jovicich et al., 2007). Under this designation, the federal government owns the 24,898-ha area, which is co-managed collectively by residents (hereafter call landowners), who make a living mostly through subsistence agriculture and extraction of timber and non-timber forest products.

Cachoeira is internally divided into individual landholdings, which each landowner manages. While households have considerable rights to and decision-making power over most forest resources (e.g., exclusive rights to harvest and sell all Brazil nuts on their landholding), government guidelines and restrictions also apply. Landowners practice swidden agriculture in previously forested patches for 2 to 3 years (typically planting corn, rice, beans, and manioc) and then move on to the next patch, leaving the first one to regenerate secondary forest (Cotta et al., 2008). This model of cultivation provides small plots (0.5 – 1.5 ha) that normally have at least one edge with mature forest (Cotta et al., 2008). *B. excelsa* adults of reproductive size are typically absent in forest fallows, as agriculture is practiced in areas devoid of valuable Brazil nut and rubber (*Hevea brasiliensis*) trees. There is no precise Brazil nut harvest history for our study region, but commercial collection probably started before 1933, when a nut processing plant was installed nearby and began product exportation (Bakx, 1988). The harvest of Brazil nuts occurs seasonally, with fruits falling from mid-November to early February in our study region (Faustino et al., 2014). Based on a 6.75 ha plot that was embedded within our study area, Oliveira (2011) estimated that 77 to 85% of all fruits that fell to the ground between 2008 and 2010 were collected by the resident harvester.

2.3. In situ data collection

Primary data was collected over two field seasons in May and June of 2017 and 2018. The field component served to assess densities and sizes of *B. excelsa* in 18 swidden fallows. Interviews with current landowners of each measured fallow focused on fallow history and future perspectives.

2.3.1. Area selection

Study areas were selected on a voluntary basis. We first explained the project in a community meeting and asked for resident volunteers who would allow us to assess fallows on their properties. Landowners provided an estimated age of each fallow (the year in which the crop site was abandoned). These initial contacts led us to other interested landowners, using snowball sampling (Bernard, 2011). During this process, a resident also was identified and subsequently employed as a research assistant.

2.3.2. Density and sizes of B. Excelsa in fallows

To accurately mark the edges of each swidden fallow, we walked the perimeter and delineated the fallow with the current landowner. Corner coordinates and fallow perimeters were recorded using a Garmin 78 s GPS (Global Positioning System) unit. With the shape of the area determined and archived, we then separated the fallow into sufficiently small sections that could be walked and inventoried. While fallows were of diverse configurations, our basic inventory approach was to create transect lines every 25 m, which were perpendicular to the longest edge of the plot. The team leader would walk in these guiding transects, while a second member would zigzag between the leader and an imaginary parallel line of 12.5 m from the transect line, searching carefully for all *B. excelsa* individuals greater than 1.5 m in height. Once the end of the first transect was reached (which was one of the edges of the plot), the leader would walk the second transect line while the other team member would search the remaining half of the 25 m transect. This procedure was repeated until all fallow sections were inventoried and all *B. excelsa* individuals were found, marked with flagging and assigned a sequential number for subsequent measurements.

A number of measurements were made on each tree. The first measurements were categorical: (1) Liana cover (0 = no liana coverage of the tree crown; 1 = ≤ 2/3 liana coverage; and 2 = greater than 2/3 liana coverage) and (2) Crown position, using Alder and Synnott (1992) guidelines (Suppressed, Intermediate, Co-dominant and Dominant). Then, a mark was made on the subject tree at 1.3 m in height to be used as a reference to measure DBH with steel metric diameter tapes, and tree height and crown height using a hypsometer (Haglöf – vertex laser VL402). To measure crown width, a measurement tape was held at each crown end under the last leaves that would form the longer width of the tree crown, followed by the same procedure for the transversal axis to the first measurement. Based on these measurements, crown form was afterwards assigned: "poor" crown form to trees with greater than 50% difference between maximum crown width and its perpendicular width, while "good" was used for the rest of the trees. For a handful of trees, crown width could not be measured with precision due to liana cover, and these trees were assigned "poor" crown form. Tree and crown height were also measured using a measuring tape when tree height was within reach; otherwise, the hypsometer unit was used. Individual tree competition was estimated using the same hypsometer unit and applying Bitterlich sampling (also known as "horizontal point sampling") described in Kershaw et al. (2016). In summary, every tree near the subject tree was assessed via horizontal point sampling, measuring its distance to the subject tree and DBH when the nearby tree was considered to be in competition with the subject tree, using a basal area factor of 9 m^2 ha^{-1}.

Statistical analyses of the data acquired in the fallow inventories were performed using the programing language R (version 3.4.3) and the RStudio software companion (version 1.1.414) (RStudio Team, 2016; R Core Team, 2017). Due to the non-normal nature of the data, three non-parametric tests were employed. The relationship between swidden fallow age and DBH was tested using Spearman's correlation coefficient, crown position and the number of competing trees using a Kruskal-Wallis test, and fallow age and DBH distribution using a Wilcoxon rank-sum-test.

2.3.3. Settlement-wide productivity estimates

To put production projections of sampled fallows into context, we estimated the productivity of Brazil nuts for the whole settlement. To do this, the research assistant visited the majority (93%) of the 86 landholdings in the entire 24,898 ha Settlement. Each landowner provided estimates of landholding Brazil nut production for the 2017–2018 period. Area shape files were not available for all Settlement landholdings, and only a little over half had been individually demarcated. Thus, to approximate landholding spatial distribution, GPS points of each house location corresponding to each landholding were obtained from the federal agency responsible for Cachoeira (Instituto Nacional de Colonização e Reforma Agrária - INCRA). Additionally, landholder estimates were used to approximate landholding size where demarcations were lacking. Area and production data obtained were used to estimate productivity (*lata* ha^{-1}) of each landholding. A "*lata*" ("can" in English) is a local measurement unit, corresponding to approximately 11 kg of unshelled nuts before drying (Wadt and Kainer, 2012). Spatial distribution of productivity was represented in the study site map (Fig. 1), which was created using the R packages "sf"(Pebesma, 2018), "ggplot2" (Wickham, 2016) , "raster"(Hijmans, 2017), "ggsn"(Baquero, 2017), "ggpubr"(Kassambara, 2018), "grid"(R Core Team, 2017), and "gridExtra" (Auguie, 2017). To compare these estimates to the fruit projections from the simulation model created during this study, we transformed *lata* ha^{-1} to fruit ha^{-1} using a factor of 62.4 (fruits per *lata*), calculated using the following relational values:

- 1 *lata* ≈ 11 kg of fresh-weighted unshelled nuts (or seeds) (Wadt and Kainer, 2012);
- 1 seed (fresh weight) = 9.8 (± 2 SD) g (n = 600 seeds) (Kainer et al., 1999); and
- 1 fruit = 18 (± 2.6 SD) seeds (n = unknown) (Viana et al., 1998).

2.3.4. Past and future fallow use

A mix of unstructured and semi-structured interviews was used to gather historical fallow information (e.g., age, crops cultivated and frequency of use) and landowner perspectives on fallow potential for Brazil nut production (Approved by IRB: IRB201701118). Interviews were first initiated in the fallow during the delineation process to facilitate discussion and help the landowner feel comfortable. These first unstructured interviews consisted of a discussion with no pre-determined questions, where the content was decided by the informant, and the focus by the interviewer, always with minimal control over the informant's response (Bernard, 2011). Subsequently, at a different opportunity, a line of questioning was pursued to gather additional fallow information and get a sense of how the landowner perceived this project potential. Sites of the 9 landowners whose fallows were inventoried during the first field season were revisited to provide a physical map of their landholding, highlighting the house and fallow(s) locations within his/her property and a summary of each *B. excelsa* tree inventoried in each fallow. This easily led to application of a simple questionnaire with guiding questions to conduct semi-structured interviews (Bernard, 2011) about past and future fallow use. Additionally, an open-ended discussion was initiated regarding the potential of fallows and this research project. This same procedure was followed with three additional landowners who entered the study in the second season, although it was not possible to return a map and inventory summary.

To assess the accuracy of age estimates provided by landowners, we used remotely sensed imagery to locate plots and verify the last clearance event. Using the Landsat 5 historical dataset (1985 to 2010) and two Sentinel-2 images (from 2017 and 2018) available at Google Earth Engine (Gorelick et al., 2017), we searched for changes in vegetation cover around the estimated year which could indicate a clearance event. Some swidden fallows were too small to be definitively identified in the 30 m spatial resolution provided by Landsat 5, but overall, our spot-checked imagery largely verified landowner estimates within a year or two. One remotely sensed image revealed a fallow that was cleared 6 years prior to the landowner estimation. In this unique case, we utilized the age suggested by the remotely sensed analysis.

2.4. Simulating fruit production

To estimate potential productivity of *B. excelsa* in swidden fallows, an individual-based model (IBM), hereafter referred to as a "simulation", was developed, consisting of three models: growth, survivorship and fruit production of the *B. excelsa* populations for the next 40 years. Insufficient information was available to include recruitment of new individuals into the established populations. IBMs simulate each individual in a population as a single object, considering individual trees as the basic unit of a forest (Newnham, 1964; Huston et al., 1988; Liu and Ashton, 1995). Each tree responds differently to environmental stress, growth, and reproductive patterns, and each differs in size, behavior (Liu and Ashton, 1995), and neighbor effects (Huston et al., 1988). IBMs are typically used to mimic forest dynamics by tracking species and size-specific demographic behaviors (DeAngelis and Gross, 1992). Simulation inputs were from two sources: in-situ inventories described above, and primary and secondary data from prior fieldwork, including previously-developed models and corresponding parameter estimates (Staudhammer et al., 2013; Bertwell et al., 2017). Upon scrutinizing the fallow database, five inventoried trees were excluded from the simulation, because they were determined to exist prior to the clearing event. Of these five trees, two preexisting trees were confirmed by the landowner, one tree was planted concurrently with the first crop, and two had diameters incompatible with the claimed fallow age.

2.4.1. Diameter increment equations

To estimate growth for trees with original or calculated DBH < 10 cm (179 inventoried trees), we adapted Staudhammer et al.'s (2013) basal area increment (BAI; $cm^2\ yr^{-1}$) equation for juveniles trees. This equation was based on 54 trees sized 5 cm ≤ DBH < 50 cm, growing on a 420-ha mature forest site within ~ 30 km of our field sites:

$$BAI = -20.508 + 0.023r + 0.702DBH - 8.873f + 4.532cfgp - 1.2939cftp \tag{2-1}$$

where:

- r is rainfall during the preceding three months (mm),
- f is a binary indicator of whether the individual had initiated fruit production,
- $cfgp$ is a binary indicator of crown form (good = 1 vs poor = 0),
- $cftp$ is a binary indicator of crown form (tolerable = 1 vs poor = 0).

Since no trees < 10 cm DBH had initiated production, $f = 0$ in our IBM. Because we only were able to discriminate between good and poor crowns, we combined the tolerable category with the good category, such that $cftp = 0$ in our IBM.

At every annual step of the 40 years (until transition to size of 10 cm DBH), the result from this equation was added to the calculated basal area (BA) of the tree, and the resultant new diameter was used as input in the next cycle of the model. When the 10 cm DBH threshold was crossed, the DBH for that year would be set at 10 cm. To estimate growth of trees with ≥10 cm DBH, we used a second growth equation developed by Bertwell et al. (2017). This second equation was developed based on 174 trees greater than 10 cm DBH ≤ 260 cm located within a 192-ha area of forest within our study site. Additionally, because it is one of the only *B. excelsa* growth models developed from a robust data set that was collected annually and over a long-term period of time (6 years), we consider it to be the best equation to represent growth in our model, even though our study was for fallows, not mature forest. We applied the equation to estimate Diameter at breast height increment (cm $year^{-1}$; d_i) as follows:

$$d_i = 0.3841 + 0.000261r - 0.0000643DBH^2 + 0.000000256DBH^3 \tag{2-2}$$

The result of the equation was added to the previous DBH of trees ≥ 10 cm DBH to determine the new DBH for each year.

2.4.2. Survivorship equation

Bertwell et al. (2017) also developed a 14-year survival model, based on trees growing on the 420-ha site of mature forest located within ~ 30 km of our field sites. The equation for predicted probability of survival over 14 years (P) was as follows:

$$logit(P) = 3.713 - 0.010DBH - 2.636f_1 - 1.086f_2 - 1.487p + 0.607v + 0.761c \tag{2-3}$$

where:

- f_1 is a binary indicator for crown form (poor = 1 vs good = 0),
- f_2 is a binary indicator for crown form (tolerable = 1 vs good = 0)',

- p is a binary indicator for the 'suppressed' crown position ($p = 1$), versus all other classifications ($p = 0$),
- v is a binary indicator for greater than 25% liana load ($v = 1$), versus $\leq$ 25% ($v = 0$), and
- c is a binary indicator for whether lianas were cut

In our IBM, $c = 0$, since lianas were not cut in our fallow trees. As in Equation (2)-(1), we only were able to discriminate between good and poor crowns, combing the good and tolerable categories, such that $f2 = 0$ in our IBM.

To estimate annual survival probability, results obtained by Bertwell et al.'s (2017) 14-year survival model were transformed with the inverse logit function and elevated to the power of 1/14. Integrating stochasticity, our model generated a uniform random number between 0 and 1 and compared it to the survival probability of each tree calculated with Equation (2–3); trees with random numbers less than or equal to this threshold survived.

2.4.3. Fruit production equation

Fruit production was estimated using the equation developed by Bertwell et al. (2017), which assumes that trees under the mature forest canopy initiate production only upon attaining ~ 40 cm DBH (Zuidema and Boot, 2002). Therefore, the equation was only applied to estimate annual production (fruits year^{-1}; F) for trees ≥ 40 cm DBH as follows:

$$F = -192.1 + 5.799DBH - 0.018DBH^2 \quad (2\text{-}4)$$

To provide a basic perspective of potential landowner earnings, projected nut production from fallows on each property was monetized. These earnings were derived from simulated production quantities, Brazil nut values acquired at IBGE/SIDRA (2018), and currency exchange rates from OANDA (2018). While the value of Brazil nut fluctuates year to year, we used average price paid for a *lata* of Brazil nuts (US$ 10.24) in the last five years (2013 – 2017) to reduce the effect of price inflation or deflation.

2.4.4. Rainfall estimates

Annual rainfall data was obtained from the National Institute of Meteorology in Brazil (INMET - Instituto Nacional de Meteorologia, n.d.), which was collected between 1970 and 2017 at the capital city of Rio Branco, Acre (112 km from our study site). Three years were excluded (1978, 1991 and 1992) from the data set, because some monthly data was not available. Average annual rainfall ranged from 933.2 to 2689.4 mm. Rainfall data was selected from the historical data at random for the first year, adding another stochastic element to our simulation. Subsequent years followed the same sequence as the historical data, with the years cycling back to the first year of the data (1970) when following the last year (2014). The same rainfall data was applied to all individuals in the simulation.

2.4.5. Sensitivity analysis and simulation outputs

A sensitivity analysis was conducted to determine how parameters from the equations (intercept and coefficients) and variables of the simulation (i.e., rainfall, crown form, DBH) influenced key outputs. Simulation's variables and equation's parameters were individually and systematically altered to inspect how these changes affected final results.

The simulation was run fifty times and monitored outputs included: average DBH, fruit production, and cumulative fruit production 10, 20, 30 and 40 years into the future. Values equal to zero were excluded when calculating average diameter or fruit production, as DBH was set to zero if the tree died, and production set to zero if the tree was ≤40 cm DBH; therefore, the average production values reported only consider reproductively mature trees.

3. Results

3.1. Swidden fallow profiles

The 18 fallow plots inventoried ranged in age from 12 to 60 years old. All landowners reported that they had initiated the cutting and burning of these plots. All but one reported subsequently planting common crops of rice, corn, beans and cassava before leaving plots to fallow. Four landowners, however, reported planting a second crop cycle prior to fallow. Although some landowners in our region convert agricultural plots to pasture, none did so in our study. Swidden fallows ranged in size from 0.41 to 4.18 ha (Mean ($\bar{x}$) = 1.316, ± 0.830 SD) (Table A-1). *B. excelsa* tree count per fallow ranged from 6 to 47 trees ($\bar{x}$ = 13.889, ± 10.742 SD). Average densities for all inventoried Brazil nut trees were 11.78 (± 7.21 SD) trees ha^{-1}, while for saplings (DBH < 10 cm), average densities were 8.73 (± 6.31 SD) trees ha^{-1} and for juveniles and adults (DBH ≥ 10 cm) average densities were 3.30 (± 2.72 SD). Because participation in the study was voluntary, the 18 fallows sampled were not randomly distributed, but did represent a sizeable portion of the Settlement (Fig. 1). Regardless of fallow age, larger trees had greater light availability than smaller trees as assessed by crown position (Fig. 2). There were no suppressed trees larger than 20 cm DBH, and all trees larger than 30 cm DBH had co-dominant or dominant crown positions. As the age of the fallows increased, a greater fraction of smaller trees was suppressed.

Diameter at breast height was significantly different by fallow age (p-value = 2.2e-16), increasing with fallow age (Fig. 3). Also, DBH had a negative relationship with number of competing trees surrounding each *B. excelsa* individual (p-value = 0.02316, Spearman rho = −0.1436) (Fig. 4). The number of competing trees was also significantly different by crown position (p-value = 0.001763).

3.2. Landowner perspectives on fallow potential

Landowners almost unanimously were surprised at the high numbers and densities of *B. excelsa* individuals encountered in their fallows. This seemed to stimulate them to add that they did not intend to convert the fallow to use for agriculture or pasture in the future. Additionally, two said that if they needed the fallow for other uses, they would try to preserve the existing Brazil nut trees by departing from the traditional slash and burn techniques. This would be accomplished by felling all trees except *B. excelsa*, allowing logs to dry, and then using controlled fire to reduce remaining logs to ash. Four landowners reported that it would be better to manage the fallows to increase *B. excelsa* density and sizes rather than just wait for natural regeneration and growth to occur. One said that it would be interesting to enrich "poor" patches of the forest by planting timber, Brazil nut trees and fructiferous trees to feed humans and game animals once the agricultural cycle was completed. One landowner expressed doubt with our statement that fallows harbor higher densities of *B. excelsa* than mature forest.

3.3. Simulation model results

The integrated simulation model of growth, mortality and fruit production per fallow indicates that basal area per hectare of Brazil nut increases by 2534% (± 707 SE) on average over the 40-year projection period (Fig. 5). The fallows from the three oldest fallow age classes (20–22; 26–29; 48–60) tend to follow a similar increase in basal area through time, regardless of initial fallow age. However, the youngest age class (12–17 years) had the greatest basal area at all future ages when compared to other age classes.

Cumulative fruit production projections obtained by the simulation (Table A-2) showed that after 10 years, 2308 total fruits would be produced in the four fallows that most quickly yielded productive *B. excelsa* trees. In these four fallows, most fruits (96.67%) were produced

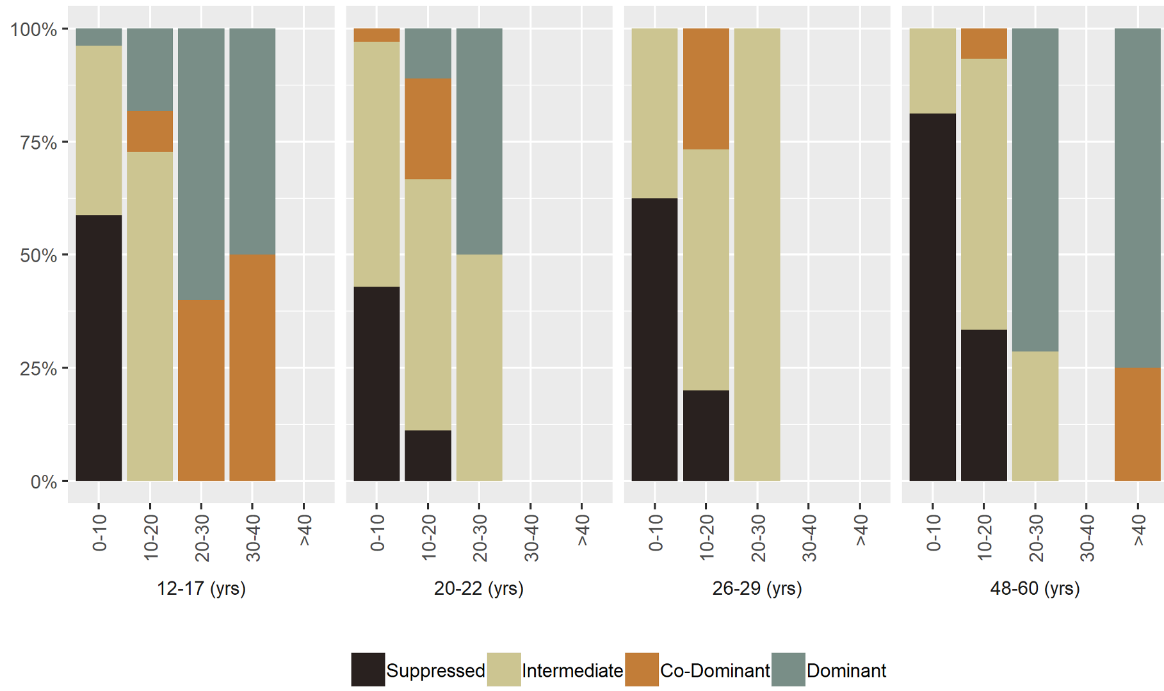

Fig. 2. Crown position (suppressed, intermediate, co-dominant and dominant) of *B. excelsa* by DBH class (cm) in four fallow age classes.

in the two oldest fallows, rather than the two youngest that were under 17 years of age at the time of our inventories. After 30 years, 13 of 18 fallows of all ages were projected to exhibit cumulative production ranging from 14 to 3891 (fruits ha^{-1}). By the final projected time interval (40 years), all fallows were predicted to produce fruits, with cumulative production averaging 1475 (± 359 SE) fruits per hectare.

Projected annual fruit productivity increased over time as more trees achieved reproductive maturity. For example, productivity of Fallow O at 10, 20, 30 and 40 years was 26, 82, 161, 581 fruits ha^{-1}, respectively. Once a fallow started to produce, it tended to increase productivity over time. At 40 years, all fallows were projected to yield fruits ($\bar{x}$ = 319, ± 53 SE fruits ha^{-1}), with three of the youngest class fallows (M, E and L) in the top five productivity fallows (Fig. 6).

At any given decade, once the fallow had started to produce, similarities emerged when comparing projected fallow productivity to the spatial distribution of current productivity obtained from landowner estimates (Fig. 1). This held true except in three low production fallow predictions (A, B and P), located in high production landholdings and visible on the settlement-wide productivity estimates map (Fig. 1). As for the three highest productivity fallows, they were all located in

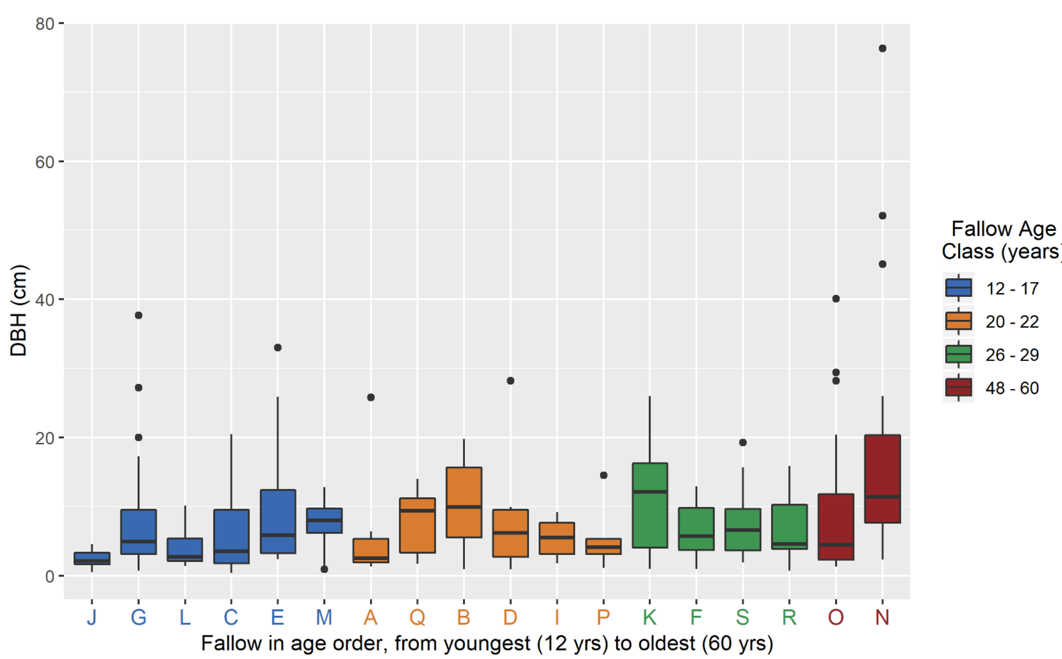

Fig. 3. DBH distribution per fallow arranged in fallow age order. Four fallow age classes were selected based on natural clustering. Boxes encompass the first and third quantiles (25% and 75% of the data, respectively). Horizontal lines are drawn at the median (50% percentile) value. Vertical lines extend 1.5 times the interquartile range above the upper and below the lower quartiles. Observations outside this range are marked separately.

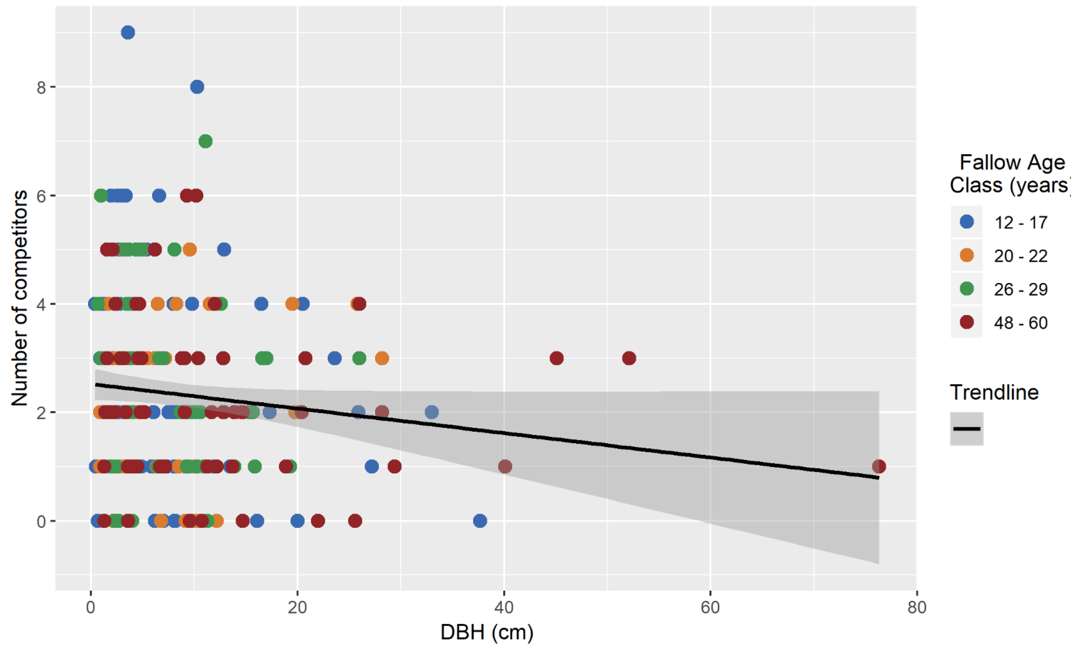

Fig. 4. DBH and number of competitors to every tree in the data set, colored by fallow age class. Trend line and its standard error show a modest negative relationship.

medium to high productivity areas. Finally, the third most productive fallow based on our predictions was generated from the fifth youngest fallow.

Extrapolating from the fallows predicted to produce nuts into the future, our findings suggest that landowners could expect to increase their income per hectare of fallow at every decade by the following USD amounts [based on IBGE/SIDRA (2018) and OANDA (2018)]:

- 10 years: $\bar{x}$ = \$7.5, SE ± 3.99, ranging from \$0.33 to \$27.34
- 20 years: $\bar{x}$ = \$8.38, SE ± 3.89, ranging from \$0.35 to \$36.75
- 30 years: $\bar{x}$ = \$14.55, SE ± 5.21, ranging from \$2.21 to \$57.17
- 40 years: $\bar{x}$ = \$55.06, SE ± 10.48, ranging from \$11.59 to \$151.59

The sensitivity analyses demonstrated that the growth model was especially sensitive to changes in rainfall. Both growth equations returned higher DBH values with higher rainfall, and lower DBH values for lower rainfall.

4. Discussion

Individual tree-based growth models are appropriate for estimating tree growth regardless of species mixture, age distribution, and applied silvicultural systems (Hasenauer, 2006). They can also be used to envision detailed stand structure dynamics, and can be even better than stand level models (Peng, 2000). Understanding individual tree dynamics is valuable to elaborate management on an individual basis as we attempt to do herein to estimate future Brazil nut production of each tree in each fallow.

4.1. Fallow profile

Of the fallows studied, most had a well-defined shifting cultivation cycle, which was practiced similarly by all landowners. Density of saplings (≥1.5 m height and < 10 cm DBH) in our inventoried fallows was higher than that reported by Cotta et al. (2008) from fallows located in close proximity to ours (8.7 (± 6.3 SD) vs 5.2 trees ha^{-1}).

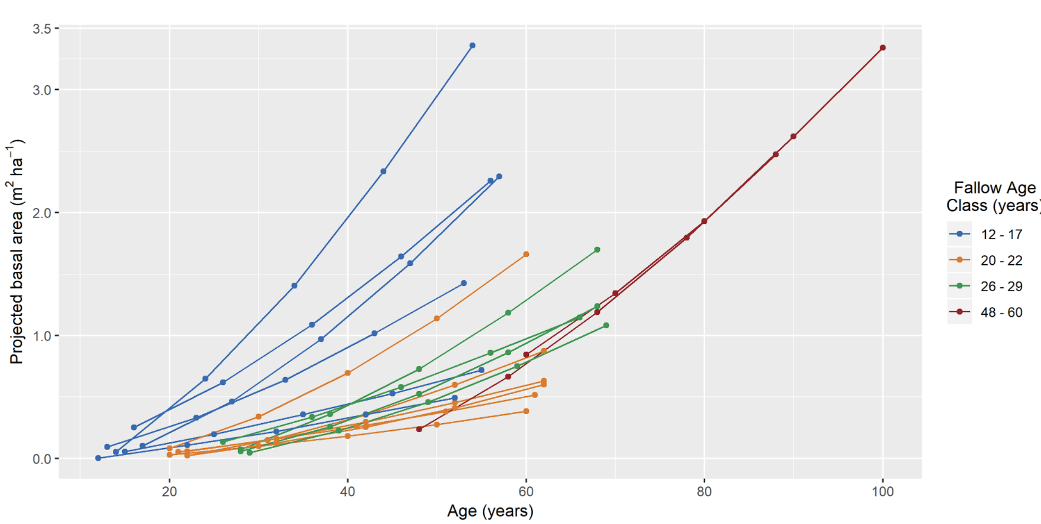

Fig. 5. Average sum of basal area of *B. excelsa* per hectare of each fallow, colored by age class.

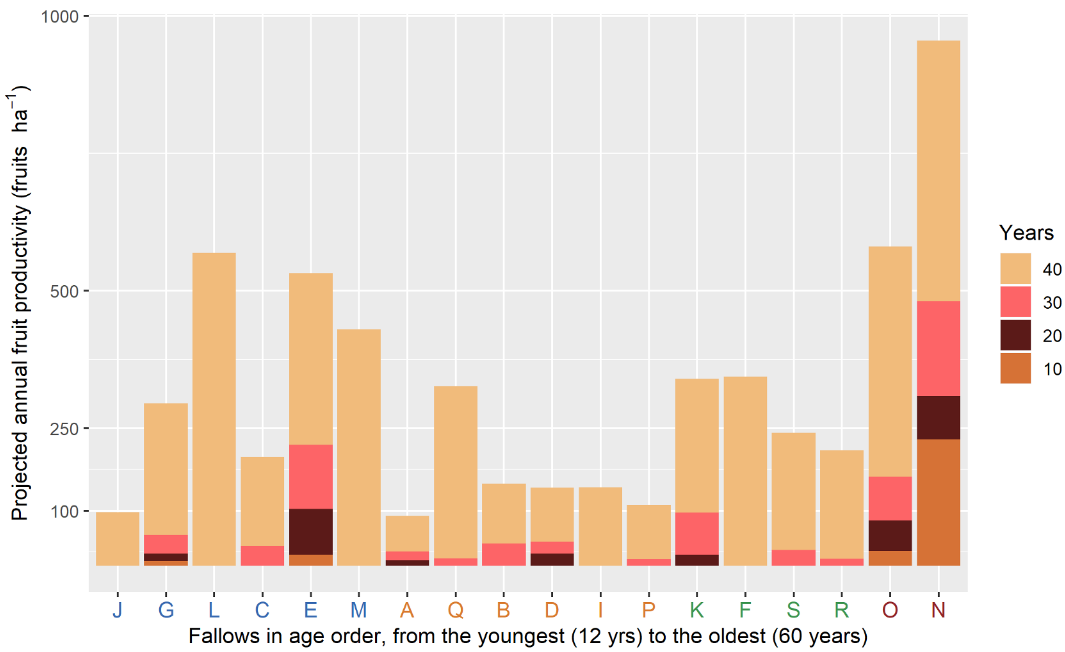

Fig. 6. Projected annual *B. excelsa* fruit productivity for each fallow at the end of 10, 20, 30 and 40 years, ordered by landowner fallow age estimates. Letters are color coded to represent fallow age classes (blue = 12–17 yrs.; orange = 20–22 yrs.; green = 26–29 yrs.; and red = 48–60 yrs.) based on natural clustering.

Density of trees larger than sapling stages (≥10 cm DBH) can only be compared to density of *B. excelsa* in mature forest due to lack of studies in old fallows. Our fallow inventories revealed that densities of trees ≥ 10 cm DBH tended to be higher than *B. excelsa* densities found in nearby mature forest located within our study site ($\bar{x}$ = 3.30, ± 0.6 SE trees ha^{-1} vs $\bar{x}$ = 2.5, ± 0.3 SE trees ha^{-1}) (Wadt et al., 2008). Density of *B. excelsa* in fallows tend to be higher due to light and nutrient availability (Kainer et al., 1998; Cotta et al., 2008). Extrapolating from our analyses, we can assume that this higher density in younger fallows translated to higher density in older fallows as well, which were represented by the two older fallows of our inventory (O and N, 48 and 60 years old respectively). The density of individuals ≥ 10 cm DBH in these two fallows was higher than in nearby mature forest (6.51 and 10.87 trees ha^{-1} vs 2.5 ± 0.3 SE trees ha^{-1}) (Wadt et al., 2008).

As expected of a naturally regenerating system, the larger trees experienced reduced competition from their smaller surrounding individuals. This was also true for crown position. Trees that are dominant and co-dominant tend to have a smaller number of competing trees, while suppressed trees have a tendency to have more trees competing for above and/or below ground resources (Canham et al., 2004).

4.2. Landowner perspective

Despite the scientific evidence that swidden fallows provide better conditions for Brazil nut recruitment and regeneration than mature forest (Cotta et al., 2008), one interviewed landowner expressed that mature forests are richer in Brazil nut densities than could ever be attained in mature fallows. All other landowners agreed with our research premise - that abandoning previous agricultural plots could increase Brazil nut productivity because of the higher *B. excelsa* densities encountered in fallows. In addition, two landowners interviewed expressed that Brazil nut trees in fallows should be managed to enhance densities and stimulate growth, rather than simply abandoning them. Indeed, protecting *B. excelsa* seedlings in agricultural clearings has been reportedly put into practice by over 2/3 of Brazil nut harvesters in the border region of Bolivia, Brazil and Peru (Duchelle et al., 2014). Additionally, approximately 90% of these harvesters reported practicing another simple management technique to increase fruit yields, that of liana cutting. Lianas compete with their host trees for above- and below-ground resources (Grauel and Putz, 2004; Schnitzer et al., 2005), and a liana cutting experiment revealed that liana cutting specifically increased Brazil nut production in mature forest by threefold 14 years after treatment (Kainer et al., 2014). Furthermore, one interviewee pointed out that these proactive management practices could be applied to other socioeconomically important species found in fallows. Montagnini and Mendelsohn (1997) demonstrated that smallholder management of fallows for timber yield could be profitable. Also, Sears et al. (2017) document how Peruvian small farmers manage agricultural fallows to produce the fast-growing pioneer timber species *Guazuma crinite*. Mahogany (*Swietenia macrophylla*) and cedar (*Cedrela odorata*), two valuable timber species, have also been managed when regenerated in higher densities in swidden fallow (Dubois, 1990). However, enrichment planting of timber species is only economically viable if start-up investment and maintenance costs are kept minimal, so that costs do not overcome profits (Keefe et al., 2012). This economic logic would also apply to potential Brazil nut management investments in fallows.

4.3. Simulation model outputs

The output of the productivity model does not show a linear relationship between fruit production and fallow age. The patterns of production are also highly dependent on the initial size distribution of trees and the size of the fallows. The three fallows with the highest projected productivity were already contributing with reproductively mature *B. excelsa* trees at our study inception. Mathematically speaking, the cumulative production was high because these fallows had multiple large-diameter trees, and some were visibly reproductively mature at the time of our inventory and their diameters were close to or higher than 40 cm DBH, which is the threshold used by our production equation.

In terms of income, our simulation suggests that four landowners could increase annual nut harvest revenues in < 10 years ($\bar{x}$ = \$7.50, ± 3.99 SE per ha of fallow), and at least seven of them could have increased profits in 20 years ($\bar{x}$ = \$8.38, ± 3.89 SE per ha of fallow), which is a reasonable timeframe considering that no money or time was invested following abandonment of their agricultural plots.

These per hectare values are consistent with lower range of Amazon basin estimates from Strand et al. (2018), and to put them into a household context, average 2006–07 annual household income (N = 47) from Brazil nut collection was estimated as U$ 765 (± 973 SD) at a nearby extractive reserve (Duchelle et al., 2011). As for the last two decades of the simulation, income increases were predicted for most landowners within 30 years, and for all landowners within 40 years. This is expected, assuming fallow trees survive and increase in age and size. However, the more into the future projected, the more likely swidden fallows (and *B. excelsa* individuals growing within) could be compromised. Economic situations could change, and plots could be used for different purposes. Additionally, control of the property (passed to next generation or another landholder) could affect how fallow areas are managed. Here is where application of management techniques that promote *B. excelsa* growth and survival could play an essential role in conserving, transforming and maintaining the fallow to be more economically valuable. Fallows could be managed to accelerate growth by eliminating competition (lianas or trees), and thus diminish time until reproductive maturity.

The settlement-wide productivity map provides an estimate of the spatial distribution of current Brazil nut production in the study area. Generally, high productivity areas suggested by the map coincide with projected high production fallows (with the exception of three fallows). Similarly, the projected low productivity fallows tended to occur in low production areas demonstrated by the map. Our growth and production equations were more reflective of the high and medium productivity sites, yet application of these estimates to low production areas (such as I and J), resulted in production estimates equivalent to their location.

Finally, production values are likely to be additionally influenced by factors not captured in our study. For example, a possible explanation for the three fallows (A,B, and P) located in high productivity areas of the settlement, yet projected to generate low productivity, is the proximity of these fallows to major roads and logging. Traffic could drive scatterhoarding rodents to more isolated areas, not permitting natural establishment of *B. excelsa*. Another peculiarity of the production estimates that is not explained by our study is that the fifth youngest fallow (E) was the third most productive. One possible explanation is that this particular fallow was clear-cut, burned and simply abandoned, rather than planted to crops. The relatively higher productivity in this non-agricultural plot potentially could be attributed to the favorable growth environment immediately following site burning, whereby *B. excelsa* seedlings (versus agricultural crops) could have taken advantage of greater nutrient, water and light availability (Kainer et al., 1998).

4.4. Key assumptions of the simulation

Due to a scarcity of data on growth, recruitment and survival of *B. excelsa* in swidden fallows, equations used in the simulation represented mature forest conditions versus the more representative secondary forest conditions. Recruitment of new individuals was not included, as the lack of data specific to recruitment in swidden fallows would result in a large increase in uncertainty in the simulation model components. Because fallows provide better soil and light conditions to extant Brazil nut trees, essential environmental conditions that drive growth, our equations likely contain conservative DBH increment estimates and represent an underprediction of potential fallow productivity. Brazil nut fruit production is variable among years at the population and individual tree levels (Kainer et al., 2007), yet our fruit production model considers average annual fruit production, not taking into account the year-to-year variability. We believe, however, that longer-term fruit production is being well represented considering that the fruit production equation was developed within the same area and with a robust dataset. Finally, rainfall used in the simulation was obtained from a meteorological station 112 km from our study site; however, the time series adopted were composed by more than 40 years of data, and thus we believe that rain patterns of our site are well-represented.

4.5. Future model considerations

While mathematical models are adequate to estimate values based on the data available and given initial values, they never truly represent the unpredictable future. However, they are useful tools to evaluate different scenarios and support decision-making based on real inputs. Our simulation is the first to explore the production of Brazil nut in secondary forest. Furthermore, most data used to construct our equations was from datasets collected on site. However, they also represented mature forest conditions, which could have influenced underprediction of growth and nut production, considering that swidden fallows provide better light and nutrient availability. To improve the current simulation model therefore, we suggest measuring *B. excelsa* recruitment, growth and survival in swidden fallows to better reflect population dynamics under these modified conditions.

5. Conclusion

We conclude that swidden fallows could translate into greater production of Brazil nut if densities are kept high. Looking at the densities of the two older fallows, we can assume that previous research conclusions have merit in suggesting that higher recruitment rates in fallows do translate into higher *B. excelsa* densities, and thus potentially higher nut production. However, it is not possible to assume that this is the reality for the whole study area, because some of the lower productivity landholdings based on our productivity map suggest caution that low production tends to be a constant, despite the slightly higher *B. excelsa* densities observed in the inventoried fallows. In summary, we believe that areas with high production of Brazil nut could generate swidden fallows with higher densities of trees, and thus generate higher levels of nut production, a conclusion mirrored by most participant landowners.

CRediT authorship contribution statement

Eduardo S. Bongiolo: Methodology, Investigation, Formal analysis, Writing - original draft. **Karen A. Kainer:** Conceptualization, Methodology, Validation. **Wendell Cropper:** Methodology, Validation. **Christina L. Staudhammer:** Conceptualization, Validation, Formal analysis, Writing - review & editing. **Lúcia Helena Oliveira Wadt:** Conceptualization, Resources, Supervision.

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.

Acknowledgements

This work was funded by the International Biodiversity Foundation, School of Forest Resources and Conservation (SFRC - UF) and the Tropical Conservation and Development program (TCD - UF), with field support of the Brazilian Agricultural Research Corporation (Embrapa). We also thank Cachoeira residents for hosting this research, particularly the field assistants who were essential to the conclusion of this study.

Appendix

Table A1
Summary of each landholding and its respective inventoried fallows. Count of individuals is the number of *B. excelsa* inventoried and used in the model.

LH[a]	LH Brazil nut production (*lata*)[b]	LH area (ha)[c]	LH Brazil nut productivity (fruits ha^{-1})[d]	Fallow Code	Fallow Age (years)[e]	Count of Individuals	Fallow area (ha)	Overall density (Individuals ha^{-1})	Sapling density (Individuals < 10 cm DBH ha^{-1})	Juvenile and adult density (Individuals ≥ 10 cm DBH ha^{-1})
Alt	400	325.4	76.70	Q	20	11	0.83	13.22	8.41	4.82
AlD	650	213.7	189.76	N	60	26	1.38	18.92	8.00	10.87
Bb	70	164.4	26.57	J	12	6	1.01	5.93	5.93	0.00
Cah	800	369.1	135.25	A	20	7	2.01	3.48	2.98	0.50
				B	21	8	1.81	4.42	2.21	2.21
				P	22	6	1.04	5.77	4.81	0.96
Faz	700	238.7	183.00	C	15	7	0.91	7.70	5.50	2.20
				O	48	32	1.69	19.00	12.47	6.51
Lah	680	241.7	175.58	L	14	13	0.41	31.72	29.28	2.44
				M	17	13	0.67	19.46	16.47	2.99
Poa	700	937.1	46.61	G	13	47	4.18	11.25	8.86	2.39
PoaII	400	300.0	83.20	F	28	12	0.76	15.76	11.82	3.95
Ret	280	330.0	52.95	E	16	12	0.80	15.06	11.30	3.75
				D	22	7	1.41	4.97	4.26	0.71
				S	28	15	1.53	9.81	7.20	4.82
				R	29	11	1.24	8.84	6.43	4.82
SC	700	400*	109.20	K	26	10	1.08	9.24	3.70	5.56
SJ	70	561.2	7.78	I	22	7	0.94	7.46	7.45	0.00

a: Landholding, b: Data based on landowner-reported estimates of total nut production for 2017–18. *Lata* ≈ 11 kg of unshelled nut, c: Data based on area shape files provided by selective timber management plan, d: Values calculated using property nut production divided by area and multiplied by the factor of 62.4 fruits/*lata*, e: Fallow age is based on year of crop site abandonment, *Area estimated by landowner because area shape file was not available.

Table A2
Projected *B. excelsa* fruit production (fruits yr^{-1}) of each fallow and productivity (fruits ha^{-1} yr^{-1}) of each landholding at the end of each 10-year interval. Data are based on inventoried fallows only.

Landholding	Fallow	Fallow Area (ha)	Projected annual productivity of fallows in each landholding (fruits ha^{-1} $year^{-1}$)				Projected cumulative fruit productivity of each fallow (fruits ha^{-1})			
			10 yrs.	20 yrs.	30 yrs.	40 yrs.	10 yrs.	20 yrs.	30 yrs.	40 yrs.
Alt	Q	0.83	0	0	16	393	0	0	14	1241
AlD	N	1.38	167	224	348	692	2054	2608	3891	6629
Bb	J	1.01	0	0	0	97	0	0	0	183
Cah	A	2.01	0	2	16	72	0	28	191	423
	B	1.81					0	0	149	802
	P	1.04					0	0	12	421
Faz	C	0.91	10	32	76	300	0	0	174	853
	O	1.69					176	538	1144	2997
Lah	L	0.41	0	0	0	924	0	0	0	1284
	M	0.67					0	0	0	1354
Poa	G	4.18	2	5	13	71	44	142	347	1301
Poa II	F	0.76	0	0	0	452	0	0	0	1098
Ret	E	0.80	4	25	61	226	33	518	1651	3160
	D	1.41					0	93	333	701
	S	1.53					0	0	88	974
	R	1.24					0	0	19	804
SC	K	1.08	0	18	89	315	0	57	433	1979
SJ	I	0.94	0	0	0	152	0	0	0	349

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