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Forest Loss Related to Brazil Nut Production in Non-Timber Forest Product Concessions in a Micro-Watershed in the Peruvian Amazon

Gabriel Alarcon-Aguirre [1,2,3,4], Maritza Mamani Mamani [2], Rembrandt Ramiro Canahuire-Robles [1,2,3,4], Telesforo Vasquez Zavaleta [1], Joel Peña Valdeiglesias [1,3], Jorge Diaz Revoredo [5], Liset Rodríguez Achata [3,4,6], Dalmiro Ramos Enciso [3,7] and Jorge Garate-Quispe [1,2,3,4,8,*]

[1] Departamento Académico de Ingeniería Forestal y Medio Ambiente, Facultad de Ingeniería, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru; galarcona@hotmail.com or galarcon@unamad.edu.pe (G.A.-A.); rcanahuire@unamad.edu.pe (R.R.C.-R.); tvasquez@unamad.edu.pe (T.V.Z.); jpena@unamad.edu.pe (J.P.V.)
[2] Centro de Teledetección para el Estudio y Gestión de los Recursos Naturales (CETEGERN), Facultad de Ingeniería, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru; marizza_19_25@hotmail.com
[3] Earth Sciences & Dynamics of Ecology and Landscape Research Group, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru; liset.investigacion@gmail.com (L.R.A.); dramos@unamad.edu.pe (D.R.E.)
[4] Ecology & Restoration of Tropical Ecosystems Research Group, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru
[5] Departamento Académico de Derecho y Ciencias Políticas, Facultad de Educación, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru; jrevoredo@unamad.edu.pe
[6] Departamento Académico de Ciencias Básicas, Facultad de Ingeniería, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru
[7] Departamento Académico de Ingeniería de Sistemas e Informática, Facultad de Ingeniería, Universidad Nacional Amazónica de Madre de Dios, Puerto Maldonado 17001, Peru
[8] Department of Evolutionary Biology, Ecology and Environmental Sciences, Faculty of Biology, University of Barcelona, 08028 Barcelona, Spain
* Correspondence: jgarate@unamad.edu.pe

Citation: Alarcon-Aguirre, G.; Mamani Mamani, M.; Canahuire-Robles, R.R.; Vasquez Zavaleta, T.; Peña Valdeiglesias, J.; Diaz Revoredo, J.; Rodríguez Achata, L.; Ramos Enciso, D.; Garate-Quispe, J. Forest Loss Related to Brazil Nut Production in Non-Timber Forest Product Concessions in a Micro-Watershed in the Peruvian Amazon. *Remote Sens.* **2023**, *15*, 5438. https://doi.org/10.3390/rs15235438

Academic Editor: Georgios Mallinis

Received: 10 October 2023
Revised: 16 November 2023
Accepted: 17 November 2023
Published: 21 November 2023

Abstract: Madre de Dios is considered an important center of biodiversity in Peru due to its extensive Amazonian forests. However, the forests are under growing pressure due to land invasion, agricultural expansion, and gold mining. This makes support for forest management very important. This study aimed to evaluate the relationship between forest loss, land cover, land-use changes, and Brazil nut (*Bertholletia excelsa* Humb. & Bonpl) production in forest concessions in the Peruvian Amazon (2004–2020). Remote sensing techniques were used to classify images using the random forest algorithm, which was applied to the Landsat-5 thematic mapper, Landsat-7 enhanced thematic mapper, and Landsat-8 operational land imagery. Brazil nut production data from 2004–2020 was provided by the Regional Forest and Wildlife Service of Madre de Dios. In forest concessions, the forest area decreased continuously over the whole study period (160.11 ha/year). During the same time period, the change in forest cover in the concessions from Brazil nut to other uses was 4681 ha. At the same time, the authorization and extraction of Brazil nuts varied during the study period but did not show a downward trend. We found a significant and inverse relationship between the conversion of forest to agricultural land and Brazil nut production. However, there were insignificant relationships between forest loss, the persistence of agricultural and forest areas, and Brazil nut production. Therefore, despite the forest loss in the forest concession areas, Brazil nut production has not decreased. Production may not be affected because land pressure is higher near access roads, affecting only the areas near the roads rather than the actual areas where the Brazil nut-producing trees are located. Our results showed that nut production in non-timber forest product concessions would be negatively affected by deforestation and forest degradation, but only slightly.

Keywords: Landsat; random forest; land cover and land use change; agriculture; non-timber forest products

1. Introduction

Some tropical forest plant species produce non-timber forest products (NTFPs), which are used by people and businesses for food, well-being, forest conservation, and profits [1]. The department of Madre de Dios is located in the lowlands of the Peruvian Amazon, a region recognized worldwide as one of the most biologically rich areas on Earth. The region is recognized in Peruvian legislation as the "Biodiversity Capital of Peru" (Law No. 26311). Madre de Dios is part of one of the largest intact tracts of forest left in the Amazon. More generally, the western Amazon is one of the most biologically and culturally diverse areas in the world, with a high diversity of flora, the largest number of mammal, bird, and amphibian species on the continent, and many indigenous cultures. Forest concessions and protected areas in Madre de Dios provide important economic benefits to the local population through nature-based tourism and NTFPs [2–5]. However, without proper planning, socioeconomic activities in tropical forests (such as logging and agriculture) endanger biological diversity [1]; this problem has worsened in Peruvian tropical forests in recent years, primarily as a result of gold mining [4,6] and agriculture [2].

In this context, some species of tropical forest plants yield NTFPs with a high economic value [5,7–9]. For example, the Brazil nut tree (*Bertholletia excelsa* Humb. & Bonpl.) is one of the most important NTFP species in South American tropical forests [10] and the tree has great economic importance [11] as a significant NTFP with an international export market, which requires standing forests for sustained production [12]. Approximately 30% of Madre de Dios is covered by forests dominated by Brazil nut trees, which generate substantial economic benefits and support forest conservation [13,14]. It is estimated that the Amazon region of Madre de Dios exports an average total of 2672.6 tons of shelled Brazil nuts with an FOB (free on board) value of USD 37.7 million [13,14]. Within the Brazil nut value chain, this product contributes 67% of the income of the families involved in Brazil nut harvesting, who represent 22% of the population of Madre de Dios [12–14].

In Madre de Dios, Brazil nut concessions have been granted by the National Institute of Natural Resources (INRENA) since 2004. Concessionaires must submit general forest management plans (GFMP) for NTFP harvesting. In addition, concessionaires may submit complementary plans for timber harvesting [15]. The allowance for timber plans creates strong internal pressures on the Brazil nut concessions, along with external pressures due to agricultural activities outside of the concessions [12–15].

The scientific community widely recognizes the significance of incorporating remote sensing data for evaluating forest degradation, due to its cost-effective potential for assessing large areas [16]. In an evolving socio-economic context, plant community surveys and mapping are crucial for quantitative analysis of vegetation–climate interactions and environmental protection and management [17]. Deforestation is the conversion of forests to other forms of land use and the reduction of forest cover or photosynthetic capacity over a long period of time [2,18]. It is estimated that the average deforestation rate in the Peruvian Amazon between 2001 and 2021 was 134,528.20 $\mathrm{ha/yr^{-1}}$. In Madre de Dios, during the same period, the rate was 13,584.15 $\mathrm{ha/yr^{-1}}$ [19]. Forest loss reduces the production of organic matter [1,2,20], generates carbon emissions into the atmosphere [21], contributes to climatic variability, and decreases water storage in the atmosphere and in soils [21]. Nevertheless, the effects of specific disturbances on forest ecosystems vary considerably, depending on their scale and frequency [22]. Furthermore, deforestation causes changes in seed and fruit production [10] and leads to forest desiccation and changes in its floristic composition [21,23].

Several studies have assessed the impact of Amazon deforestation on the production of NTFPs, using selected species at the local and regional scales [7,8,24,25]. Although environmental monitoring is mandated by law to determine the direction and dynamics of these changes [22], in order to develop management plans for NTFPs on a regular basis, the impacts of deforestation on stakeholders in supply chains and their processes and flows are not well understood [9]. Local communities, traders, and consumers may find it difficult to understand how deforestation might affect their social and economic activities [8,10,12]. Brazil nut extraction is an economic activity carried out by indigenous communities and by other local communities with forest concessions [8,12], and all of them are threatened by deforestation [12] because it can have negative effects on Brazil nut production [26]. Despite this threat, there is limited information on the relationship between forest loss and Brazil nut production in forest concessions [2,20]. To develop strategies to adapt to environmental changes, it is important to understand the effects of deforestation on NTFP [1].

This study analyzed the relationship between forest loss and Brazil nut production (fruit extraction) in Madre de Dios. For this purpose, we evaluated Brazil nut authorizations and extraction during the 2004–2020 period and related it to forest loss in the Manuripe River micro-watershed. In this article, maps and figures are presented to quantify the forest loss. We discuss the implications of the findings for Brazil nut production in order to identify strategies for effective adaptation to environmental changes and contribute to policies to sustain Brazil nut extraction as a conservation strategy for biodiversity in forests.

2. Materials and Methods

2.1. Study Area

The study area is located in the southeastern Peruvian Amazon (11°26′03″ and 12°22′27″S, 70°25′03″ and 70°53′59″W) (Figure 1). The Manuripe micro-watershed is covered by primary forest used for Brazil nut production and encompasses an area of 4923.2 km^2. The area delimited for the study includes 554 forestry concessions granted by the Peruvian government and occupies a total area of approximately 3565.42 km^2. According to Holdridge [27], the climate is tropical, being warm and humid, with an average annual rainfall of 2120 mm and an average annual temperature of 26.5 °C [28]. The topography of the micro-basin ranges from 200 to 550 m above sea level (Figure 1).

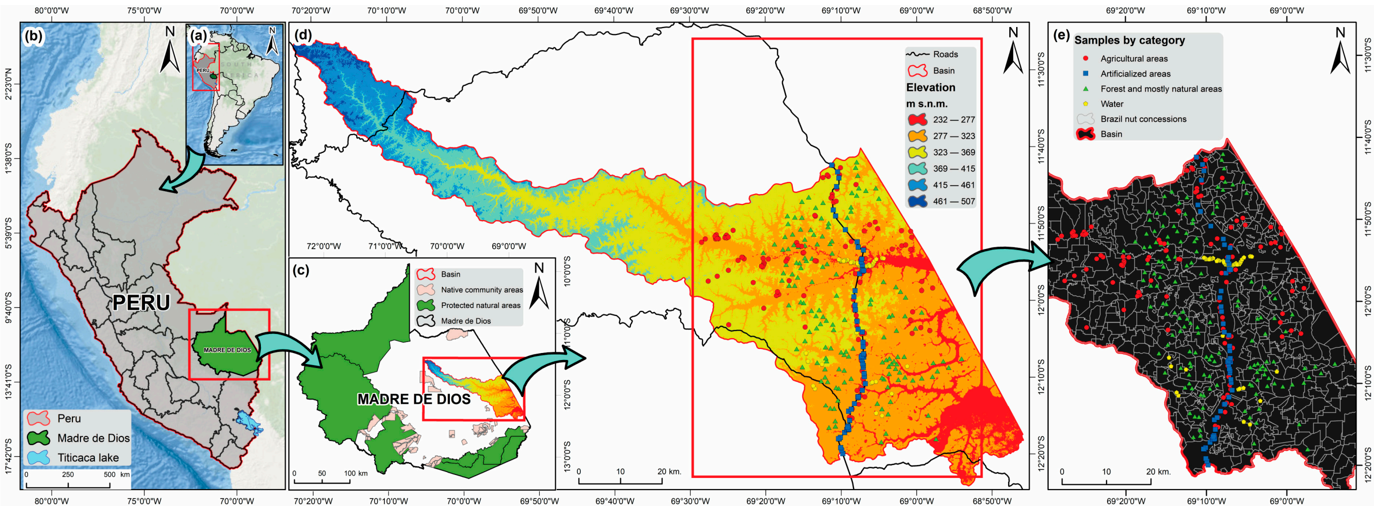

Figure 1. Location of the study area: (**a**) South American scale; (**b**) Peruvian scale; (**c**) regional scale; (**d**) the micro-watershed level of the Manuripe River and (**e**) field survey points in the study area.

2.2. Data Processing

2.2.1. Landsat Imagery, Land Use, and Land Cover Change

Satellite images from the Landsat Collection 2 Level 1 program (sensor 5 TM, 7 ETM+ and 8 OLI) were used for the study. Three Landsat-5 TM, 7 ETM+, and 8 OLI scenes were used to cover the study area: path/row 002/068, 002/069, and 003/068. The images were downloaded using the Google Earth Engine (GEE) platform [29]. The Landsat-5 TM, 7 ETM+, and 8 OLI satellite images were acquired between May and August for each year in the study period (2004–2020) (Table S1 in the Supplementary Materials) at times with less than 10% cloud cover. Those months coincide with the dry season in the Amazon and with agricultural and forestry activities. The data were analyzed using the World Geodetic System (WGS84) and have a spatial resolution of 30 m. The processing was carried out for annual periods. Initially, the Landsat images were pre-processed to minimize the influence of acquisition dates, mosaic creation, and atmospheric correction [30].

The sensor data from Landsat-5 TM (years 2004 to 2011), 7 ETM (year 2012), and Landsat 8 OLI (years 2013 to 2020) were converted from digital numbers (DN) to surface reflectance data using the top of atmosphere (TOA) method with GEE [2,30,31]. In the case of Landsat 7 ETM+ data, we first adjusted the focal plane to improve band alignment and then incorporated the updated numbers into Landsat Collection 2 Level 1 data processing.

The random forest (RF) method was used for the supervised classification [32]. The classification categories were based on the CORINE land cover methodology [33], as adapted by the Peruvian Ministerio del Ambiente [34]. As a first step, a collection of stable samples was created for each of the map legend categories to be mapped. We used 100 trees for each classification region. A total of 32 variables were used, along with 8 metrics, which were the result of the combination of bands (spectral bands, spectral indices, and height derivatives) and reducers (median, amplitude, standard deviation, minimum, maximum, and percentiles). The training areas were elaborated with a hierarchical legend applied at Level I under certain spatial criteria and thematic details: (1) forest and mostly natural areas, (2) agricultural areas, (3) water surfaces, and (4) artificial areas (Table S2 and Figure S1 in the Supplementary Materials). Maps were surveyed at a scale of 1:30,000 and areas smaller than 0.5 ha were merged to their nearest neighbor [35,36].

The validation was carried out through the distribution of points on the map. Historical information (2004–2019) was collected through projects carried out by the Universidad Nacional Amazónica de Madre de Dios (UNAMAD), as well as by other collaborating institutions (the Consorcio Madre de Dios-Pando-CMP and the Consorcio Madre de Dios-CMD, led by the University of Florida and financed by USAID/ICAA) on land cover and land use. For the 2020 data, verification was performed in the field and with high-resolution imagery (WorldView 0.38 m × 0.38 m, PerSAT-1 0.7 m × 0.7 m, and PlanetScope at 3 m × 3 m spatial resolution) (Figure 2).

Garmin Map 60 CSx and Garmin Map 62 CSx GPS units were used for the field survey [31]. The accuracy of the classification of the annual periods was performed using the confusion matrix and the kappa index (k) [2,31]. We used 382 sampling points, selected by a stratified simple random sampling process according to the following categories: (1) forest and mostly natural areas—150 samples, (2) agricultural areas—120 samples, (3) water surfaces—50 samples, and (4) artificial areas—62 samples. The number of samples was calculated using a confidence level of Z = 1.96, an acceptable margin of error of 5%, and a probability of occurrence of 0.5. The land-cover maps used for each year were produced by the Spatial Data Infrastructure Unit (SDI) of the Sub-management of Land Development of the Regional Government of Madre de Dios.

The average annual rate of deforestation was calculated to quantify forest loss; the spatial differences of the initial and final areas and times (A1 and t1 and A2 and t2, respectively) were obtained for an assigned period (R) (Equation (1)) [6,31,37–39].

$$R = (A1 - A2)/(t2 - t1) \tag{1}$$

The values obtained in Equation (2) were expressed in terms of the annual percentage rate of change (q) (Equation (4)), which was obtained using the following equation [31,39]:

$$q = (A1/A2)^{\left(\frac{1}{t2-t1}\right)-1} \tag{2}$$

The change in coverage between 2004 and 2020 was measured by the spatial difference in coverage for each epoch (Equation (3)) [6,31,37–39].

$$\text{Epoch } 2004 \times 10 + \text{Epoch } 2015 \ldots .2020 \tag{3}$$

The processing was performed using Google Earth Engine and ArcGIS 10.8® at the Remote Sensing Center for the Study and Management of Natural Resources (CETEGERN) of UNAMAD [31].

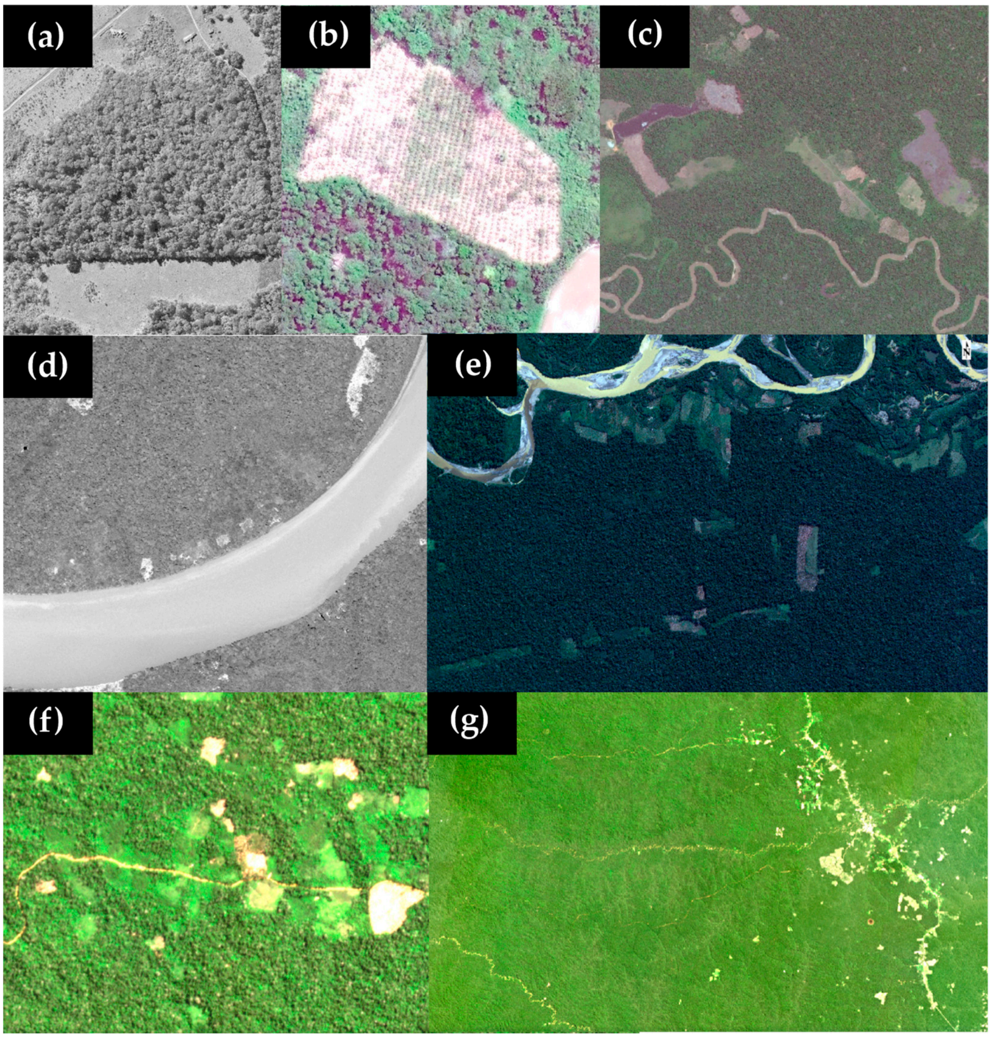

Figure 2. Validation of forested and mostly natural areas, agricultural areas, and water surfaces with WorldView images at 0.38 m × 0.38 m spatial resolution (**a**–**c**), PeruSAT-1 at 0.7 m × 0.70 m spatial resolution (**d**), and 2.8 m × 2.8 m (**e**) spatial resolution, and PlanetScope images at 3 m × 3 m spatial resolution (**f**,**g**).

2.2.2. Brazil Nut Production and Land Use and Land Cover Change

Information on the production of Brazil nuts in forest concessions in the Manuripe micro-basin for the period 2004–2020 was provided by the Regional Forestry and Wildlife Management Service (GRFFS-MDD) [40]. This source provides authorizations and production data for the 554 concessions. For the analysis, we compared whether Brazil nut production was associated with forest loss and an increase in areas of use other than forest product extraction. For this purpose, Spearman's correlation coefficient was used to analyze the relationship between land use and land-cover changes and the production of Brazil nuts (extracted and sold) [1].

3. Results

3.1. Forest Loss

According to the spatio-temporal analysis of land cover and land use in Brazil nut concessions in the Manuripe River micro-basin from 2004 to 2020 (Figure 3), the loss of forest cover is mainly caused by the conversion of forested areas to agriculture. The dynamics of forest cover change have been progressive, but not accelerated. The highest percentages of increase were in 2003 (4.65%), 2004 (3.36%), 2005 (7.63%), 2008 (3.37%), 2013 (4.93%), 2014 (4.08%), 2015 (4.72%), 2019 (4.22%), and 2020 (3.24%).

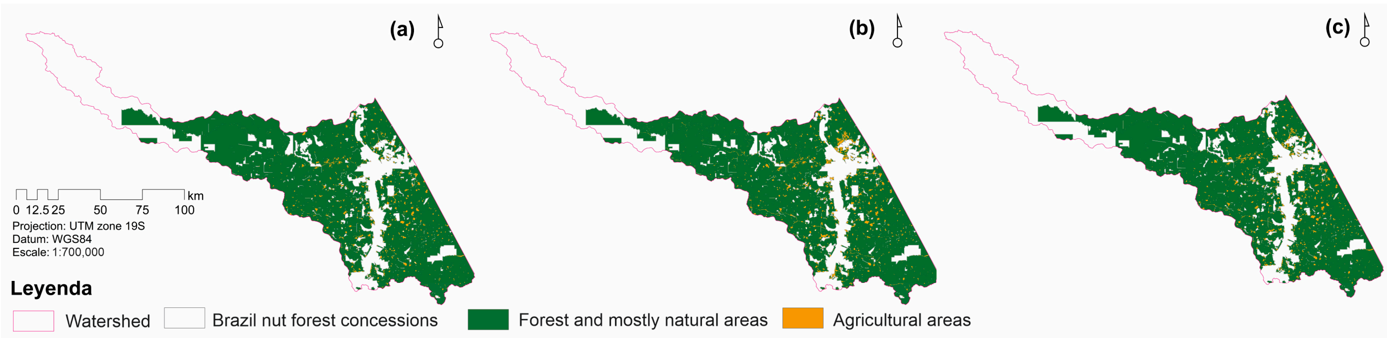

Figure 3. Land use in Brazil nut forest concessions in the micro-basin of the Manuripe River–Madre de Dios, for the years 2004 (**a**), 2012 (**b**), and 2020 (**c**).

The results show that at the beginning of the study period (2004), 6197.41 ha of the forest had been converted to agricultural use (Table S3 and Figures 3, 4, S2 and S3). However, in 2020, non-forest cover had increased to 9435.12 ha, with spatial variations in the study area (Figures 5, S2 and S3). In general, the spatiotemporal analysis shows a progressive decrease in forests and mostly natural areas, which is proportional to the increase in agricultural areas.

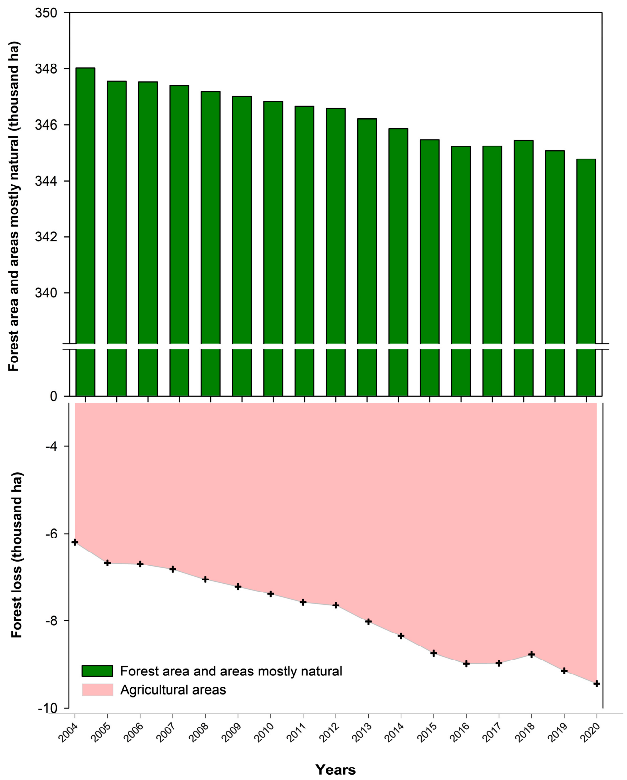

Figure 4. Loss of forest cover according to the type of productive activity in Brazil nut forest concessions in the Manuripe River micro-basin.

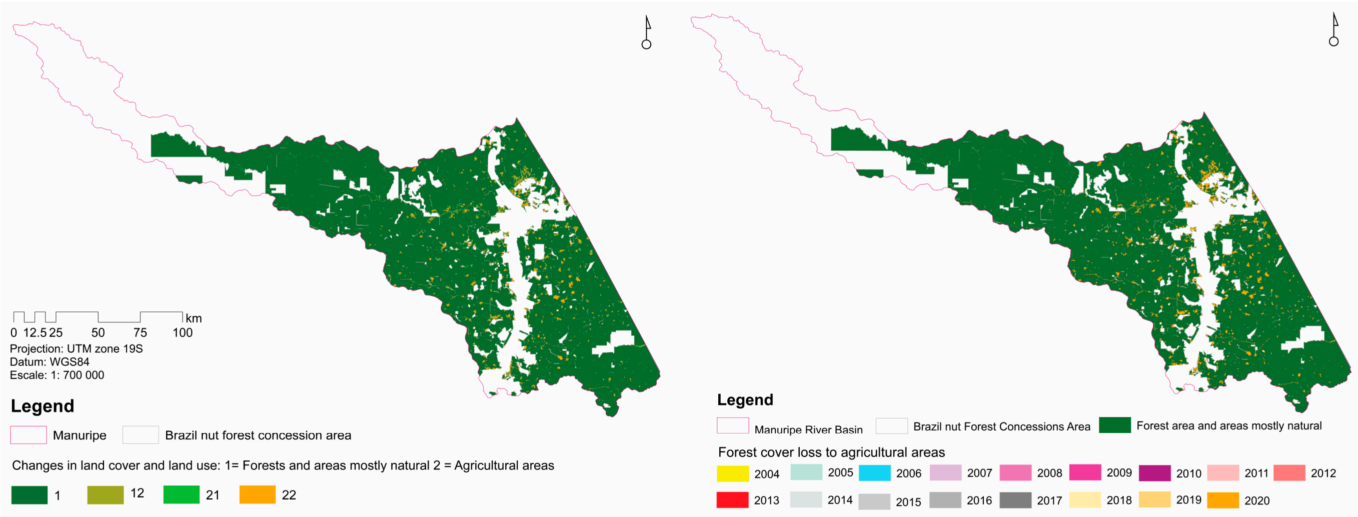

Figure 5. Land cover and land-use changes in Brazil nut forest concessions in the Manuripe River micro-basin–Madre de Dios between 2004 and 2020: left, global change; right, historical change.

The average forest area lost per year in the study area was roughly 160 ha (Table 1). This corresponds to an annual rate of loss (q) of 0.046% between 2004 and 2020. The conversion of forests to agricultural areas varied among the years being evaluated, from a minimum of 29.06 ha (0.008%) in 2005–2006 to a maximum of 479.53 ha (0.138%) in 2004–2005. In addition, for 2012–2013, 2014–2015, and 2018–2019, the findings indicate more forest loss than the overall average, a loss of 374.23 ha (0.108%), 394.68 ha (0.114), and 373.35 ha (0.108%), respectively.

Table 1. Rate and average annual rate of forest loss (deforestation) in the study area.

Years	Annual Rate of Forest Loss (%)	Average Annual Total Forest Loss (ha) (r)
2004–2005	0.138	479.53
2005–2006	0.008	29.06
2006–2007	0.036	125.19
2007–2008	0.069	239.87
2008–2009	0.047	162.02
2009–2010	0.048	165.01
2010–2011	0.055	191.47
2011–2012	0.021	73.13
2012–2013	0.108	374.23
2013–2014	0.095	327.56
2014–2015	0.114	394.68
2015–2016	0.069	239.50
2016–2017	−0.003	(−) 10.35 *
2017–2018	−0.058	(−) 200.16 *
2018–2019	0.108	373.35
2019–2020	0.082	283.90
2004–2020	0.046	160.11

* Vegetation cover.

Despite the increase in forest loss due to agriculture, there were also decreases in agriculture in certain years: 10.35 ha in 2017 and 200.61 ha in 2018. These findings correspond to an annual loss rate (q) of −0.003 (10.35 ha/year) and −0.058 (200.16 ha/year). This would be due to abandoned or temporarily uninhabited areas where natural regeneration means that the vegetation is recovering through successional processes but it cannot yet be considered forest, due to the time elapsed and the characteristics of the vegetation, as well as the risk of exposure to renewed agricultural activities (Table 1 and Figure 3).

Model Accuracy

To assess the reliability of the classification of historical data, the categories of forests and mostly natural areas and agricultural areas were evaluated (See Table 2). The results show relatively high (0.61–0.80) and very high (>0.81) correlations, confirming the reliability of mapping forest loss and the change of cover to other uses in Brazil nut forest concessions [41,42]. In terms of user accuracy, the forest and mostly natural areas had a probability of accuracy of more than 90%, while the agricultural areas had a probability of accuracy of more than 75%. These data represent the purity of the correctly assigned mapping unit and the appropriately classified control elements. Regarding agricultural areas (>75%), after characterizing the sample points of the agricultural areas, we found points related to forests and mostly natural areas, such as permanent crops and successional transition areas demonstrating abandoned areas with natural formations of *Mauritia flexuosa* (locally known as aguaje) and mixed forests, with the presence of the genus Guadua (paca).

Table 2. Classification accuracy.

Years	Overall Accuracy (%)	kappa Coefficient (κ)	User's Accuracy (%)	
			Forest and Mostly Natural Areas	Agricultural Areas
2004	82.80	0.80	97.02	79.76
2005	85.39	0.82	94.43	77.17
2006	82.50	0.80	97.32	80.06
2007	82.50	0.80	97.32	79.86
2008	84.80	0.81	95.02	77.76
2009	85.80	0.78	94.02	76.72
2010	83.00	0.80	96.82	79.56
2011	85.50	0.81	94.32	77.06
2012	82.60	0.78	97.22	79.96
2013	84.00	0.81	95.82	78.56
2014	84.70	0.81	95.12	77.86
2015	84.90	0.80	94.92	77.66
2016	85.60	0.81	94.22	76.96
2017	86.00	0.80	93.82	76.56
2018	83.20	0.81	96.62	79.36
2019	84.65	0.80	95.17	77.91
2020	86.81	0.81	93.14	76.88

3.2. Land Use and Land-Cover Change (LULC)

The land use and land cover data show a trend of the loss of forested areas to agriculture (Table 3). However, the amount of forest converted to agriculture varied among the different years. The results of forest cover change showed the lowest value in 2005–2006 (196.39 ha) and the maximum in 2019–2020 (1023.67 ha). The mapping of forest loss shows an irregular temporal increase (Table 3 and Figures 5, S4 and S5).

Table 3. Land cover and land-use changes in Brazil nut forest concessions in the Manuripe River micro-watershed.

	Land-Use Change (ha)			
Years	Forest Persistence	Persistent Agricultural Areas	Forest to Agricultural Areas	Agricultural Areas to Secondary Vegetation
2004–2005	347,486.70	6118.15	542.21	71.60
2005–2006	347,356.46	6495.10	196.39	170.71
2006–2007	347,307.68	6597.01	217.64	96.32
2007–2008	347,089.92	6682.37	333.08	113.28
2008–2009	346,896.63	6887.37	303.43	131.22
2009–2010	346,727.59	7098.96	279.86	112.24

Table 3. *Cont.*

Years	Land-Use Change (ha)			
	Forest Persistence	Persistent Agricultural Areas	Forest to Agricultural Areas	Agricultural Areas to Secondary Vegetation
2010–2011	346,570.44	7300.79	268.12	79.31
2011–2012	346,439.17	7430.69	210.47	138.33
2012–2013	346,146.40	7581.10	432.98	58.18
2013–2014	345,665.31	7806.30	536.50	210.56
2014–2015	345,335.79	8194.28	541.21	147.37
2015–2016	345,028.23	8517.14	454.37	218.92
2016–2017	344,971.61	8683.29	275.88	287.87
2017–2018	345,022.70	8523.94	236.20	435.81
2018–2019	345,069.57	8752.63	383.28	13.17
2019–2020	344,093.97	8370.37	1023.67	730.64
2004–2020	343,370.47	4711.07	4681.36	1455.76

The overall change in forest concession areas from Brazil nut production to agriculture was 4681.36 ha (2004–2020). In the agricultural areas in the study years, 4711.07 ha were persistent. The conversion of forest to agriculture, combined with the persistence of agriculture in cleared areas, resulted in a twofold increase in agricultural areas from 2004 to 2020 (Figure 4). However, the spatial analysis also shows small, cleared areas that were abandoned and then recovered. These areas represent 31.10% of the conversion from forest to agricultural areas (2004–2020), of which 50.19% occurred between 2019 and 2020; this situation could be explained by immobilization due to the COVID-19 pandemic. Nevertheless, it is very likely that these areas will continue to be used for agriculture (Table 2, Figures 5, S4 and S5). It should also be noted that the lowest (2005–2006) and highest (2019–2020) quantifications of the spatial changes in crops and pastures occurred with greater frequency in the vicinity of road infrastructure (Table 2, Figures 5, S4 and S5) [2,31,43–45].

3.3. Land Use and Land-Cover Change and Brazil Nut Production

Brazil nut production shows an irregular trend, with increasing rates of forest loss in NTFP concessions in the Manuripe micro-watershed (Figure 6). We suggest that two factors could affect Brazil nut production. The first is timber extraction, which represents an internal factor. Brazil nut harvesting does not prohibit the extraction of timber in NTFP concessions, although the extraction is regulated by the Forest Service (GRFFS-MDD). In many cases, concession holders respect the effective areas where *B. excelsa* trees are located; in other situations, extraction also occurs in the effective areas. There remains a lack of reliable information on the relationship of Brazil nut trees (phytosociology) with other forest species and how this relationship affects fruit production. The second factor concerns agriculture and cattle-raising activities, which are external processes that exert pressure on concessions near infrastructure and waterways.

It can be observed that there is an inverse relationship between forest loss and authorized and extracted Brazil nut production (Figure 6). There is also a minimal but progressive increase in forest loss that negatively affects Brazil nut production (Figure 6). This was identified when evaluating Brazil nut production using Landsat spatial data quantification. From the historical production of Brazil nuts with respect to forest loss and changes of use, peculiar data are noted in the years 2010 and 2011. There was a higher level of authorized (6.62 million kg–9.08 million kg) and extracted (5.81 million kg–7.57 million kg) Brazil nut production (Figure 6). In general, however, production follows a decreasing trend alongside rising forest loss.

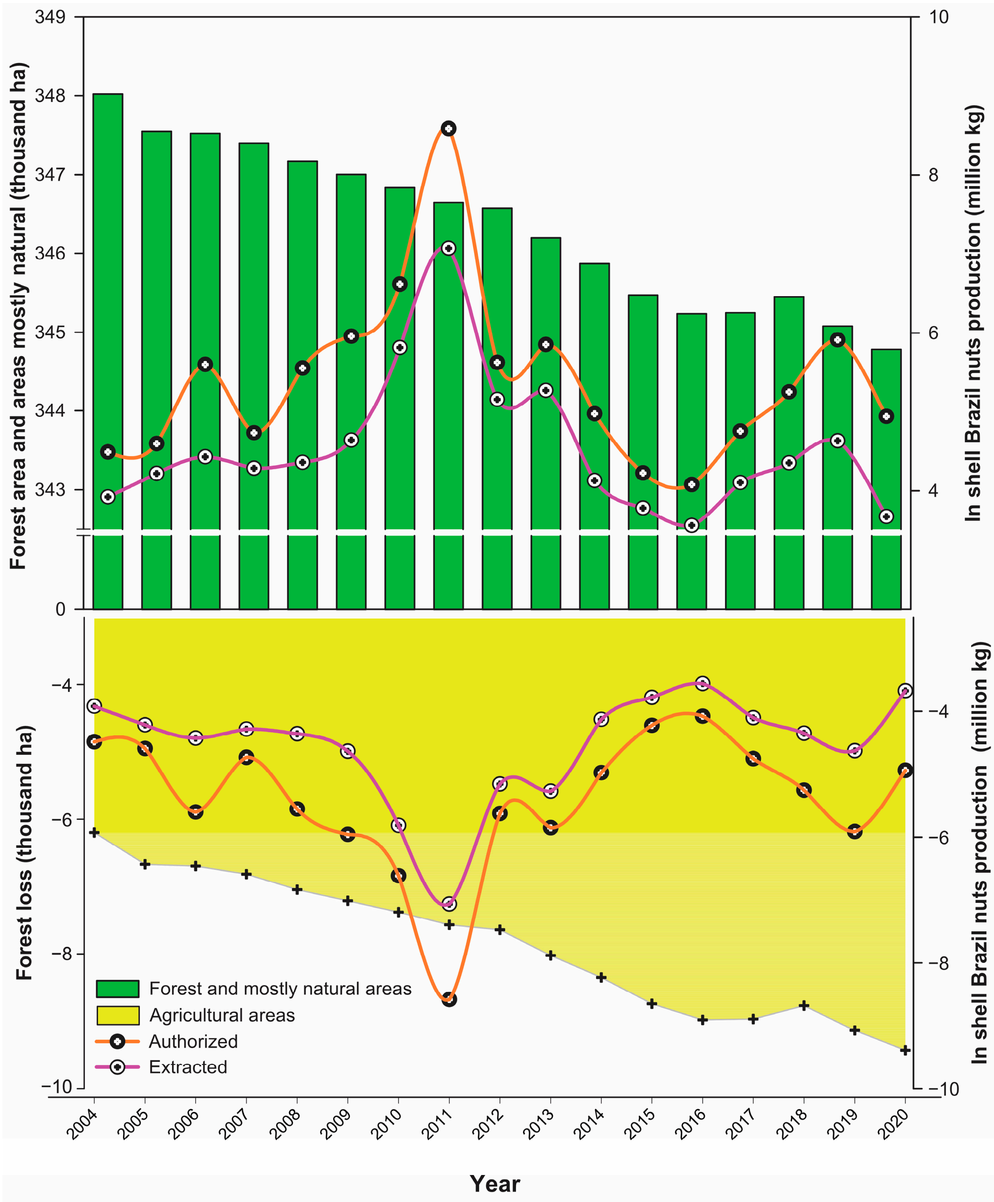

Figure 6. Representation of the relationships between Brazil nut production in forest concessions for NTFP purposes, forest loss, and land-use change in the Peruvian Amazon area of Madre de Dios.

To evaluate the statistical significance of the findings in Figure 6, we ran correlation analyses (Table 4). The results of the Spearman correlation analyses between Brazil nut production and land-use changes showed a significant inverse relationship between land cover conversion from forest to agricultural use and Brazil nut production (rho = −0.52, $p < 0.05$). However, forest persistence, agricultural area persistence, the change of agricultural areas to secondary vegetation, and forest loss had insignificant relationships ($p > 0.05$) with Brazil nut production (Table 4).

Table 4. Results of the Spearman correlation analyses among Brazil nut production, forest loss, and land-use changes in the Peruvian Amazon area of Madre de Dios.

	Forest Persistence	Agricultural Areas Persistence	Forest to Agricultural Areas	Agricultural Areas to Secondary Vegetation	Average Annual Forest Loss	Cumulate Forest Loss
Agricultural area persistence	−0.95 ***					
Forest to agricultural areas	−0.29	0.22				
Agricultural areas to secondary vegetation	−0.57 *	0.39	0.02			
Average annual forest loss	0.04	−0.02	0.84 ***	−0.44		
Cumulative forest loss	−0.97 ***	0.96 ***	0.36	0.44	0.08	
In-shell Brazil nut production	0.44	−0.33	−0.52 *	−0.33	−0.17	−0.41

* $p < 0.05$; *** $p < 0.001$.

4. Discussion

4.1. Forest Loss

In Madre de Dios, Peru, forest cover and biodiversity are currently threatened by infrastructure, agriculture, and gold mining [2,44]. Monitoring of the resulting changes involves the use of remote sensing technologies [46]. Using satellite monitoring, we observed an average forest loss of 160.11 acres/year due to agriculture between 2004 and 2020, with an annual rate of change of 0.046% [47,48].

In the study area, agriculture exerts pressure on Brazil nut extraction in concession forests. Our findings are similar to those of both Peruvian and international researchers. For example, MINAM [19] estimated a total of 62,486 ha of deforested area in the province of Tahuamanu by 2020. More locally, and as part of the study area, MINAM [19] quantified 19,746 ha of forest loss from 2001 to 2020 for the district of Tahuamanu and 30,773 ha for the district of Las Piedras.

The results of the present study indicate that the deforested areas in the Brazil nut forest concessions in the Manuripe River micro-watershed for 2019 and 2020 account for 9138.71 ha and 9435.12 ha, respectively. Likewise, Tuesta [49] analyzed land-use changes in the districts of Iberia, Tahuamanu, and Madre de Dios from 2004 to 2016, using Landsat-5 TM and 8 OLI images. Their results quantified a deforestation of 4824.09 ha in 2004, 12,260.08 ha in 2011, and 17,063.72 ha in 2016. In all periods, agriculture was the main driver of forest change. The average data on forest loss and rate reported by MINAM [19] determined a figure of 3236 ha/year (0.17%) for the province of Tahuamanu, 1018.58 ha/year (0.31%) for the district of Tahuamanu, and 1558.58 ha/year (0.22%) for the district of Las Piedras. Similarly, Chávez et al. [50] quantified a value of 1792 ha/year (0.14%) for the province of Tahuamanu, and Tuesta [49], analyzing the district of Iberia, quantified a value of 1019.97 ha/year (0.42%). These results differ slightly from the average annual rate of the study area (0.046%) and show a higher proportion with the average annual loss (160.11 ha). This could be due to spatial and temporal differences in the studies. However, they coincide with the increasing trend of forest loss to agriculture.

On the other hand, Alarcon-Aguirre, Canahuire, Guevarra, Rodriguez, Gallegos, and Garate-Quispe [2] evaluated the dynamics of forest loss in Madre de Dios. Although our results were not consistent with previous studies, due to their being spatially different areas, they were consistent in terms of the trend of annual forest loss. The results are similar to the study and show an increasing trend in deforestation, with an annual rate of forest loss of 0.21% and an average loss of 59.28 km^2/year between 1999 and 2018. Agriculture was responsible for the largest changes in forest use. While Chávez, Huamani, Fernandez, Bejar, Valera, Perz, Brown, Domínguez, Pinedo, and Alarcón [50] observed deforestation trends in Tahuamanu Province over a 15-year period (1999–2011), the results showed a gradual increase from 7770 ha in the years 1996–2001 to 19,516 ha in the years of the 2006–2011 trajectory of change. The results confirm our findings and provide further evidence of how agriculture has influenced the temporal dynamics of LULCC through the periods pre- and post-paving of roads.

In the present study, forest cover declined from 348,021.26 ha in 2004 to 344,783.54 ha in 2020, which corresponds to an annual loss rate (q) of 0.046% (160.11 ha/year) (Table 1 and Figures 3 and 4) [2,47,51]. In the study area, 3237.72 ha of forest cover has been lost in 17 years, compared to the total accumulated loss of 9435.12 ha up to 2020. This represents a minimal loss compared to other lands in Madre de Dios, as well as other Amazonian regions of Peru and the Amazon basin in general (Figure 4). However, the threat that agriculture poses to forests cannot be ignored [2,52,53]. The expansion of agricultural crops and intensive livestock farming are two agricultural activities that increase forest loss, and these findings have been supported by previous studies [16,48,51,53]. These findings were corroborated by Tarazona and Miyasiro-López [16], who showed that the increase in the rate of deforestation is linked to extensive cattle ranching and agriculture, the latter being expressed in an increase in the monoculture of papaya (*Carica papaya* L.), cocoa (*Theobroma cacao* L.), soybeans (*Glycine max* L.), and rice (*Oryza sativa* L.) as the most important crops.

4.2. Land Use and Land-Cover Change

Between 2001 and 2006, the Peruvian government initiated the paving of the Interoceanic Highway, which marked the beginning of increased changes in land cover and land use [31,45,50]. The impending paving of the road corridor increased the value of the land and led to migration and land settlement, resulting in a rise in those areas under crop cultivation and pasture. This had a greater impact on areas closer to the highway [2,31,43–45].

The temporal dynamics of deforestation are closely related to the timing of the installation of new infrastructure. In 2010, the consortium in charge of construction completed the paving of the Interoceanic Highway in Madre de Dios. Since the completion of the Interoceanic Highway, the most significant and impactful deforestation has occurred in this region [2,6,19,31,54]. The highway facilitated migration to Madre de Dios [6] and fostered the expansion of urban areas and the agricultural frontier [2,31,44,45,50]. To a lesser extent, the highway also threatened the security of forest concessions [2,19,45,50,55].

Furthermore, the spatial pattern of deforestation is closely related to the location of infrastructure. According to Southworth, Marsik, Qiu, Perz, Cumming, Stevens, Rocha, Duchelle, and Barnes [43], in Madre de Dios, the distance to roads influences the change of use from forests to other land use. This is due to the fact that infrastructure improves connectivity, transportation, and trade, which exacerbates landscape change [44]. Baraloto, et al. [56] analyzed the impact of roads on forests in the tri-national Amazonian frontier, specifically Madre de Dios-Peru, Acre-Brazil, and Pando-Bolivia (MAP). They found that within 5 km of roads or unpaved roads, the highest rates of forest loss occur. Areas closer to access infrastructure have more fragmented or deforested areas than those that are farther away [56].

Studies closer to the level of geographical scope showed the conversion of forest for agricultural use; for example, Tuesta [49] reported the district of Iberia in 2016 as having 12,496.39 ha and Chávez, Huamani, Fernandez, Bejar, Valera, Perz, Brown, Domínguez, Pinedo, and Alarcón [50] studied the province of Tahuamanu in 2011 and reported 20,160 ha. These data differ from the study area and this could be due to the evaluation being at the level of the Manuripe micro-watershed, on which the study focuses, while Tuesta [49] and Chávez, Huamani, Fernandez, Bejar, Valera, Perz, Brown, Domínguez, Pinedo, and Alarcón [50] refer to a larger geographic scope. Also, although the micro-watershed is exposed to the pressures of changing land use due to agriculture, the state provides legal protection for non-timber forest concessions, which could minimize this effect.

The results are similar to those of other studies that have identified agriculture as the main driver of systematic forest conversion, such as the assessment of the dynamics of forest loss in the southeastern Peruvian Amazon. Alarcon-Aguirre, Canahuire, Guevarra, Rodriguez, Gallegos, and Garate-Quispe [2] estimated the loss of 84,141.08 ha of forest in Madre de Dios between 2014 and 2018, and agriculture was the main cause of the increase in deforestation (72.9%).

At the same time, Anderson, Asner, and Lambin [55] found that Brazil nut concessions that complied with their sustainability commitments have lower deforestation rates. Concessions that were fined had a higher deforestation rate (0.129%/year) than concessions that were not fined. The legal and physical security provided by forest concession permits, voluntary management, and certification requirements all serve to work against possible agricultural encroachment [55,57–59]. In the same sense, deforestation tends to be higher on titled agricultural lands than in the territories of recognized and titled indigenous communities, which in many cases develop forestry activities and are, therefore, governed by the regulations of the Peruvian National Forest Service (SERFOR) [58], the impact of which was analyzed by Montalvo [60].

4.3. Land Use, Land-Cover Change, and Brazil Nut Production

Deforestation not only reduces forest cover but also decreases primary forest production. The deforestation of Amazonian forests reduces the aboveground biomass [61]. Deforestation causes forest fragmentation, which alters seed and fruit production [62]. Deforestation also leads to landscape fragmentation, which could result in a decrease in the density and diversity of Brazil nut fruits in NTFP concessions. The decline in NTFP potential is exacerbated by pressure from external influences, such as agriculture on the edges of forest concessions [1,63]. In non-forested edges, the annual mortality rate of trees with trunks larger than 60 cm in diameter increases by more than 200% within 300 m of the edge [1,64].

We found a significant relationship between land cover, land-use changes, and Brazil nut production. Specifically, there was a significant and inverse relationship between the conversion of forest to agricultural land and Brazil nut production (rho = -0.52, $p < 0.05$). However, there were insignificant relationships between the persistence of agricultural land and the persistence of forests with Brazil nut production.

The lack of a significant relationship between forest persistence and Brazil nut production may be due to the fact that the physical and legal security of the effective area where individual Brazil nut producers are located does not hinder production [2,19,45,50,55]. Similarly, the drastic punishments meted out for the deforestation of Brazil nut trees in Peru may mitigate the deforestation of such trees, permitting continued production. However, in Brazil, where the cutting of Brazil nut trees is also illegal, activities related to Brazil nut production have decreased in the most deforested municipalities of the Amazon [65].

The lack of a significant relationship between agricultural persistence and Brazil nut production also begs for an explanation. Migration and pressure for agricultural land are most intense near the Interoceanic Highway. Southworth, Marsik, Qiu, Perz, Cumming, Stevens, Rocha, Duchelle, and Barnes [43], Baraloto, Alverga, Quispe, Barnes, Chura, da Silva, Castro, da Souza, de Souza Moll, and Chilo [56], and Perz, et al. [66] all showed greater agricultural areas and lower forest value near the highway corridor. These studies found that the distance to roads influenced the deforestation rate. Nevertheless, the pressure on the forest due to land-cover change and land use for agriculture does not directly affect the effective area of Brazil nut trees. Therefore, although not significant, there is a direct relationship between forest conservation and Brazil nut production.

That said, previous studies have shown that tropical deforestation, ecosystem fragmentation, and the isolation of Brazil nut trees from conspecifics can negatively affect seed production and fruiting. Our results showed that nut production in NTFP concessions would be negatively affected by deforestation and forest degradation, but only slightly. The extent to which tree isolation from conspecifics affects reproductive success remains largely unknown [26,67]. However, with growing deforestation within forest concessions, the impact of tree isolation could increase in the future [26,67].

The results of the mapping and research show that forest loss due to deforestation for conversion to agricultural use has a minimal but significant impact on Brazil nut production. This shows that internal pressure from timber extraction in Brazil nut concessions has not yet had an impact on Brazil nut production. To all these factors, we must add soil and climatic conditions that may affect Brazil nut production [1,62]. Therefore, in addition to the direct effects of deforestation, indirect effects due to climate change from carbon emissions may operate, via decreased rainfall and the increased length of the dry season, to reduce Brazil nut productivity [1]. In the Amazonian region of Madre de Dios, future studies could determine how the intensity of timber extraction in NTFP concessions, the rate of deforestation, and natural variations in soil and climate affect Brazil nut production.

In another context, Madre de Dios (Peru) shares borders internationally with the countries of Bolivia (Pando) and Brazil (Acre), and shares similar socio-economic, environmental, and cultural characteristics. The production and trade of Brazil nuts is one of them. According to studies conducted by Quaedvlieg, García, and Ros-Tonen [12], Cortegana [68], Salazar et al. [13], and Ruiz and Paucar [69], Brazil nut harvesting is an activity with minimal impact on the forest, but with a high socio-economic impact on Amazonian communities. However, due to the proximity of the tri-border regions (Madre de Dios, Pando, and Acre), part of the origin of Brazil nut production and commercialization is not adequately recorded by the GRFFS-MDD. In this regard, the Forest Service should implement a Brazil nut traceability system so that future studies can show a more precise relationship between the dynamics of forest loss and Brazil nut production.

5. Conclusions

Our results showed that the main cause of forest conversion in the study area was agriculture. In 17 years (2004 to 2020), 9435.12 ha of forest were lost, with an annual rate of 160.11 ha/year (q = 0.046%). The most intense forest loss occurred in 2004–2005 and 2014–2015, with an annual rate of 479.53 ha/year and 394.68 ha/year, respectively. Despite the increase in forest loss due to agriculture, there were also decreases in some years. This was due to the presence of abandoned or temporarily uninhabited areas where natural regeneration occurred through successional processes, but the vegetation cannot be considered forest: 10.35 ha in 2017 and 200.61 ha in 2018, with an annual loss rate (q) of −0.003 (10.35 ha/year) and −0.058 (200.16 ha/year). During the study period, 4681.36 ha of forest were converted for agricultural use.

Forest loss minimally reduced Brazil nut production in the NTFP concessions. The results indicate that there is an inverse but significant relationship between land cover conversion from forest to agriculture and Brazil nut production. However, only insignificant relationships were found between forest conservation, agricultural persistence, and Brazil nut production. This indicates that timber extraction and pressure from the agricultural frontier on NTFP concessions have not yet significantly reduced Brazil nut production. However, the Regional Forestry and Wildlife Management Service of Madre de Dios should implement traceability as a security and control measure to verify the origin of Brazil nut production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15235438/s1, Table S1. Landsat image database information. Table S2. Land cover map legend adapted to the study area. Table S3. Land use in the study area. Figure S1. Landsat satellite image, spectral signatures in 2020 R (6), G (5), and B (4) bands: (a) forest and mostly natural areas, (b) agricultural areas, (c) artificialized areas, and (d) water surface. Figure S2. Land use in Brazil nut forest concessions in the Manuripe River micro-basin–Madre de Dios, for the years 2004 (a), 2005 (b), 2006 (c), 2007 (d), 2008 (e), 2009 (f), 2010 (g), and 2011 (h). Figure S3. Land use in Brazil nut forest concessions in the Manuripe River micro-basin–Madre de Dios, from the years 2012 (a), 2013 (b), 2014 (c), 2015 (d), 2016 (e), 2017 (f), 2018 (g), and 2019 (h). Figure S4. Change in land cover and land use in Brazil nut forest concessions in the Manuripe–Madre de Dios River micro-watershed, for the years 2004–2005 (a), 2005–2006 (b), 2006–2007 (c), 2007–2008 (d), 2008–2009 (e), 2009–2010 (f), 2010–2011 (g), and 2011–2012 (h). Figure S5. Changes in land cover and land use in

Brazil nut forest concessions in the Manuripe River micro-watershed–Madre de Dios, for the years 2012–2013 (a), 2013–2014 (b), 2014–2015 (c), 2015–2016 (d), 2016–2017 (e), 2017–2018 (f), 2018–2019 (g), and 2019–2020 (h).

Author Contributions: Conceptualization, G.A.-A. and M.M.M.; methodology, G.A.-A. and M.M.M.; software, M.M.M., G.A.-A., R.R.C.-R., D.R.E. and J.G.-Q.; validation, G.A.-A. and J.G.-Q.; formal analysis, M.M.M., G.A.-A., T.V.Z. and J.G.-Q.; research, M.M.M., G.A.-A., J.P.V. and J.G.-Q.; research, M.M.M. and G.A.-A.; data curation, M.M.M. and G.A.-A.; writing—original draft; research, G.A.-A.; data curation, R.R.C.-R.; writing—preparation of original draft, M.M.M. and G.A.-A.; writing—revising and editing, G.A.-A., J.G.-Q. and T.V.Z.; visualization, G.A.-A., L.R.A., J.P.V., J.D.R. and J.G.-Q.; supervision, G.A.-A., R.R.C.-R. and J.D.R.; project administration, G.A.-A.; fund raising, G.A.-A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was sponsored by the Centro de Teledetección para el Estudio y Gestion de Recursos Naturales CETEGERN, and it was funded by the Vicerrectorate for Research (contract 009-2021-UNAMAD-VRI) of the Universidad Nacional Amazónica de Madre de Dios in Peru.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We thank Guadalupe Nalvarte for her assistance regarding field data collection during the validation process. We thank the Gerencia Regional Forestal y de Fauna Silvestre de Madre de Dios (GRFFS-MDD) for providing information on Brazil nut production and mobilization from 2004 to 2020 in the study area. We also thank Stephen Perz for his suggestions and review of the English version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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