

What processes drive degradation of intact tropical forest?

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The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others

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Abstract

Degradation of tropical forests affects people's livelihoods by reducing the availability of key resources. However, the drivers of degradation and the potential impact it has on the income of local communities are poorly understood. Fruits of the palm tree, *Mauritia flexuosa*, are an important non-timber forest product in the northern Peruvian Amazon, but harvesting has typically been done by cutting down trees with fruit. This study aimed to identify the drivers of degradation caused by this unsustainable harvesting practice, and estimate its impact on the potential income to local communities. As *Mauritia flexuosa* is dioecious (i.e. with separate male and female individuals), the proportion of female palms in a stand was used as the indicator of variation in degradation levels.

In 70 stands, across six river basins and 27 communities, the proportion of female palms varied widely (0.03 – 0.52). The travel time from each community to the principal market of Iquitos was the most variable for explaining variation in degradation levels ($r^2=0.19$, $p < 0.001$): palm swamps located farthest (> 30 hrs) from Iquitos had a higher proportion of female trees. The harvesting technique was the second most important explanatory variable ($r^2=0.17$, $p < 0.001$): the proportion of female trees was significantly higher (by 0.13) in those stands where the palms were climbed, rather than cut down, for harvesting. The watershed and the travel time to the harvest area from each community were also linked to the levels of palm swamp degradation ($p < 0.006$ and 0.001). Based on the significant relationships between travel times and degradation levels, the proportion of female trees was mapped across the palm swamps of the northern Peruvian Amazon. Using estimates of the average production and price of fruit, an overall annual potential income based on the current condition of these stands was estimated at 57.6 million USD, emphasising the potential importance of *Mauritia flexuosa* fruit harvesting for the regional economy. However, the use of climbing techniques could, over time, increase this value by 32.5 %. This finding indicates the cost that historical degradation imposes on communities today, but also the potential for sustainable management to contribute to improving incomes and supporting conservation in this region.

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1. Introduction

Managing degradation within tropical forests is a key environmental, social and economic issue (Thompson et al., 2013; Murdiyarso et al., 2008). For example, forest degradation is an important source of greenhouse gas emissions, contributing 2.1 Gt CO₂ e yr⁻¹ to the atmosphere, which is equivalent to approximately one third (6.2 Gt CO₂ e yr⁻¹) of emissions globally due to deforestation (Pearson et al., 2017). However, at the same time, some activities that cause degradation are also economically important within tropical forest landscapes. For example, wood and non-timber forest product (NTFPs) harvesting contribute 1.9 % and 10 % of gross domestic product (GDP) in South America and Africa respectively (FAO, 2014; Molnar et al., 2007). Designing policies that reduce degradation whilst maintaining sustainable use of tropical forest resources is, therefore, a key challenge and understanding the processes that drive degradation in the first place is an essential first step.

An initial problem is the difficulty of defining forest degradation (Thompson et al., 2013; FAO, 2009). Forest degradation has different interpretations related to the activities that people perform in the forest (FAO, 2011), as well as the type of ecosystem and the kind of resource that is extracted. This lack of consensus on its definition increases uncertainty for estimation and monitoring (de Andrade et al., 2017). Overall, degradation is not related to a change in land use as the ecosystem can likely recover from the damage that has been caused. Some definitions focus on the implications for supporting human activities, such as “the reduction of the capacity of a forest to provide goods and services, which involve, a variation on the structure and function of the forest” (FAO, 2002; ITTO, 2005). In contrast, other definitions focus on the implications for forest structure: according to Hosonuma et al. (2012) and Armenteras et al. (2016), forest degradation implies a contraction in canopy area and is linked to a release of carbon from the forest.

Secondly, another important issue related to degradation is that it is difficult to measure (Thompson et al., 2013). This is principally because of the drivers and nature of degradation changes according to the type or use of the ecosystem and the

resource of interest. For example, remote sensing techniques have been used to assess the contribution of forest degradation to greenhouse gas emissions at both regional and global scales (Pearson et al., 2017; Baccini et al., 2017; Miettinen et al., 2014; Joshi et al., 2015; de Andrade et al., 2017). However, most remote sensing techniques have a limited ability to identify fine-scale changes in ecosystems (for instance, changes in vegetation structure and species composition, or selective exploitation), which means that subtle modification of the land surface or canopy area in dense forest cannot be detected (Baccini et al., 2017; Lambin, 1999; Joshi et al., 2015; Asner et al., 2004).

Where degradation is the result of resource extraction, the distance from the market may be an important determinant of degradation levels due to its close link to activities to extract the resources. For example, Ahrends et al. (2010) found that distance from the city was related to variation in levels of degradation in the forests around Dar es Salaam in Tanzania over a period of 15 years. At the start of the study, the closest zone up to 20 km from the city, was exposed mainly to charcoal production; the second zone up to 50 km, was used for logging of medium-value species and the third zone (>50 km) was used for logging of high-value species. However, at the end of the study period, the high demand for resources in the city had reduced the capacity of forest near the city to supply it and extractive activities had expanded their area of influence. Charcoal production was now dominant up to 50 km, the logging of medium-value species was dominant between 50 and 170 km and the extraction of high-value timber started at 170 km (Ahrends et al., 2010). Therefore, as resource run out, communities may intensify extractive activities in new zones in order to supply demand. Similarly, in Myanmar, deforestation and forest degradation patterns were affected by spatial and topographic factors linked to selective resource exploitation through logging which decreased according as the distance and altitude from the nearest city and village increased (declining 15 % and 35 % per kilometre and 50 m of elevation respectively) (Mon et al., 2012). Again, the distance from population centres was an important predictor of degradation levels.

However, there are other factors in addition to distance from population centres that may influence degradation levels. For example, expansion of the transport system due to paving new roads, an increase of the agricultural border through extensive agriculture, the capacity of the species being harvested to regenerate, policies and government incentives, the price of the resource in the market, as well as the introduction of different management techniques can all modify how simple proxies like distance may be related to degradation levels (Lambin, 1999; Bhomia et al., 2018; Mon et al., 2012; Medrilzam et al., 2014). These factors can also change over time, leading to degradation patterns that are more related to the history of management than current pressure (Ahrends et al., 2010). For example, Casanova and Pacaya (2016) demonstrated that the introduction of new techniques for fruit gathering for *Mauritia flexuosa* palms in Peru, such as setting criteria for the number of palm trees or the number of racemes to be harvested, reduced degradation levels close to some villages in Amazonia.

In this study, I use *Mauritia flexuosa* stands (aguajales) as a model ecosystem for understanding the processes driving degradation in tropical forests. *M. flexuosa* (aguaje) is a canopy palm species (30 - 40 m height) with dense foliage (>70%) that can become monodominant in flooded or swampy areas of Amazonia (Quinteros et al., 2016; Malleux, 1982; Kahn and Mejía, 1990; Janovec et al., 2013). Aguajales protect permanent watersheds and help to maintain biodiversity and carbon stocks (Quinteros et al., 2016) and aguaje fruits are an important non-timber forest product in the Peruvian Amazon. 12,900 to 24,000 fruit-bearing palms are reported to be felled annually to supply the demand for fruit in Iquitos (Delgado et al., 2007; Sampaio and Dos Santos, 2015; García, A. and Pinto, 2011), and this resource represents the main income for many forest dwellers: for example, in the Parinari Community Association in Loreto, aguaje harvesting generates an average monthly income of USD 424 to USD 727 per person (Casanova and Pacaya, 2016). *M. flexuosa* is dioecious - meaning that only female trees bear fruit - which, linked to the high demand for its fruit and the typical harvesting technique of cutting down female palm trees, means that the gender ratio is a useful indicator of the degradation status of different stands (Baker et al., 2010; Fig. 1) that can readily be measured in the field.

This study provides an assessment of the degradation status of palm swamp ecosystems in the Peruvian Amazon, where degradation is defined as variation in the proportion of female trees within aguaje stands. This study asks what factors (natural and anthropogenic) determine variation in the proportion of female individuals within palm swamp forests in the Peruvian Amazon, including accessibility, such as the travel time from aguaje stands to the nearest community and the main market, as well as the intensity of extraction and the technique used to collect the fruit (Fig. 1). These relationships were then used to map degradation levels of the palm swamp forests across the main region where they occur, and estimate the potential value of this resource to local communities.

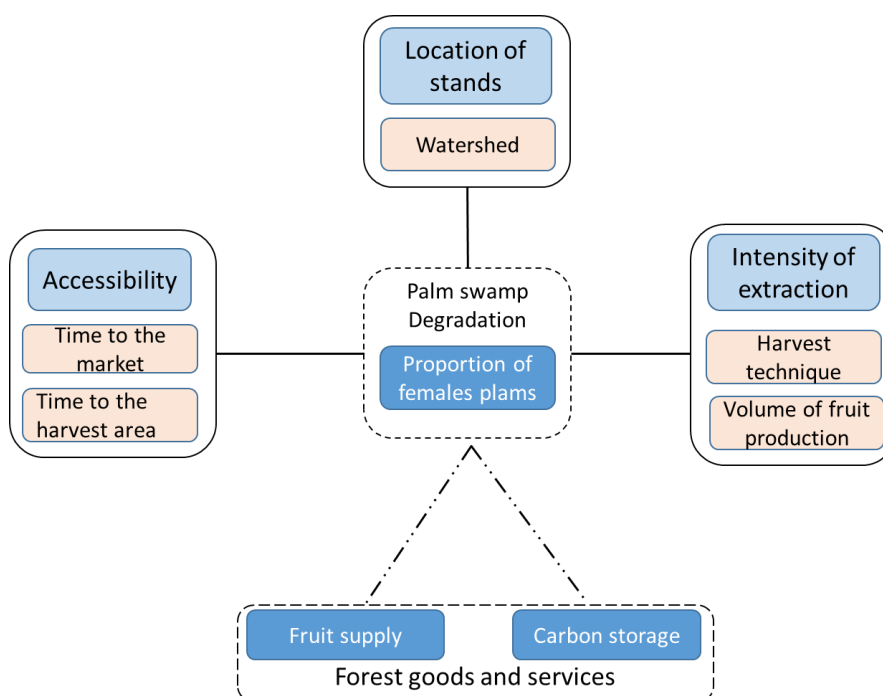


Figure 1. Variables analysed in this study to assess their influence in the change of the proportion of female trees, the indicator of degradation variable. The explanatory variables were classified based on criteria of the harvesting process into three categories: **Accessibility**, which involves the travel time from the community to both the main market and the stands in the forest. **Location of stands**, this category is represented by the watersheds, due to palm swamps are widely distributed in the study area along river basins varying in their characteristics of transport. **Intensity of extraction**, which involve the method of fruit collection used and the volume of fruit

harvested per each community. The decrease in the proportion of female trees could affect the function as a provider of goods and services of palm swamp forest.

2. Aims and research questions

This study aims to understand variation in the levels of degradation among Amazonian palm swamp forests. Specifically, the thesis aims to understand the drivers and spatial patterns of degradation and estimate the cost of degradation to local communities.

Aims

- To identify and quantify the impact of the drivers of degradation within palm swamp forests in Amazonia.

Objectives

- Compile and measure the level of palm swamp degradation from across the Pastaza Marañón basin in the northern Peruvian Amazon.
- Identify the processes that influence variation in the proportion of female trees across different palm swamp forests.
- Model spatial variation in the proportion of females of *Mauritia flexuosa* across the palm swamp forests of the northern Peruvian Amazon.
- Simulate the proportion of female trees within *Mauritia flexuosa* stands that could be achieved using sustainable harvesting techniques and estimate the additional value that improving the health of these ecosystems could provide to communities.

3. Methodology

3.1. Study area

This project was carried out in the palm swamps of the Peruvian Amazon. Amazonian forests are one of the most extensive natural regions of Peru covering an area of 778,450 km² (77 535 384 ha), which is equivalent to approximately 60% of the country's area (MINAM, 2009; Virapongse et al., 2017). The main palm swamps are found in the region of Loreto, which is located in the northeast of Peru (Appendix 1). This region is characterised by a warm, humid and rainy tropical climate with a mean temperature 28 °C (Kometter, 2013; Marengo, 1998; Bhomia et al., 2018) and a daily average minimum and maximum temperature of 20-22 °C and 29-31 °C respectively. The average annual rainfall of the region is around 3000 mm, and the frequency of precipitation is almost constant across the year with no regular dry season (Marengo, 1998; Kometter, 2013; García, E., 1998).

3.1.1. Description of palm swamp forests

Palm swamps ecosystems cover 5.5 million hectares approximately in the Peruvian Amazon (MINAM, 2015). Their origin is linked to seismic activity resulting from the uplift of the Andes (Rodriguez et al., 2002) that created depressions associated with the Pastaza – Marañón (Pastaza depression) and Ucayali – Marañón basins (Ucamara depression), due to continuous subsidence during the Pliocene and Quaternary (Dumont and Fournier, 1994; Rodriguez et al., 2002; Appendix 2).

The local name of “aguajal” is due to the presence of individuals of *Mauritia flexuosa* (“aguaje”), which is the dominant species (Malleux, 1982). The number of individuals of juveniles and adults can vary from 450 – 600 palms/ha (Malleux, 1982; Sampaio et al., 2008).

3.1.2. Mauritia flexuosa L.f.

Mauritia flexuosa (aguaje) is a native Neotropical palm tree, characterised by its large size (35 – 40 m in height) and maximum diameter at breast height (DBH) of 60 cm. This palm has different names through the Amazonia basin. In Peru, it is called “aguaje” or “achual” whilst in Venezuela it is known as “moriche” and in Brazil as “muriti”, “miriti”, “buriti” or “palmeira dos brejos” (Carrera, 2000; Del Castillo et al., 2006). The species is dioecious and therefore has separate male and female individuals. The fruit is an elliptical-globular drupe, 3 – 7 cm long, with a mean weight of 40 to 85 g (Bejarano and Piana, 2002; CIMA, 2012a). The phenology of this species varies throughout the region, but the peak of the fruit season is linked to variation in the level of the river (Khorsand Rosa et al., 2014). In Peru, in stands along the Amazon, peak fruiting is from May to August, whilst stands along the Marañón and Ucayali rivers basins present a peak from September to March; in the remaining months, fruiting occurs at a lower intensity (Horn et al., 2018; Casanova and Pacaya, 2016; Vacalla, 2014).

The fruit of *Mauritia flexuosa* is mainly consumed locally. Because of the high demand in Iquitos, a city with a population around half a million people (437,376 inhabitants; INEI, 2015), *M. flexuosa* constitutes one of the most commercialised resources in the Peruvian Amazon. In Iquitos, 20 – 23 tonnes of fruit is consumed daily (600 tons monthly approximately; Gonzales and Torres, 2010; Casanova and Pacaya, 2016). In addition to selling the fruit without any further processing, there are also semi-processed products such as “chupete” (water ice or popsicle), ice cream and jams that are made from the fruit (Del Castillo et al., 2006; Gonzales and Torres, 2010; Appendix 5). The nutrition provided by this fruit is of great importance within Amazonian communities: 100 g of the pulp contains 0.29 – 1.062 mg of Vitamin A which is five times higher than carrot and spinach, and it has a similar proportion of oleic acid to olive oil (Carrera, 2000; Del Castillo et al., 2006). In recent years, national and international companies are also commercialising this resource as a food supplement and for cosmetics (as powder and in capsules, or as shampoo or oil; ITP-CITE, 2018; Appendix 6).

3.2. Sampling area

This study was undertaken in the area of influence of the Marañón, Ucayali and Amazon rivers, which are the three main rivers basins of Loreto (Fig. 2). Degradation levels were measured at sites on both the main rivers and their tributaries: the Samiria and Tigre rivers for the Marañón and the Itaya and Nanay rivers for the Amazon. These areas constitute the origin of the majority of fruit harvested and marketed in Loreto (Horn et al., 2018; Endress et al., 2018; Appendix 2).

3.3. Degradation indicator

Because *Mauritia flexuosa* is a dioecious species, and female individuals bearing fruit are removed by the traditional technique of fruit harvesting of cutting down trees, the proportion of females palms is a good indicator of degradation levels in this ecosystem (Baker et al., 2010; Hergoualc'h et al., 2017). The gender ratio of *Mauritia flexuosa* in an undisturbed stand was reported as 1:1 in the Colombian Amazon (Khan and de Granville, 1992), and a similar ratio of male and female trees (1.1 :1) was found in two experimental plantations of this species in Jenaro Herrera in the Peruvian Amazon (Bejarano and Piana, 2002; Falen and Honorio, 2018; Freitas, L. et al., 2019). In other words, in an undisturbed condition, it is possible to find 50 % male and 50 % female individuals. This baseline knowledge of the gender distribution of these stands makes it possible to estimate the impact of cutting down female trees on the health of these populations.

3.4. Sampling sites and methods

This study included datasets from two types of sampling: permanent plots and transects. Permanent plots that are distributed among palm swamp areas in the Marañón, Ucayali and Tigre river basins provide information about the variation in the proportion of female of *Mauritia flexuosa* in largely undisturbed forests. These plots were established primarily to understand natural variation in forest structure,

composition and dynamics of these forests. The information of phenology is from the Peruvian Amazon Research Institute – IIAP and the Amazon Forest Inventory Network (RAINFOR) and was collected inside the RAINFOR permanent plots during the establishment and recensus carried out from February 2017 to December 2018, as part of the “Monitoring Protected Areas in Peru to Increase Forest Resilience to Climate Change” (MonANPeru) project.

Each plot covers 0.5 ha and has a rectangular design (50 x 100 m). In addition to measurements of all trees ≥ 10 cm diameter, the data from the plots provide phenological information such as the presence of flowers, fruit and the number of racemes for each individual of *Mauritia flexuosa*. This information was used to determine the gender for each adult palm and consequently calculate the proportion of females for each plot. Plot data was compiled from ten permanent plots: JEN-14, JEN-15 (Jenaro Herrera - Ucayali river), VEN-01, VEN-02, VEN-03, VEN-04, VEN-05, PRN-01 (Veinte de Enero and Parinari - Marañón river), SAM-01 (PVC Pithesia - Samiria river) and PIU-02 (Piura - Tigre river; Table 1).

Each site has information of historical exploitation and data on the proportion of female trees. In order to connect the variation in the proportion of female trees to the factors that drive degradation in palm swamps, each site was classified into two categories:

No current use (abandoned palm swamps): includes areas of palm swamp that were exploited in the past but where the resource is no longer extracted. Harvest activities stopped 3 to 15 years ago in the areas from this category.

Active harvest: include areas of palm swamps where the communities are extracting the resource actively. These areas are frequently visited every fruiting season.

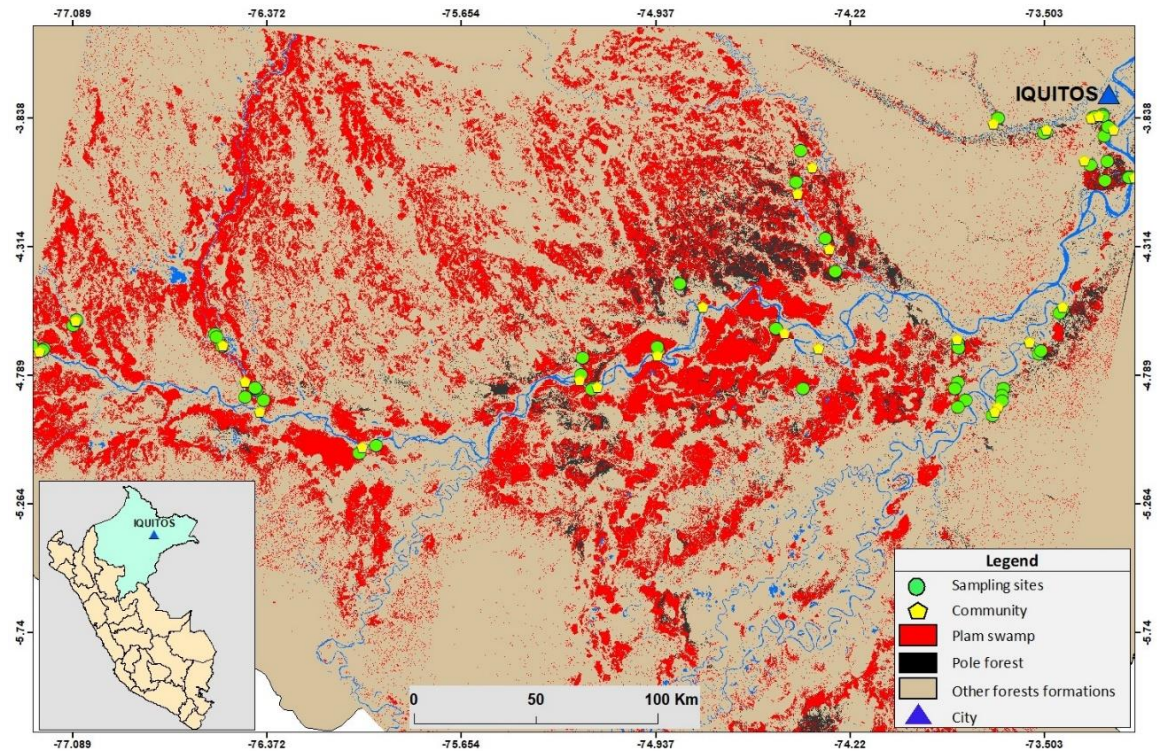


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Transect data comes from three sources. A group of 13 transects were established by IIAP in stands near to the communities of Jenaro Herrera, Parinari, Veinte de Enero, PCV – Pithesia, Ollanta, Piura, Malvinas (Table 1). Data from six transects near to Jenaro Herrera were collected from June 2008 to July 2009, while information from the other communities (seven transects) was collected from

March 2017 to December 2018. In those transects, the gender of 100 adult individuals of *M. flexuosa* was recorded as well as information about the number of racemes per female tree. Due to the variation in the composition of the palm swamps, these transects vary in length. A GPS point was recorded for each palm registered from the transects.

Another dataset from 16 transects established in the upper Marañón River, in the Pastaza depression, was provided by the Wageningen University and Research - WUR from the Netherlands. The incorporation of the WUR dataset provides important information about palm swamps in the most distant zones from Iquitos - the main centre of commerce in the region. In this dataset, phenology of *M. flexuosa* was assessed in three small transects (450 x 4m) separated by 50m in each sampling site. Due to this layout, the information for each site was combined and treated as one transect, resulting in a total of 16 transects (Table 1). The WUR data included data on *Mauritia flexuosa* palms from different life stages (adult, juvenile and seedling) collected in stands near to the communities of Puerto Diaz, Santa Ana, Puerto Industrial, Indio del Peru, Nuevo Milagro and Puerto Limón. In this study, only data on adult individuals were included in the analysis.

Table 1. List of sampling sites in this study.

Data set	Site code	Community	Proportion of Females	Data set	Site code	Community	Proportion of Females
IIAP	REQ-01	Jenaro Herrera	0.21	WUR	P.LIM-2	Puerto	0.29
	REQ-04		0.06		P.LIM-3	Limón	0.43
	REQ-05		0.21		IDP-1	Indio del	0.35
	IRIC-1		0.33		IDP-2	Perú	0.38
	IRIC-2		0.24	FD	SAR-1	San José de	0.11
	JEN-14		0.36		SAR-2	Saramuro	0.22
	JEN-15		0.19		SAN-1	San Antonio	0.11
	SAPN		0.22		SAN-2		0.19
	CAPT		0.25		CUN-1	Cuninico	0.10
	AUCA		Malvinas		0.26		CUN-2
	PIUR	Piura	0.29	CLA-1	Capitán	0.14	
	PIU-02		0.10	CLA-2	Clavero	0.16	
	OLLN	Ollanta	0.31	PMIG-1	Puerto	0.15	
	SAMI	Parinari	0.33	PMIG-2	Miguel	0.24	
	SAM-01		0.46	DDM-1	Dos de	0.04	
	PARN		0.24	DDM-2	Mayo	0.10	
	PRN-01		0.25	DDM-3		0.08	
	V-ENE		0.44	NYK-1	Nueva	0.10	
	VEN-01	Veinte de Enero	0.17	NYK-2	York	0.43	
	VEN-02		0.29	SJOR-1	San Jorge	0.11	
VEN-03	0.12		SJOR-2	0.18			
VEN-04	0.31		LIM-1	Limón	0.14		
VEN-05	0.43		LIM-2		0.35		
		LIM-3	0.25				
WUR	P.IND-1	Puerto	0.26	SJR-1	San Juan	0.24	
	P.IND-2	Industrial	0.48	SJR-2		0.32	
	S.ANA-1	Santa Ana	0.27	QCH-1	Las Brisas	0.20	
	S.ANA-2		0.25	QCH-2		0.03	
	S.ANA-3		0.38	QCH-3		0.20	
	P.DIAZ-1	Puerto Díaz	0.37	REQ-13b	Jenaro Herrera	0.10	
	P.DIAZ-2		0.43	PUMA	Pumacahua	0.08	
	P.DIAZ-3		0.43	PTA-1	Puerto	0.52	
	N.MIL-1	Nuevo	0.46	PTA-2	Alegría	0.52	
	N.MIL-2	Milagro	0.39	MSH-1	Mishana	0.19	
	N.MIL-3	0.23	MSH-2	0.21			
	P.LIM-1	Puerto Limón	0.40				

IIAP: Peruvian Amazon Research Institute, WUR: Wageningen University and Research, FD: Field data collected in this study.

3.4.1. Field dataset

A complementary field dataset of 31 transects variable length to inventory at least 200 individuals in palm swamps was collected as part of this study. The fieldwork aimed to collect data in areas where there were gaps in existing information. The selection of sampling sites was based on the distribution of palm swamp mapped by Draper et al. (2014) and the Wetlands of Loreto map (Mapa de Humedales de Loreto) by the Regional Government of Loreto - GOREL (ARA, 2017). Firstly, swamps distant from areas near to the IIAP and WUR sites were selected in all watersheds in the study area. Secondly, using the database of communities of Loreto by the Peruvian Institute of Statistics and Informatics (INEI), the selected palm swamps were linked to their nearest community. Thirdly, in order to select a representative sample of the current condition of palm swamp ecosystems, data about the volume of aguaje from Horn et al. (2018) was used to discriminate communities where harvest of aguaje was registered, and information on the volume of yield allowed communities with different intensities of extraction to be selected for fieldwork as part of this study.

The new data provided information from stands along the Marañón, Ucayali, Tigre, Amazon, Itaya and Nanay rivers that were not sampled in the past, and particularly in areas that have been harvested. For each transect, a minimum of 200 individuals was registered, to be able to sample at least 10% of female palm trees in highly degraded palm swamps (i.e. at least 20 female trees). The census of palm trees was done up to a distance of 20 m for each side along the transect. Only adults of *Mauritia flexuosa* palms were registered and the determination of gender was based on the presence of floral organs (flowers and fruit). Information about the number of racemes and the height of the palm tree was also recorded. This field dataset comprised data from the communities of San Jose de Saramuro, San Antonio and Cuninico in the Marañón river; Capitán Clavero and Puerto Miguel on the Ucayali river; Nueva York on the river Tigre; Limón, Puerto Alegría and Las Brisas on the river Itaya; San Juan Raya and Mishana in the Nanay River (Table 1, Appendix 4).

3.4.2. Sample size

Sample size is strongly linked to the precision of the resulting estimates of the proportion of female trees. The appropriate sample size was tested and estimated by using the binomial distribution to analyse how sampling different numbers of individuals influence the confidence limit associated with the estimate of the proportion of female individuals (Fig. 3). The binomial distribution is appropriate for analysing the probabilities of occurrence of a specific response when a variable has two possible outcomes, such as the gender (male or female) for an individual (Philippou and Antzoulakos, 2011; Wilson and Hardy, 2002). A simulation study showed that confidence limits were greater when the number of individuals was lower (Fig. 3). However, sampling 200 individuals provide reasonable levels of confidence in estimates of the proportion of female trees, across all levels of degradation - the baseline ratio (50 %), half of the natural ratio (25 %) and the minimum proportion of female (10 %; Fig. 3). A sample of 300 – 400 palms shows only a small reduction in confidence limits compared to a sample size of 200 palms.

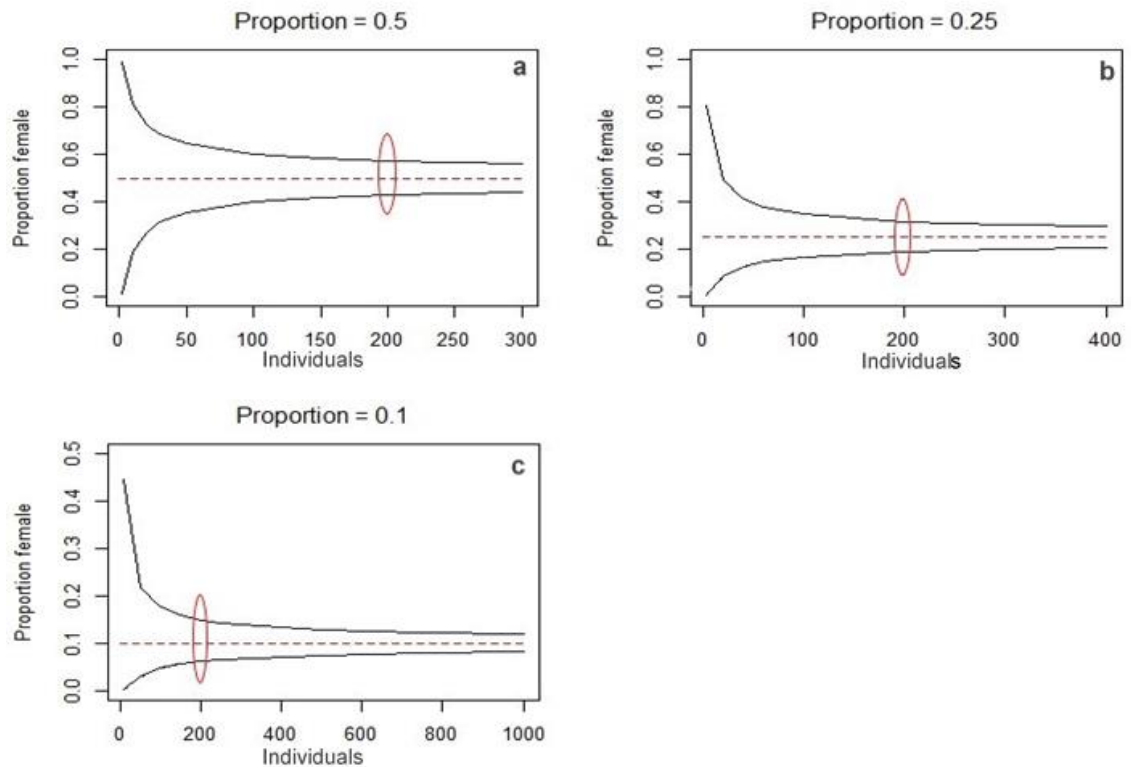


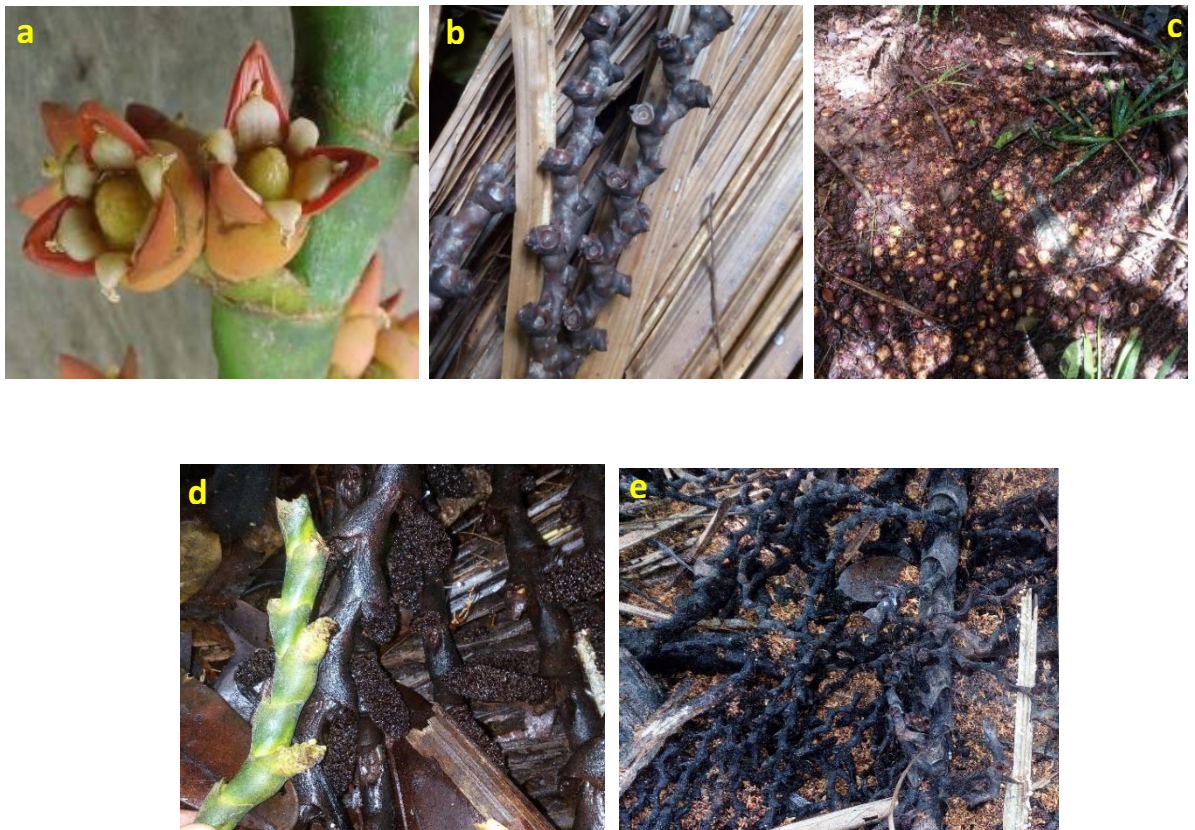
Figure 3. Determining the sample size for estimating the proportion of *Mauritia flexuosa* palms. Confidence limits from the binomial distribution (solid lines) illustrate how variation in the number of aguaje palms affects the confidence in the estimate of the proportion of females in the sample. (a) variation in the confidence limit with sample size for a population with 50% male and 50% female trees; (b) variation in the confidence limit with sample size for a population with 25 % female trees; (c) variation in the confidence limit with sample size for a population with 10% female trees. The dashed red lines represent the proportion of females at 50%, 25% and 10 % respectively whilst the black lines represent the upper and lower 95% confidence limits of the estimate. The red ellipses indicate the confidence limit in each example if 200 individuals are sampled.

3.4.3. Field protocol

Transects were placed at a minimum distance of 100 m from the edge of the palm swamp. In order to collect data from areas with a similar level of extraction intensity, the transects were established parallel to the border of the palm swamp. However, in communities such as San José de Saramuro, San Antonio, Cuninico, Nueva York and

Puerto Miguel where the harvesting area follows paths from the edge toward the inside of the palm swamp, transects were established parallel to the paths. The layout of the transects comprised a straight central line in the palm swamp, and the adult individuals (male and female) of *Mauritia flexuosa* were registered up to a distance of 20 m either side of the transect (Appendix 7).

Gender determination was based on the presence of floral organs (Fig. 4). The presence of flowers and fruit or remaining parts of them on the palm-tree or in the ground was used as an indicator of the gender. Individuals of *Mauritia flexuosa* palm with the height of an adult tree that did not have floral organs were excluded after careful verification in the field.



Source: **Panel a:** Gonzales and Torres (2010). **Panels b, c, d, e:** this study

Figure 4. Floral organs of *Mauritia flexuosa* used in the determination of gender. a = female flower, b = holding point of the fruit in the raceme, c = fruit on the ground, d = male flower, e = male inflorescence on the ground.

3.5. Explanatory variables

To identify drivers of palm swamp degradation, this study analysed factors associated with the levels of extraction activities. The variables selected are shown in Table 2 and described below.

3.5.1. Time to market

This variable was defined as the travel time from the harvesting community to Iquitos. The trip is done by the river and may take hours or days depending on location. This variable allows this study to assess the role of the ease of reaching the main market for determining the intensity of palm swamp degradation.

3.5.2. Time to harvest area

This variable was defined as the travel time from the community to the extraction area. To reach to the extraction area, some communities, such as San José de Saramuro, Mishana, San Antonio and Puerto Alegría, use paths through the forest, whilst for the communities of Limón, Cuninico, and Puerto Industrial, a trip by boat and walking by paths within the forest is required. For communities in the second group, the variable time to the harvest area was estimated as the sum of the travel time by boat plus the time walking within the forest.

3.5.3. Harvesting technique

Information about the harvesting method of *Mauritia flexuosa* fruit was registered through interviews with the inhabitants of the villages close to sampling sites. The interview form assigned two choices of technique (Del Castillo et al., 2006; Vacalla, 2014; Isaza et al., 2017; Appendix 8):

Cutting: This technique involves felling the palm-tree to collect the fruit. As a result, the palm dies.

Climbing: This technique implies gathering the fruit by climbing the tree.

3.5.4. The volume of production

The pressure of extraction on *Mauritia flexuosa* stands could be related to the volume of fruit harvested. This study therefore uses the number of fruit sacks, which is the unit of commercialization of this resource, to measure the pressure on the resource. The values for harvest volume used in the study were taken from data from Horn et al. (2018) and information provided by the Pacaya Samiria Natural Reserve – RNPS – SERNANP which maintains a register of harvest volume per year for this resource.

3.5.5. Location by watershed

Differences in the frequency of the type of transport for each river may also affect the likelihood of degradation. This study, therefore, classified the rivers into two categories of watersheds. The first, “Big river”, includes the Marañón, Ucayali, Tigre and Amazon where there is frequent transportation (daily) by boats called “lanchas” with large load capacity and routes that take more than one day to navigate. The second group, “Small river”, includes the Itaya and Nanay rivers and is characterised by small basins navigated by boats called “colectivos” or “peque peques” with small load capacity and routes less of than 8 hours (Appendix 2).

Table 2. A summary of the variables assessed in this study and their measurement units.

Variable	Type of variable		Indicator
Time to market	Independent	Continuous	Travel time from the community to Iquitos
Time to harvest area	Independent	Continuous	Travel time from the community to the aguajal
Harvesting technique	Independent	Categorical	The main technique used by the community
Volume of production	Independent	Continuous	Number of sacks registered annually for each village
Watershed	Independent	Categorical	Type of river
Proportion of females	Dependent	Continuous	Proportion of female trees in the stand

3.6. Data analysis

Only adult individuals of *Mauritia flexuosa* where their gender was possible to determine were included in the analysis. The proportion of females for each sampling site was obtained by dividing the number of females by the total sample size. All statistical analysis was carried out using the software R v.3.5.3 (R_Core_Team, 2019).

3.6.1. Analysis of explanatory variables

The statistical analysis consisted of analysing which independent variables individually, and in combination, are significantly related to the variation in the proportion of female trees. The analyses were conducted using the *lm* (linear model) function in R.

The analysis was based on the following equation (Rojo, 2007; Jaume and Catalá, 2001):

Equation 1

$$y = \beta_0 + \beta_1 * T.market + \beta_2 * T.HA + \beta_3 * H.tech + \beta_4 * Volume + \beta_5 * Watershed + \varepsilon$$

Where y is the proportion of female trees, $\beta_0 - \beta_5$ represent the coefficient of regression, $T.market$, $T.HA$, $H.tech$, $Volume$ and $Watershed$ are the explanatory variables (time to market, time to harvest area, harvesting technique, volume of production and watersheds respectively) and “ ε ” is the residual error.

The first model (Model 1) included all variables and the interaction between them. According to their significance in the model ($p > 0.05$), non-significant variables and interactions were then removed to create a second statistical model (Model 2).

Because cutting is the most common harvesting technique across the study area, the same statistical analysis was also applied to just sites where fruits were harvested by cutting the trees down (Model 3).

The goodness of fit for the models was determined using the r^2 and the AIC values. The fit of the model in terms of the distribution of the residuals was explored using the *DHARMA* package (Hartig, 2019; Brooks et al., 2019).

3.7. Mapping variation in the levels of palm swamp degradation

The findings of the regression analyses were used to map spatial variation in the proportion of females of *Mauritia flexuosa* across the study area. For this process, shapefiles of the hydrology of the region of Loreto and the satellite image of the distribution of palm swamps from Draper et al. (2014) were used. The process was performed using ArcGIS v. 10.4.1 (ESRI, 2015).

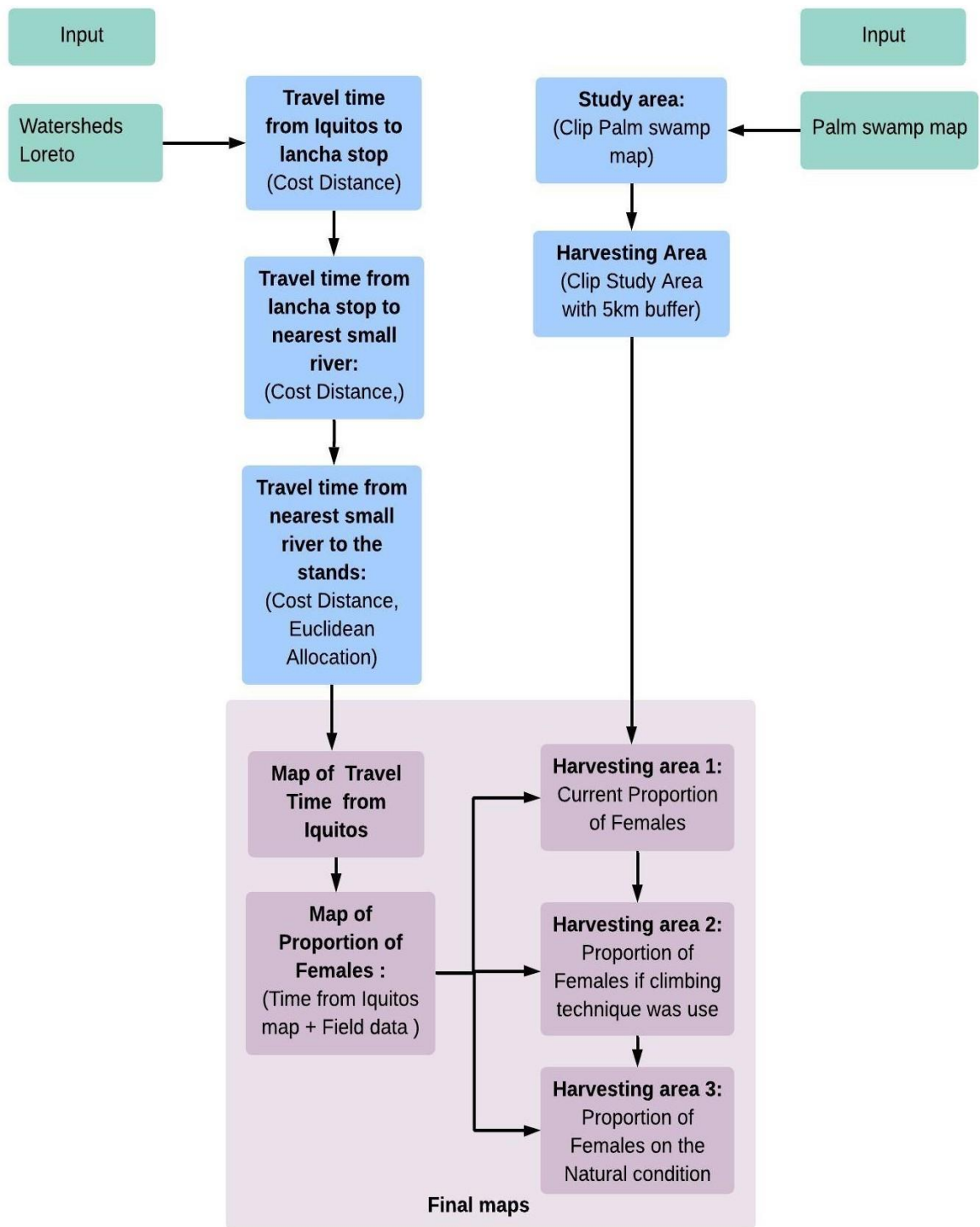


Figure 5. Flow diagram show how variation in the degradation level of palm swamps was mapped based on travel times to Iquitos. The travel time from Iquitos to each pixel containing palm swamp was calculated as the sum of (1) the time to travel from Iquitos to each community by “lancha”, (2) the time to travel by “peque peque” from each community to the nearest point to each palm swamp accessible by river, and (3) the time to walk from the river to the palm swamp. Field values of the proportion of female trees were regressed against travel times per site taken from the map to

estimate the proportion of females for the study area. Final maps of the proportion of female trees were created to represent the current degradation levels in palm swamps, and also, if climbing was used instead of cutting female trees, and if the forests were at a natural state with 50 % female trees. The harvest area in the three last maps was clipped to a 5 km buffer zone around the main rivers based on the maximum human effort to harvest the fruit.

First, the river basins shapefile for the region of Loreto were divided into two layers according to the watershed categories used in the regression analysis. Moreover, speed values in format of hour/meter (h/m) for the mean of transport of 15 km/h (0.00006 h/m) for the big river category (Alvarado, 2017; Cabrera and Montero, 2000) and 4 km/h (0.00025 h/m) for the small river category (fieldwork on this study) and 1.5 km/h (0.0006 h/m) for walking within the forest were added to the river layers. Second, the resulting river layers were converted to GIS raster format which uses pixels as a unit of measurement on the map.

Variation in the degradation level of palm swamps was mapped based on estimates of the travel times from each 1 km² pixel of the study region to Iquitos. Firstly, the “cost distance” function was used to calculate the travel time values from Iquitos to each community along the main river network which are “lancha” stops, based on boat speeds of 15 km/h for rivers in the big river category (Alvarado, 2017; Cabrera and Montero, 2000). Secondly, the travel time from each of these lanca stops to the nearest point by river to each pixel of palm swamp by “peque peque” (based on boat speeds of 4 km/h; this study) was calculated. Finally, these travel times were summed with the walking time from each point along the river to the nearby palm swamps using the “Euclidean allocation” function, based on walking speeds of 1.5 km/h, to estimate the total travel time from each pixel of Loreto to Iquitos (Fig. 5).

The estimates of the total travel time were then correlated with the proportion of female trees at each sample site, and this relationship was used to map degradation levels across the basin. In this analysis, only sites where palm trees were cut, were used.

The proportion of female trees was estimated as a function of travel time as:

Equation 2

$$PFe = t\beta_0 * a$$

where: PFe is the estimated proportion of female trees in a stand, t is the estimated travel time to Iquitos from the model, β_0 is the coefficient of the regression and a is a constant.

3.7.1. Estimating the potential value of aguaje to local communities

To estimate the potential value of the *Mauritia flexuosa* fruit harvesting to communities, the total potential area of extraction was defined as all palm swamps within 5 km of a major river. This distance was used as it is the average distance of the sampling sites in this study to the nearest river or stream. To delimit this area, the “buffer” function was used to create a polygon shape, 5 km around the nearest river. This polygon was used to clip out palm swamp areas mapped by Draper et al. (2014) that are within 5 km of a river. In total, the total potential area for *Mauritia flexuosa* harvesting was estimated as 237,400 ha.

The map of the proportion of female trees were then modified in two ways to represent two possible scenarios if sustainable management techniques were applied. Firstly, the effect of climbing on the proportion of female trees measured in this study (+ 0.13) was added to the current estimates of the proportion of female trees, to evaluate how the value of fruit production would increase if climbing was used to collect the fruit across the whole region. Secondly, a constant ratio of 50% female palm trees was used to estimate the cost of current levels of degradation compared to the natural state of these ecosystems.

The proportion of females from each of the three maps was used to estimate the gross value of fruit under the three different scenarios. For each scenario, the total value of the potential fruit harvest was estimated as:

Equation 3

$$Inc_t = \sum_{i=1}^n PF_i * APx * D * Sc * Psc$$

where PF_i is the proportion of female trees in each of n pixels, APx is the area in hectares per pixel (100 ha), and D is the average density (106 ind/ha) of palm trees registered in the sampling sites. Sc is the mean number of fruit sacks collected per palm tree in the study area (1.7 sacks): as most communities use destructive techniques to collect all the fruit per palm, in this study, the number of sacks was calculated using the total number of racemes recorded per palm multiplied by a constant (0.75 sack/raceme; Vacalla, 2014). Psc is the average price of USD 5.05 (17 PEN) per sack in the market recorded from 13 communities as part of this study. The overall projected income, Inc_t , was calculated as the sum of the value across all pixels (Equation 3).

4. Results

4.1 Variation in the proportion of females trees

This study analysed data from palm swamps distributed across 27 communities and six watersheds in the Peruvian Amazon. A wide variation in the proportion of females across the palm swamps was found: 14.3% of stands included in the study (10 sampling sites; Fig. 6) presented very low values with less than 10 % female stems. The lowest values were found in the communities of Las Brisas, Dos de Mayo and Jenaro Herrera (QCH-02: 0.03, DDM-01: 0.04 and REQ-04: 0.006 respectively) in the Itaya, Amazon and Ucayali watersheds respectively and also near to Iquitos, the main market.

On the other hand, there are also palms swamps with high proportion of females low damage by harvesting: 17% of the stands (12 sampling sites) showed low degradation, with a high proportion of females of $\geq 40\%$ (Fig. 6). From this group, the palm swamp with the best condition was found in the community of Puerto Alegría on the Itaya River: both stands sampled at that community had similar high proportions of female trees (52%, Fig. 6) Also, other palm swamps in good condition were on the upper Marañón river: the proportion of female trees was 48 % for Puerto Industrial, and 46 % for Nuevo Milagro and Bolivar.

However, most palm swamp areas presented medium levels of degradation. Forty eight of the stands evaluated (68.6%) had a proportion of female trees between 10 – 39 %. Many of these stands are under strong extraction activities currently and are important harvest points (Horn et al., 2018).

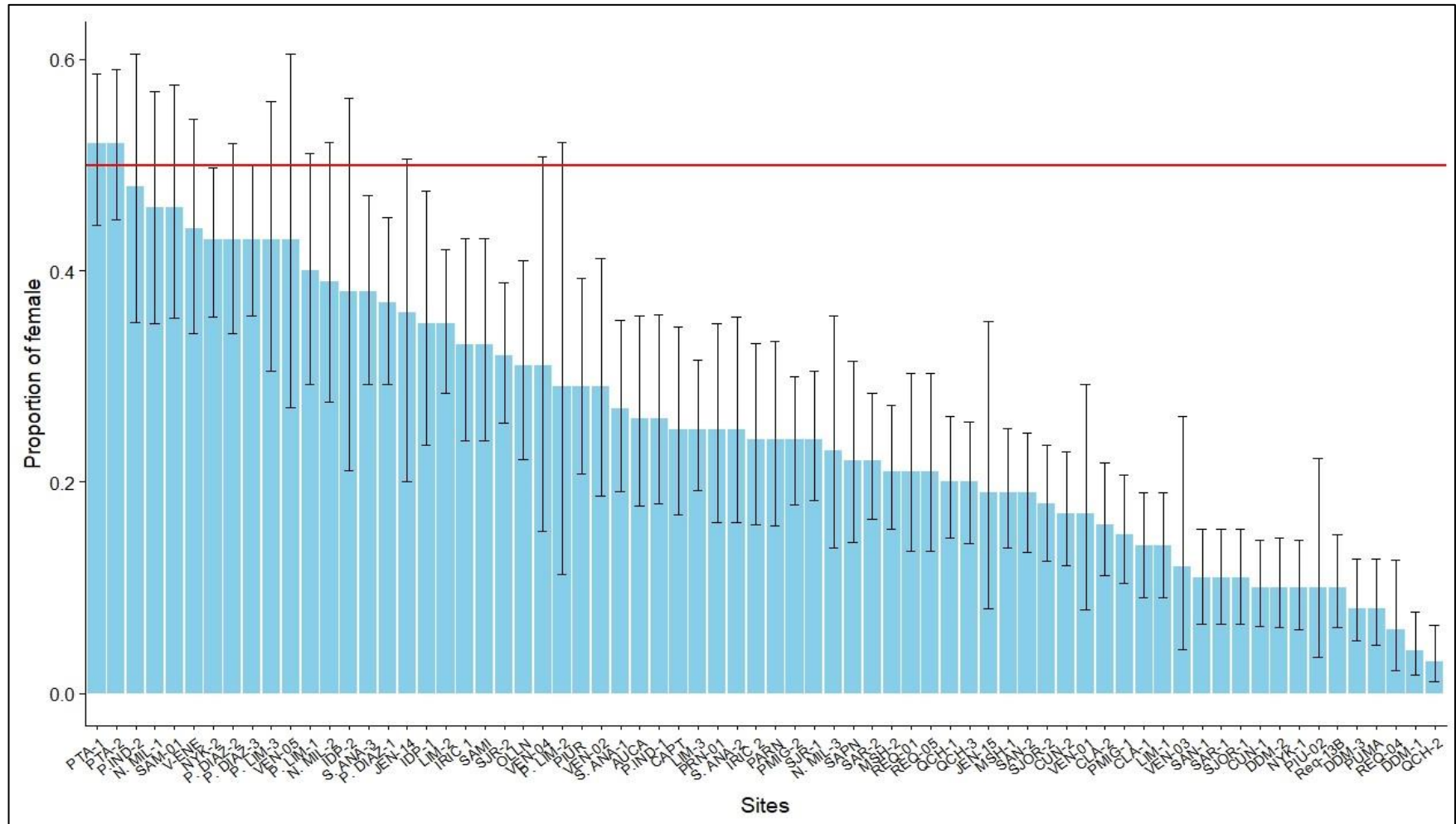


Figure 6. Variation in the proportion of females of *M. flexuosa* across the palm swamps evaluated in the Peruvian Amazon. The red line indicates the natural gender ratio of the species (50%). Confidence limits are represented by the black bars.

4.2. Processes involved in the degradation of palm swamps in the tropics.

Travel time to the market, the method employed to harvest fruits, the time spent travelling from the communities to the stands and the different watersheds were identified as the factors that were significantly related to the degradation of the palm swamps as registered by the proportion of female trees (Table 3).

Overall, Model 2, the minimally adequate model, explained 50% of the variation in the proportion of female palm trees (Table 3). Model 2 had a lower AIC value (-116.9) compared to Model 1 containing all variables (-113.1, Table 4).

Table 3 displays the different combinations of the variables assessed and their importance for explaining variation in the proportion of females of *M. flexuosa*. Model 2 shows the combination of variables that best explain variation in the proportion of female trees. Model 3 shows the combination of variables that explains variation in the proportion of female trees solely in sites where the trees are cut down for harvesting.

Table 3. Explanatory variables for the degradation of palm swamp ecosystems in the Peruvian Amazon.

Variables	Model 1				Model 2				Model 3			
	Estimate	SE	t	p	Estimate	SE	t	p	Estimate	SE	t	p
Time to market (hrs)	0.007	0.001	6.50	0.000	0.007	0.001	6.48	0.000	0.007	0.001	6.81	0.000
Time to harvest area (hrs)	0.025	0.019	1.30	0.198	0.035	0.011	3.33	0.001	0.032	0.012	2.76	0.008
Harvesting technique (cutting)	-0.160	0.046	-3.45	0.001	-0.136	0.033	-4.18	0.000				
Watershed (small river)	0.130	0.051	2.54	0.014	0.089	0.031	2.82	0.006				
Volume of production (sacks)	0.000	0.000	-0.49	0.620								
Harvesting technique / Time to harvest area (hrs)*	0.015	0.023	0.68	0.499								
Time to market (hrs)/ Watershed *	-0.005	0.005	-1.12	0.266								

* Interaction between variables, SE: Standard deviation, t: t test value; p values of 0.000 indicate $p < 0.001$

The different regression models include different combinations of variables **Model 1**: the original model which include all variables tested and the interactions between them. **Model 2**: the minimally adequate model, represents the combination of variables that best explain the variation in the proportion of females palms. **Model 3**: as model 2 but just for sites where trees are cut down. Interaction terms are the combined effect of two independent variables allows the study to assess if specific combinations of the variables contribute to explain the changes in the proportion of female trees. Interactions were only included in Model 1 and were not significant.

Table 4. Goodness fit of the regression models

	r^2	AIC	F	DF	p
Model 1	0.5	-113.1	8.63	62	0.000
Model 2	0.5	-116.9	14.91	65	0.000
Model 3	0.5	-96.5	24.31	53	0.000

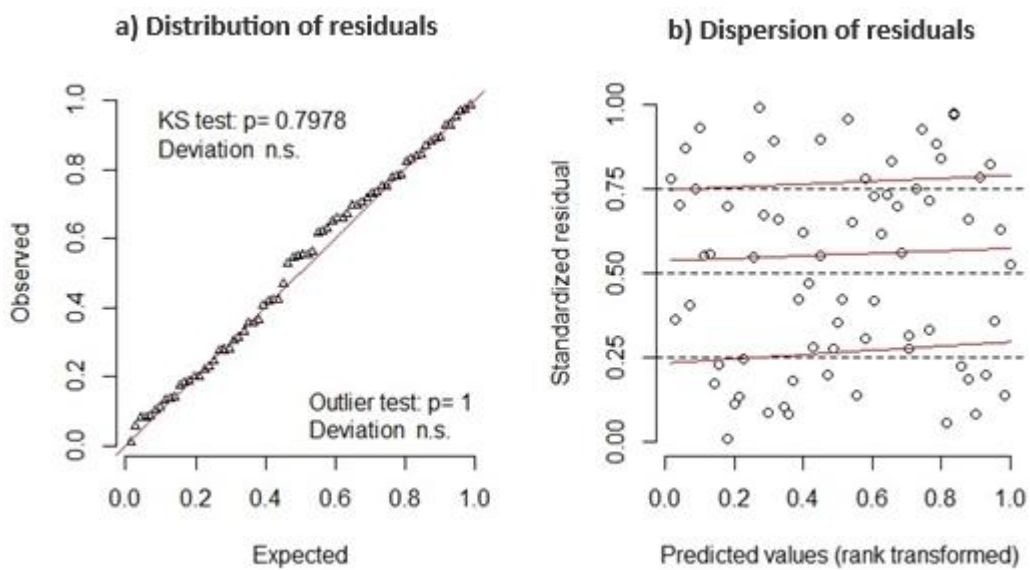


Figure 7. Verification of the residuals for Model 2. **Panel a:** the distribution of the residual values of the model closely follows a normal distribution; **panel b:** dispersion of the residuals against the predictions of the model; the red lines placed close and parallel to the direction of the quantiles (dashed lines) indicate a uniform dispersion without the presence of biases in the predictions.

Table 5. Contribution of each variable for explaining variation in the proportion of female trees.

r² values for each variable		
Variable	Model 2	Model 3
Time to market (hrs)	0.20	0.4
Time to harvest area (hrs)	0.1	0.1
Watershed	0.03	
Harvesting technique	0.17	

The greatest contributor to explaining the variation in the proportion of females in palm swamps is the travel time from communities to the main market. This variable explained the highest proportion of variation within the regression models (Table 5). In addition, the technique used to harvest the fruit was the second most important explanatory variable and contributed 17 % of the explanatory capacity of Model 2 (Table 5).

4.2.1 Time to the market and to the harvest area

The time from the community to the main market of Iquitos was a good explanatory variable for the degradation level of the palm swamps. Model 2 (Table 3) shows that when more time is required to reach to the market, *M. flexuosa* stands have a higher proportion of females ($p < 0.001$). For instance, Dos de Mayo, San Jorge and Las Brisas which are located within 5 hours of travel, show values of less than 20% (0.2) for the proportion of female trees. In contrast, palm swamps in communities very far from the market, such as Puerto Diaz and Puerto Industrial in the upper Marañón basin, have a moderate to high proportion of female palms (Figure 8).

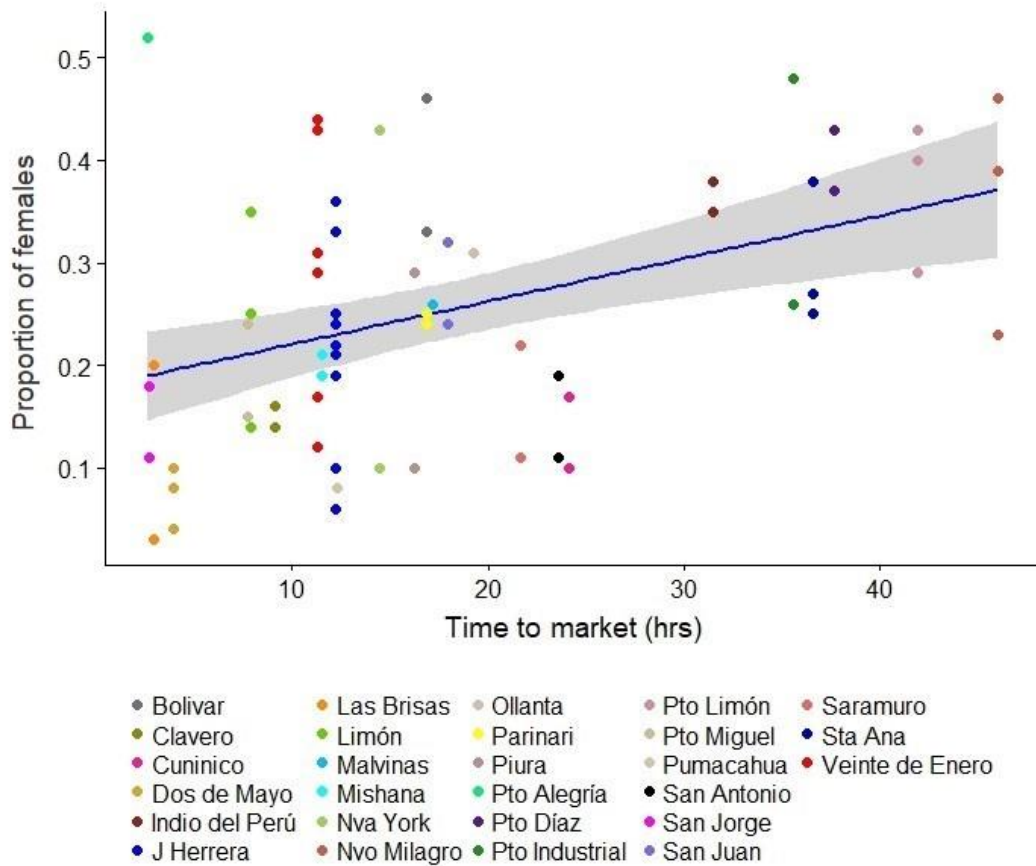


Figure 8. Relationship between the proportion of female palm trees and the travel time to Iquitos from the communities. These variables are significantly correlated ($p < 0.001$ and $r^2 = 0.42$).

On the other hand, travel time to the harvest area from each community has a weaker relationship with the indicator variable. A trend in the relationship between time to the harvest area and the proportion of females is observed in Figure 9 and shows that palm swamps that require more time (more than 5 hours) to reach them from the communities have a higher proportion of females > 0.3 . In addition, Model 2 and Model 3 (Table 3) show that for every hour that the travel time from the community increases, the proportion of female trees increases by 0.035 and 0.032 ($p < 0.001$) respectively.

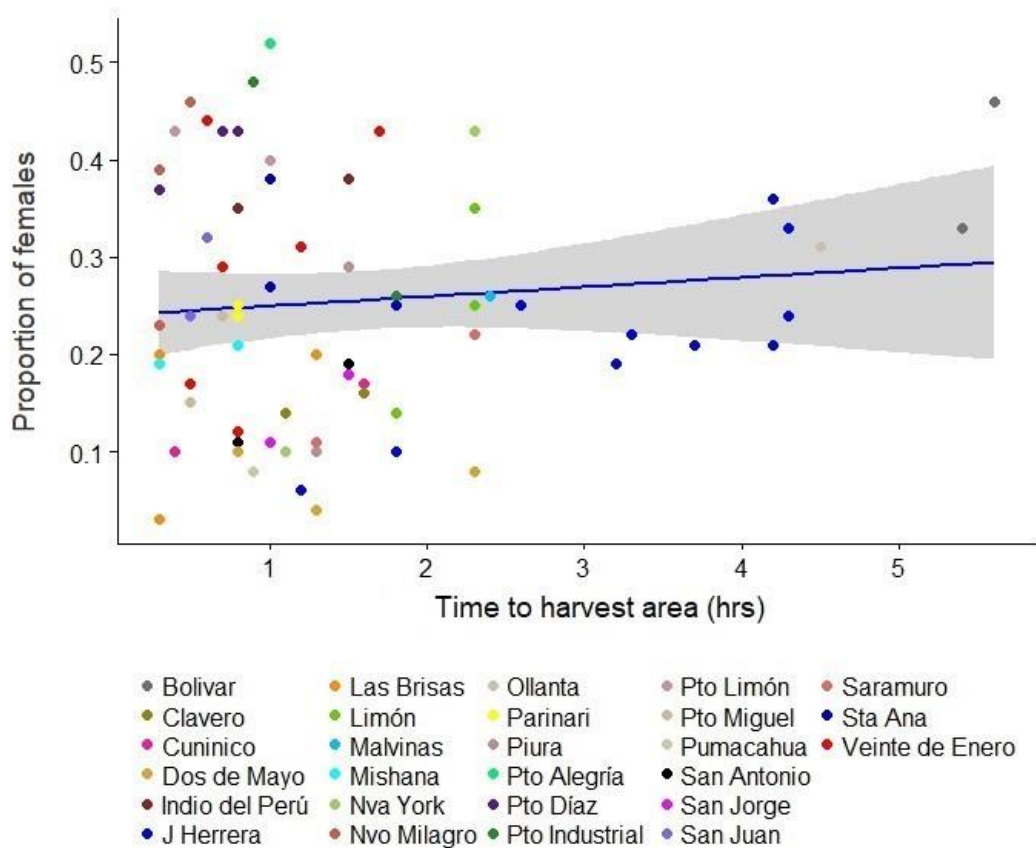


Figure 9. Relationship between the proportion of females of *Mauritia flexuosa* and the time to the harvest area. A weak correlation was found between these variables ($p > 0.05$ and $r^2 = 0.01$) but the contribution of time to harvest area to the full linear models was significant (Table 3).

Figure 9 shows that 53 (75.7%) of the sampling sites are located less than 2 hours from the nearest community, and there is a high variation in the proportion of females among sites (range: 0.03 – 0.52). Also, the data indicates that 1.5 hours is the average time that people travel to gather the resource. Access to palm swamps was by a combination of trips by boat and a path in the forest for 57% of the sampling sites while 43% of the sites were accessed only by paths in the forest (Appendix 4).

4.2.2. Harvesting technique

The method of harvesting the fruit is an important factor to explain variation in the degradation of palm swamps (Fig. 10). The commonest technique involves felling female trees: 80% of the sampling sites in this study employed this technique. Palm

swamps where trees are harvested by cutting have a mean value of 0.24 for the proportion of female trees, and include very degraded stands with just 3% or 4% of female trees.

Sites where climbing was used to harvest the fruits have a mean value of 0.32 for the proportion of female trees, with a range of 0.12 to 0.52 (Fig. 10). The use of climbing was found in communities in both categories of watershed and with a wide range of length of trip to Iquitos (2 – 17 hours). The highest (52%) proportion of female trees was found in Puerto Alegría, a community where climbing is used.

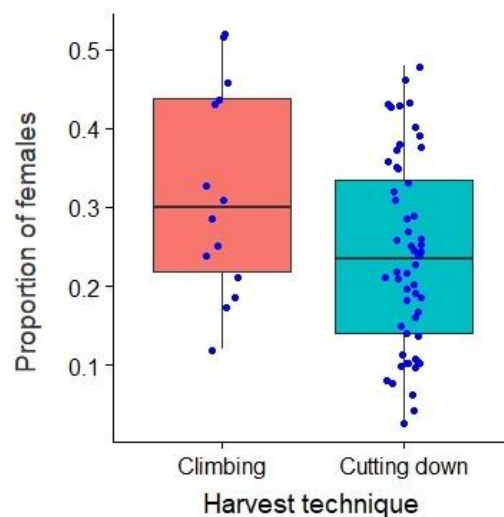


Figure 10. Comparison between the effect of the method of fruit collection on the proportion of female trees of *Mauritia flexuosa*.

Model 2 (Table 3) shows that for sites where trees are cut down, the proportion of female decreases by 0.13 ($p < 0.001$) compared to the sites where the palms are climbed. Overall, this factor was the second most important factor linked to the degradation levels of the palm swamps.

4.2.3. Watersheds

The watershed also has an effect on the level of palm swamp degradation. Similar to the harvesting technique, the proportion of female shows wide variation (from <0.10

to 0.52) for both categories of the watershed (Fig. 11). Palm swamps located within the small river category display a higher proportion of female trees (most stands ≥ 0.2) compared to those located within the “big river” category. On the other hand, an important number of stands (21 sampling sites) in the ‘big river’ category had less than 20 % female trees (Fig. 11)

Model 2 (Table 3) indicates that palm swamps along small rivers have a higher proportion of females ($p < 0.006$) compared to stands along big rivers. However, the contribution to explaining variation in the proportion of females is the lower ($r^2 = 0.03$) than the three previous factors.

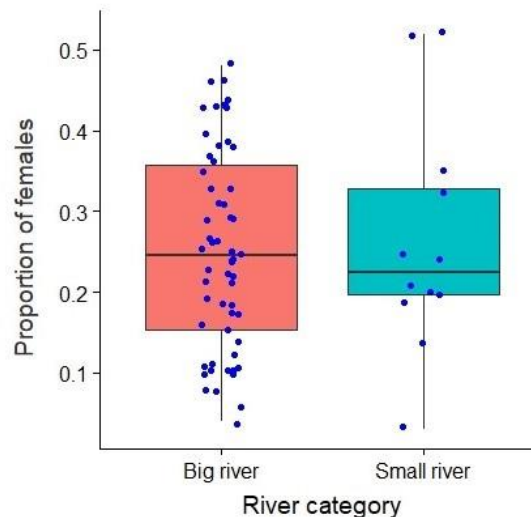


Figure 11. The difference between the proportion of females between stands that differ in the degree of accessibility by river.

4.2.4. The volume of the production and relationship among variables

Variation in the volume of fruit harvested in the sampling sites has no effect on the proportion of female for *Mauritia flexuosa* stands. Although there are differences in the number of sacks sent to the Iquitos (Horn et al., 2018), this factor does not contribute to explaining variation in the degradation of palm swamps. In the same way, the interactions between variables tested in the regression analysis (Model 1 –

Table 3) did not explain variation in the proportion of female trees among stands ($p > 0.05$).

4.3. Modelling patterns of palm swamp degradation

4.3.1. Estimating spatial variation in the proportion of female trees of *Mauritia flexuosa*

The significant relationships between travel times and the proportion of female *M. flexuosa* trees justifies the use of this parameter to model degradation levels across the region (Table 3). Travel times to Iquitos from across Loreto have a maximum value of 112 hours from the northeast area of the region (Fig. 13a). However, the access time to palm swamps located within the study area shows a range from 6 to 60 hours from Iquitos, whilst for the potential harvesting area within 5 km of rivers, travel time to reach to the stands shows a maximum value of 46 hours from Iquitos.

The relationship between the estimated travel times and the proportion of female trees from the study sites was strong (Pearson correlation $r^2=0.42$ and $p < 0.001$, Fig. 12).

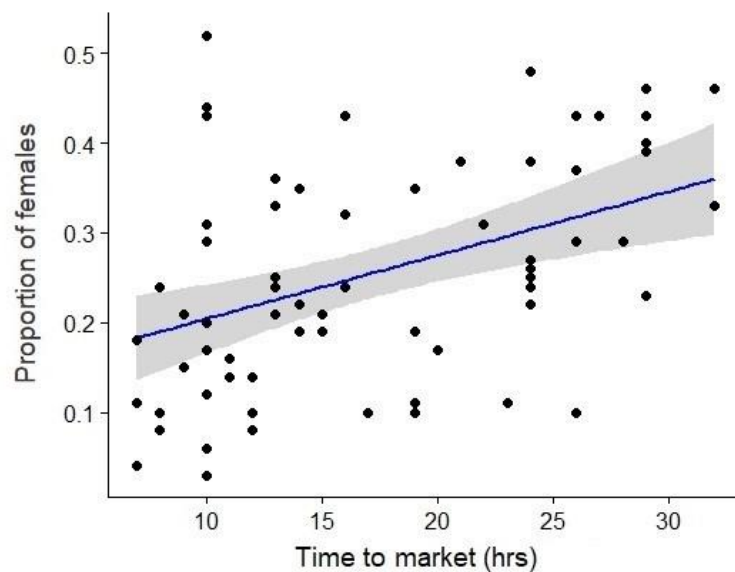


Figure 12. Relationship between the proportion of female trees and the estimated travel time to Iquitos, the commercial centre of the region.

The proportion of female trees across the study area was estimated using the relationship between the modelled travel time to Iquitos for each pixel and the field data of the proportion of females taken in each site. (Fig. 13b). The proportion of females values show a gradient from 0.09 to 0.50 (from yellow to blue). In the basin of the Amazon River as well as in the lower Ucayali and Tigre rivers (right side of the map), most stand shows a proportion of females palms from 9 – 16%. This low range is also associated with the effect of the proximity to Iquitos. On the other hand, the map shows moderate conditions for stands in the Nanay and Itaya River (16 – 25%). In addition, the estimated proportion of females for stands along the Marañón River display areas from moderate to good condition, with most stands with 21 - 37% female trees.

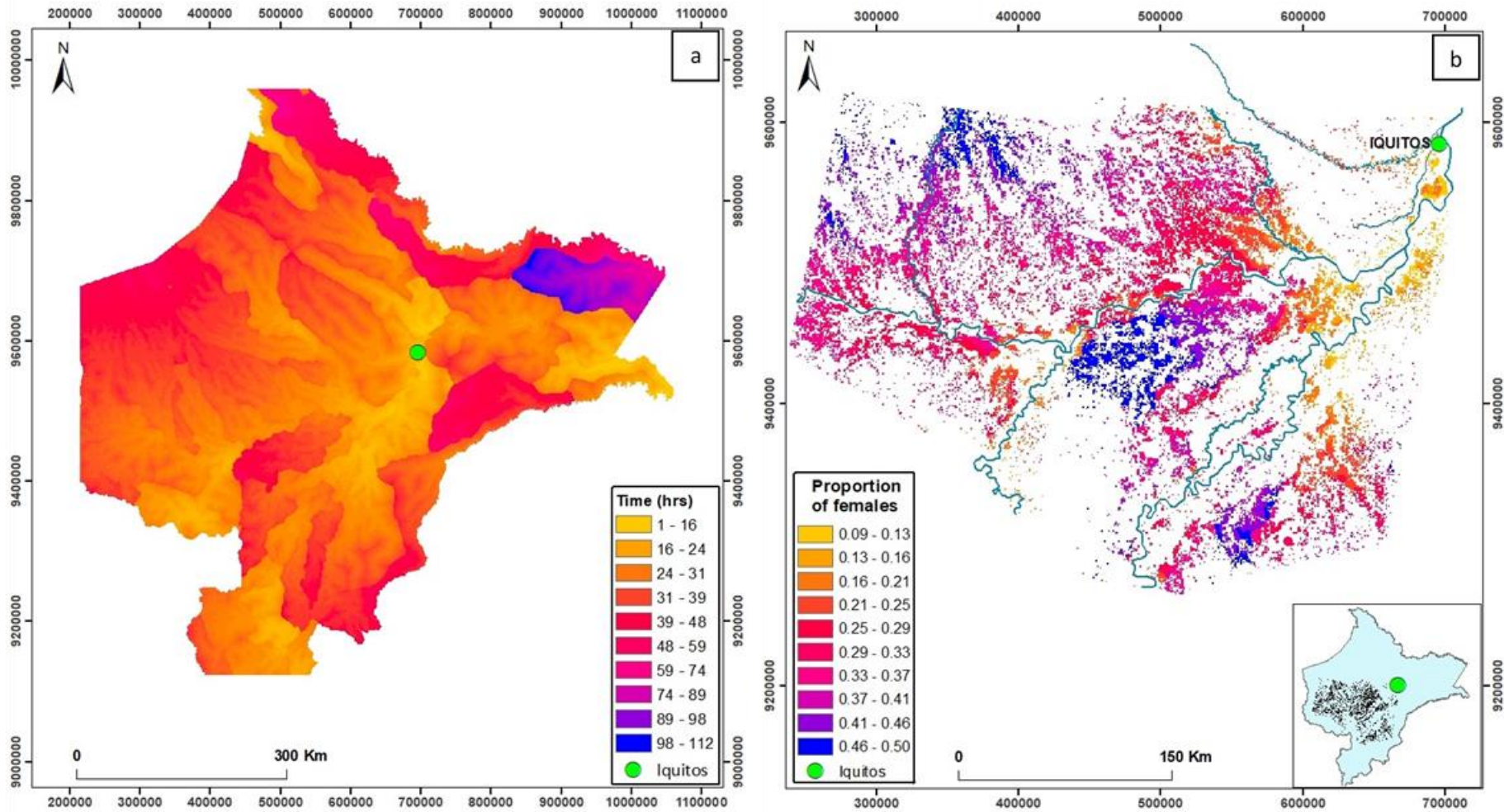


Figure 13. Panel a: Variation in the estimated travel time from across Loreto for transporting *Mauritia* fruit to Iquitos. Panel b: Estimation of the proportion of female trees across the palm swamps of the study area. Map units: UTM - WGS 1984, Zone: South 18M.

4.3.2. Simulating the effect of sustainable harvesting on the proportion of female trees of *M. flexuosa* stands

Assuming that communities can potentially harvest aguaje fruits up to 5 km from the main river, the maps were used to estimate the total potential income from harvesting aguaje fruits, given the current gender ratio (Figure 14a). The estimated potential gross income is USD 57.6 million (57'651,898) per year according to the current proportion of female trees. The value per hectare ranges from USD 82 to 455 per year. If the proportion of females across the region is increased by 0.13, equivalent to the improvement in forest health if all communities climb palms to collect fruit (**Figure 14b**), the increase in the volume of harvest contributes to increasing this value by 32.5% (USD 85'404,349) with respect to the current status. Finally, the potential revenue was estimated for palm swamps for the natural state with 50% females trees (**Figure 14c**). In this scenario, potential incomes increase by 46.7% (USD 108'124,066) respect to the current estimated income. This difference represents the potential economic loss caused by degradation of this ecosystem.

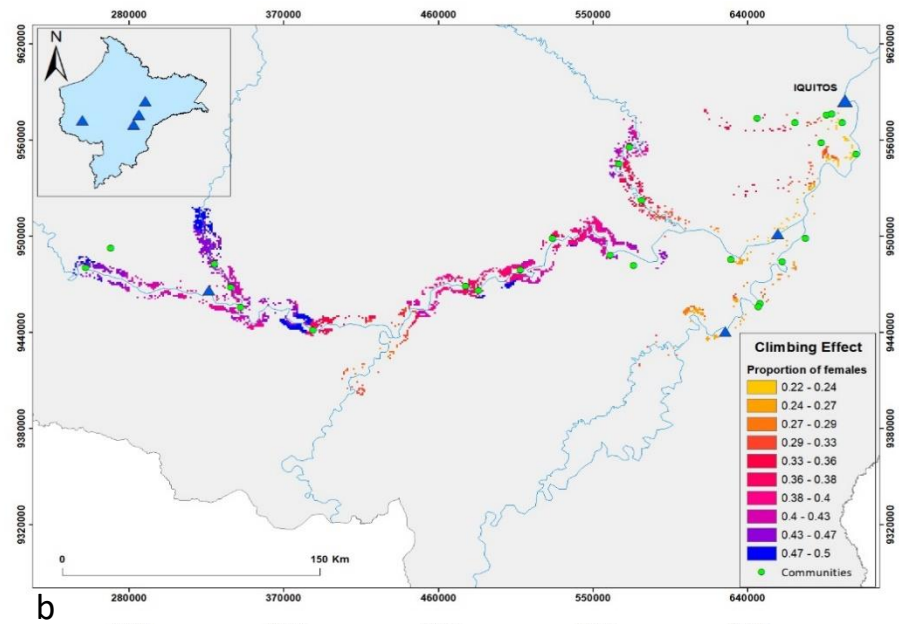
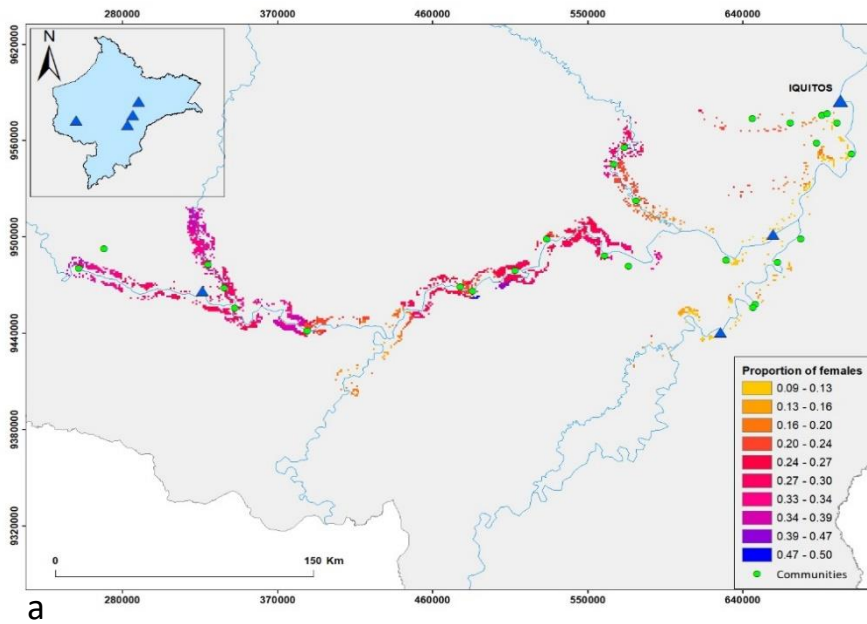
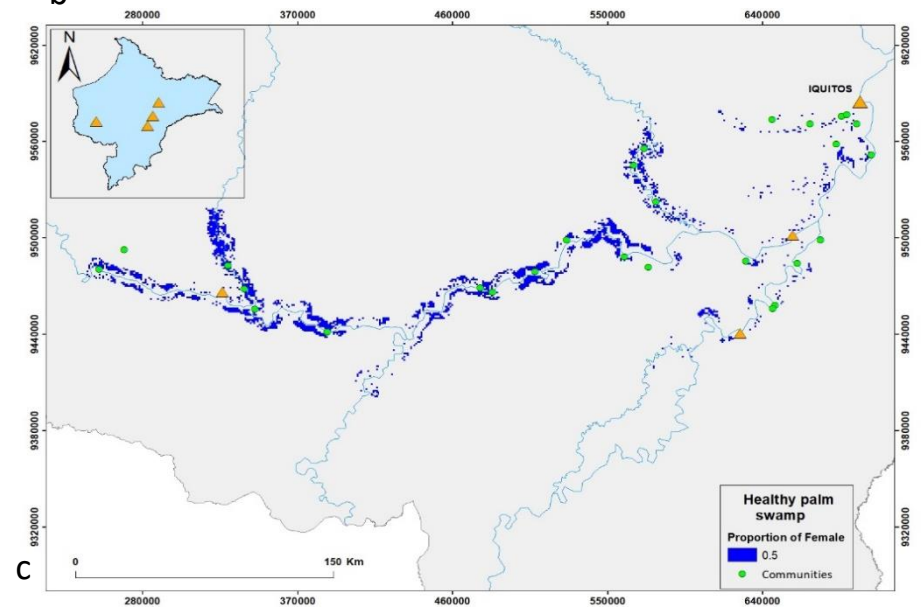


Figure 14. Estimation of the proportion of females of *M. flexuosa* within the potential harvesting area defined as 5km from a main river. **Panel a:** Estimate of the current proportion of female palms across the study area. **Panel b:** Simulated proportion of female tree if stands harvested by climbing. **Panel c:** Proportion of female trees for stands at the natural state with 50 % female trees.

Map units: UTM – WGS, Zone: South 18M.



5. Discussion

This study demonstrates that there is a significant degradation of the palm swamps of the northern Peruvian Amazon, even hundreds of kilometres from the closest city. The results support the hypothesis that female trees are more common in sites that are more distant from the main trade centre, and the unique ability to predict the baseline conditions of this resource indicates that the removal of female trees imposes a significant reduction in the potential income from fruit harvesting. However, more positively, the significant effect of the use of climbing to harvest fruits on the proportion of female trees demonstrates how simple management interventions could significantly increase incomes of local communities.

The dataset showed a wide range in the proportion of female tree across the sampling sites (0.03 – 0.52), from very degraded to stands in good condition. Similar ranges (0.0 – 0.56 and 0.0 – 0.44) in the gender distribution were reported by Van Sledright (2008) and Horn et al. (2012) for palm swamps in the Tahuayo and Napo river basins respectively. This study also shows similar maximum values for the proportion of female palm trees compared to Holm et al. (2008), Holm (2007), Horn et al. (2012) and Penn et al. (2008), who found values of 0.42 - 0.44 for palm swamps with minimal disturbance on the Marañón river, whilst this study found values over 0.46 for stands in the communities of Bolivar, Puerto Industrial, Nuevo Milagro and Puerto Alegría (Fig. 6). In addition, this study found high values for the proportion of females (0.46 – 0.48) for less disturbed stands within the Pacaya Samiria National Reserve as well as in the upper Marañón. This finding agrees with the proportion (0.49) reported by Khan and de Granville (1992) for a non-harvested forest in Colombia as well as the reports of Casanova and Pacaya (2016) 0.39 – 0.48 for palm swamps in the community of Parinari.

5.1. Factors driving degradation of palm swamps

The proximity of the stands to Iquitos plays a key role in the level of exploitation of palm swamp ecosystems. This study showed a greater proportion of females in palm

swamps further from the communities: stands located further (more than 3 hrs) from the communities present from moderate to high proportion of females (Fig. 10). A similar pattern was found by Bodmer (1994) and Van Sledright (2008) at smaller scales within the Tahuayo River, using 101 plots (25 x 25m – 50 x 50 m) collected from 24 palm swamps. Van Sledright's model was able to explain 34% of the variation in the gender ratio based on the number of seedlings and travel time by boat and walking within the forest. This result is supported by the findings of Horn et al. (2012) and Falen and Honorio (2018) reporting that each fruiting season people travel more time to extract the resource.

Travel time to the market was the main factor ($r^2= 0.20$ and 0.40 for Model 2 and Model 3 respectively) affecting variation in the proportion of females of *M. flexuosa* in Loreto. A similar pattern was reported by Ahrends et al. (2010) that distance from the nearest commercial centre (up to 220 km) determined the level of degradation of the forest in Tanzania.

5.1.1. Contribution of harvesting techniques to palm swamp degradation

This study found that 80% of the stands are harvested using destructive harvesting techniques. These results are consistent with results from other studies in the region (Del Castillo et al., 2006; Delgado et al., 2007; Trujillo-Gonzalez et al., 2011). In addition, Bodmer (1994) indicated the use of a non-sustainable method as the most common technique used by villagers in the Tahuayo River.

The harvesting technique is important for explaining variation in the proportion of female trees: this study indicated that where climbing occurs, the proportion of female trees is 0.13 higher (Table 3). The lack of information among communities about the ease of harvesting by climbing may contribute to the lack of uptake of this method. In fact, both cutting and climbing take similar lengths of time - cutting the palm takes around 20 – 25 minutes (CIMA, 2012b) whilst climbing the palm and cutting the racemes takes between 17 – 30 minutes (Falen and Honorio, 2018; Manzi and Coomes, 2009; Del Castillo et al., 2006).

It is important to note that this degradation is not limited to simply the numbers of female trees: cutting down the palms is also related to loss in the quality and genetic characteristics of *M. flexuosa* populations (Del Castillo et al., 2006; Penn et al., 2008; Delgado et al., 2007; Falen and Honorio, 2018; Ruiz-Murrieta and Levistre-Ruiz, 2011), as every harvest season, extractors fell the palms with the best quality fruit. For instance, individuals with fruit of a red coloured mesocarp (“shambo”) are the most desirable variety of aguaje. However, its high price (a sack can be sold up to USD 36) means that this variety is harvested even when the fruit is not ripe and as all the fruit from a tree is collected when it is cut down, there is no transfer of this feature to the next generation.

Fortunately, some communities are not harvesting destructively: this study found that 20 % of the swamps evaluated (14 sampling sites) are harvested applying non-destructive methods, in the Marañón, Itaya and Nanay rivers. Although the majority of the communities that apply this method are located within protected areas (PAs), this study found some communities located outside PAs that are applying or starting to change to sustainable harvesting techniques. The main motivation for these communities is to preserve the resource for continuous production over time, and access support from government and non-government organizations (NGOs). Typically, the change to the non-destructive harvest techniques starts with the guidance of government institutions or NGOs. However, it is important to highlight the experience of the community of Puerto Alegría in the Itaya River, where the change towards using climbing began around 30 - 35 years ago under the initiative of community members. Inhabitants highlighted the benefits of using this technique for promoting stable production over time and allowing the community to take special care of individuals with the best quality fruit.

Palm swamps extracted under sustainable techniques have a moderate to high (0.26 – 0.48) proportion of female trees (Casanova and Pacaya, 2016; Vacalla, 2014; Hada et al., 2013). Variation in the proportion of female trees among these sites could be related to the length of time that sustainable harvesting techniques have been used.

For instance, the change to using climbing techniques for communities within protected areas (PAs) was about 17 years ago (the first resource management plan in the Pacaya Samiria National Reserve was in 2002), whereas the community of Puerto Alegría on the Itaya River have used climbing for approximately 35 years.

Interestingly, maintaining sustainable harvesting techniques may be difficult, once established. Gilmore et al. (2013) and Horn et al. (2012) found that the Maijunas, a native tribe in the Peruvian Amazon, harvested this resource for self-consumption using the mainly sustainable method of collecting ripe fruit from the ground. However, as demand in the market increased, the use of destructive techniques became common. In addition, another reason affecting the use of sustainable harvesting techniques is the presence of harvesters from outside the community in the same palm swamp. This change can increase the intensity of the extraction (for example, to up to 100 sacks per day in the Yanayacu River), and cause a drastic change in the proportion of females (Horn et al., 2012; Gilmore et al., 2013). Whilst it is true that in the last decade, there has been a slight shift toward the use of sustainable techniques because harvesters have observed a decrease in the harvest volume (Horn et al., 2012), in this study, the use of climbing did not show a strong spatial pattern and is applied regardless of the proximity to the market or the river basin where the palm swamp is located across Puerto Alegría (Itaya River), Dos de Mayo (Amazon River) and Parinari and Puerto Díaz (Marañón).

5.2. Modelling the spatial variation of the proportion of females of *Mauritia flexuosa* and the potential income from fruit harvesting

Most previous studies have evaluated the effects of extraction and the economic potential of aguaje at small scales of a few communities, and indicate a contribution of 15 – 22% to family incomes (Bejarano and Piana, 2002; Vacalla, 2014; Freitas, L, 2012; Van Sledright, 2008; Penn et al., 2008; Manzi and Coomes, 2009). In contrast, this study is the first large-scale estimate of the economic potential of this resource. The annual gross potential income projected for the study area was USD 57 million. The major uncertainty in this value is the per hectare value of aguaje stands to local

communities, which varies widely among studies. For example, Freitas, L (2012) reported an income of USD 264 ha yr⁻¹ for palm swamps on the Marañón River, whilst Vacalla (2014) reported revenues of just USD 24 ha yr⁻¹ for palm swamps along the Yanayacu Pucate, a small tributary of the Marañón, and Casanova and Pacaya (2016) found that one hectare of palm swamp represents an income of USD 30 ha yr⁻¹. The estimation from the map here (Fig. 14b) indicates a wide range in annual income from USD 182 - 455 per hectare per year, similar to the income levels based on the per hectare production data of Chuquinbalqui et al. (2014) for Veinte de Enero (with stands with 26 % female trees) and Freitas, L (2012). However, estimates for the study area that use the per hectare values of Vacalla (2014) and Casanova and Pacaya (2016) would yield much lower estimates of USD 5.6 million and USD 7.0 million respectively. These differences in the per hectare value of aguaje stands among studies is due to variation in the methodology in how they are calculated: the lower values are based on lower intensity harvesting that just includes harvesting female trees with four or more racemes (Vacalla, 2014; Casanova and Pacaya, 2016), whilst in this study used value for revenues that were calculated assuming that all racemes are harvested.

Despite uncertainties in the total potential value, the economic potential of aguaje is similar to revenue levels from other important non-timber forest products in Amazonian such as açai fruit (*Euterpe sp.*) which is worth 9.8 to 18.6 million USD in the Brazilian Amazon (Lameira et al., 2005; USAID, 2015), and Brazil nuts which are worth 75 million USD within Bolivia, and more than 25 and 19 million USD for Brazil and Peru in 2005 (MINCETUR, 2007).

The selection of the harvest technique has an important impact on the estimated revenues from the sale of *M. flexuosa* fruit. The estimates here (Fig. 14b) indicate an increase of 32.5% in the overall income if the climbing method was employed across all accessible aguajales. A similar trend was found by Freitas, L (2012) who evaluated variation in the *M. flexuosa* stands as a result of extraction activities over a period of five years in the Marañón river basin, and indicated that cutting trees caused a reduction of 46.2% in the income from fruit sale. Of course, the benefit of any

increase from employing sustainable harvesting techniques would require time of the order of decades, given the time that it would take for currently degraded aguaje stands to recover. However, these results provide an estimate of the normally unrecognised but substantial cost that historical forest degradation places on communities today. This effect is typically only noted seen anecdotally (Soga and Gaston, 2018) – for example, in the context of this study, the intensive destructive harvesting of aguajales by the community of Dos de Mayo over many years ultimately forced them to stop this activity as the resource became unavailable within the forests surrounding the community. However, here, the rare ability to estimate the natural baseline condition of the forest allows an estimation of the impact of historical degradation.

This study shows that *Mauritia flexuosa* has the potential to play a key role in the economy of Loreto. Compared to two of the most economically important activities in Loreto, the potential value of *M. flexuosa* fruit estimated here represents 53.7% of the average revenue from timber for the region of Loreto in recent decades (USD 107'32,455) and is 26.7% higher compared to the annual value (USD 45'494,145) of oil revenues (FAO, 2018; SNMPE, 2019; Congreso–Perú., 2019; MINCETUR, 2018). Remarkably, harvesting this NTFP has the potential to rival income from these extractive industries.

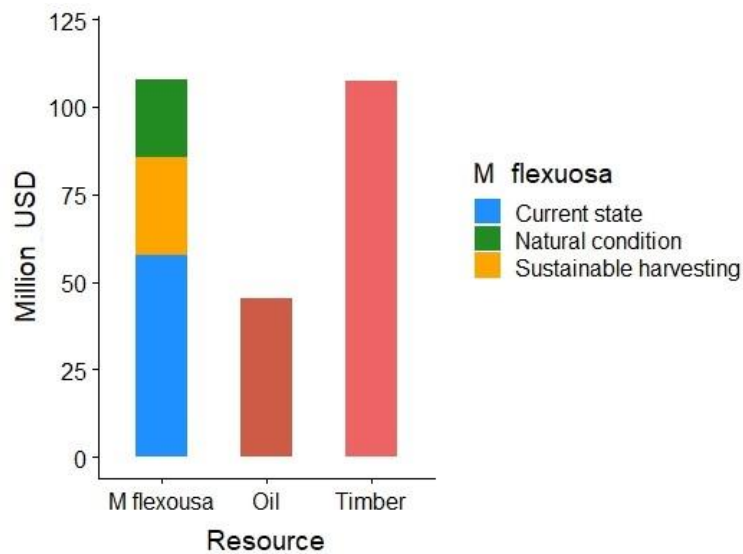


Figure 15. Comparison of the potential estimated income for aguaje harvesting and the main economically important activities of the region of Loreto. These values represent the average annual income in the last decade for oil exploitation and for the period 2015 -2018 for timber. The values are expressed in millions of USD. Current state: Estimated income for stands in the harvesting area with the current proportion of female trees. Sustainable harvesting: potential income estimated for the harvest area if all harvesting is done by climbing. Natural condition: potential income projected for the harvesting area with 50% female trees.

The field data and map presented here will be valuable for comparing with estimates of palm swamp degradation based on remote sensing products. For example, the map of degradation here contrasts with the patterns reported by Hergoualc’h et al. (2017) for one region of this area, based on analysis of Landsat and ALOS/PALSAR data. Hergoualc’h et al. (2017) mapped much higher levels of degradation alongside the Tigre river in the eastern part of this region, compared to areas in the centre of the Pacaya Samiria National Reserve. In contrast, here, these areas have very similar levels of moderate degradation. Mapping variation in the proportion of female trees directly using remote sensing data is likely to be extremely difficult, as male and female palms cannot be distinguished from their leaves, and the abundance of palms varies widely with environmental conditions. Ground-based datasets and an understanding of the factors which determine variation in degradation are likely to

remain important for estimating how resource levels, such as fruit availability, have been affected by human activity.

6. Conclusion

This study identified four factors driving degradation in palm swamp forests in the Peruvian Amazon, which explaining 50 % of the variation in the proportion of female trees across the sites surveyed. The proximity of stands to the market and the method of fruit collection played the most important roles in determining variation in the proportion of female trees, and the travel time from communities to the harvest areas and different watersheds were also significant.

This study provides the first large-scale map of the degradation levels of *Mauritia flexuosa* stands within Loreto. The potential income from fruit sale was estimated as USD 57.6 million. The income projected using climbing increases this value by 32.5% and harvesting of stands in a natural state would mean an increase of 46.7 % compared to the income for stands in their current condition.

The result of this study therefore shows that climbing represents a promising alternative for the harvest of *Mauritia flexuosa* fruits, allowing the ecosystem to recover gradually over time and improving incomes to communities. Realising this potential will require coordinated efforts by local and national governments and NGOs to set up a regulated market to stabilize fruit prices, promote sustainable harvesting and market development.

The information provided by this study will hopefully stimulate these kinds of activities as well as identify harvest zones and degraded areas for reforestation projects.

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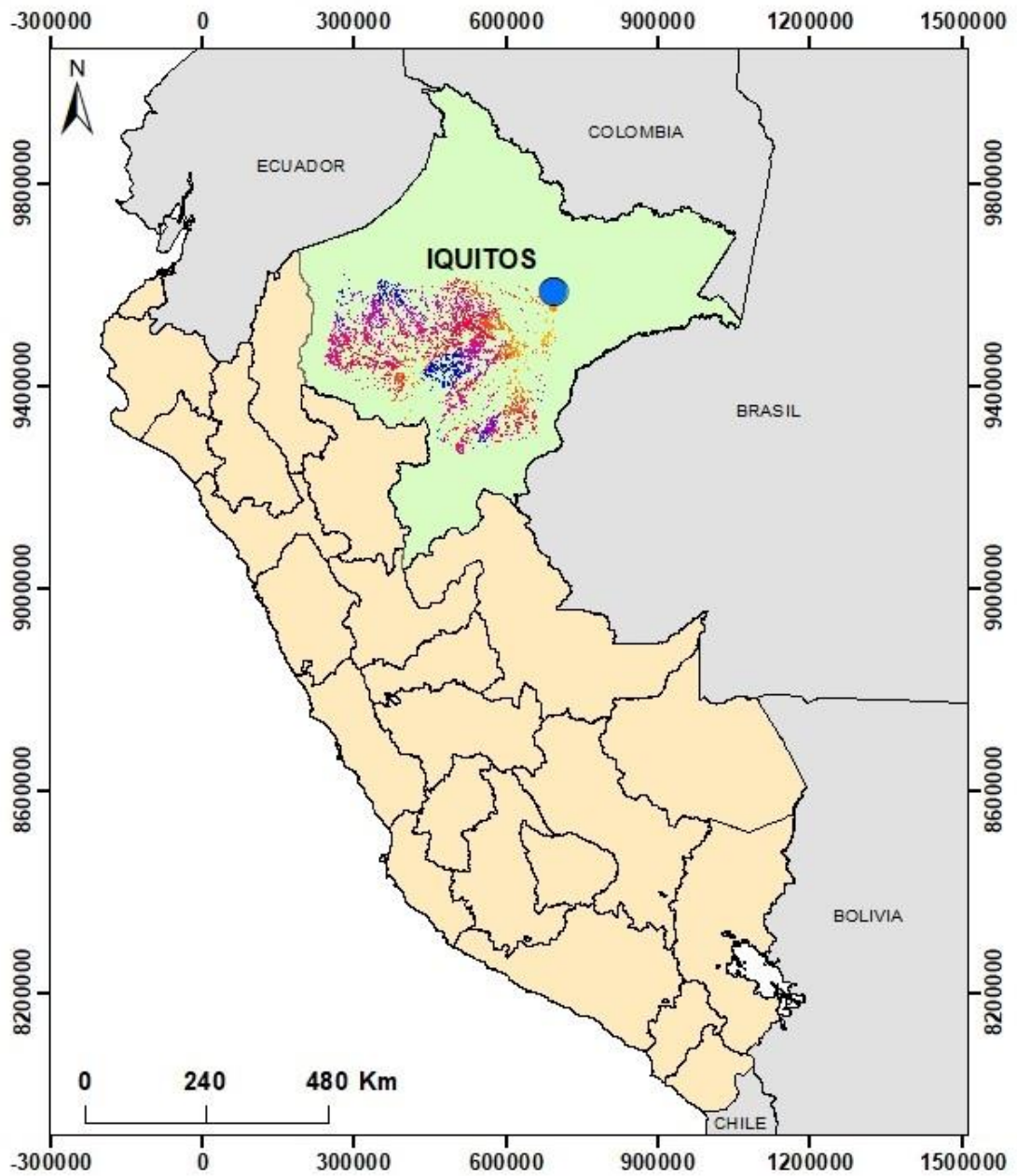
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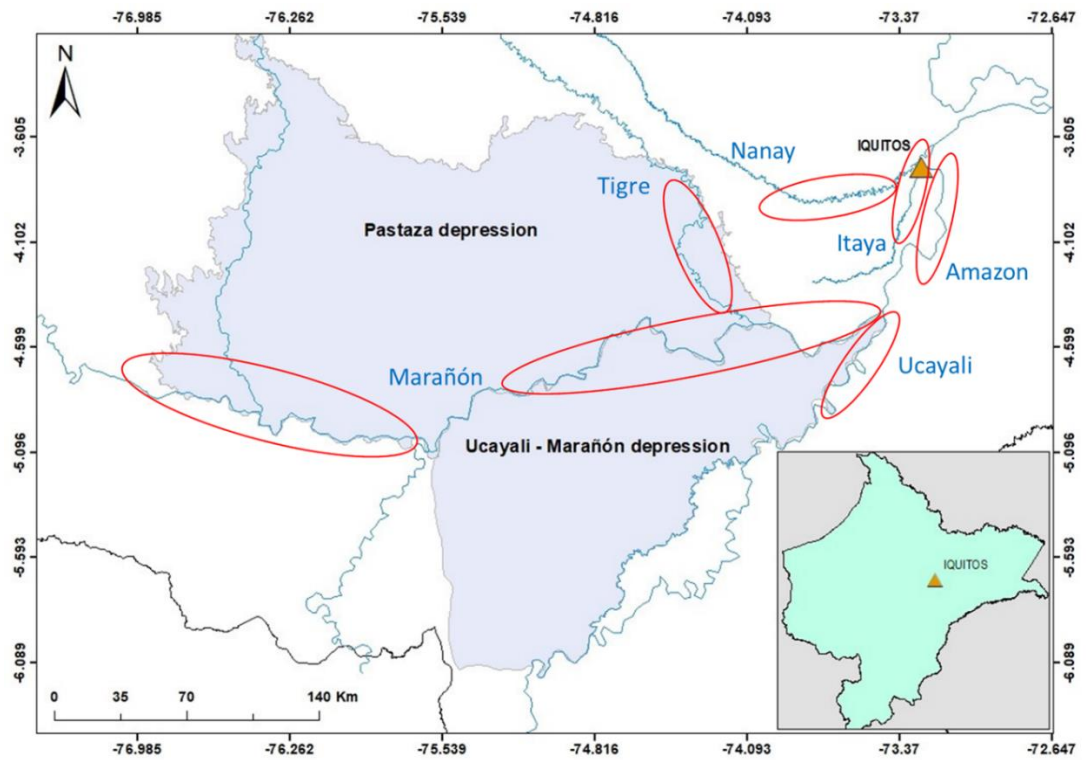
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Appendix

Appendix 1. Representation of the study area within the Peruvian territory.

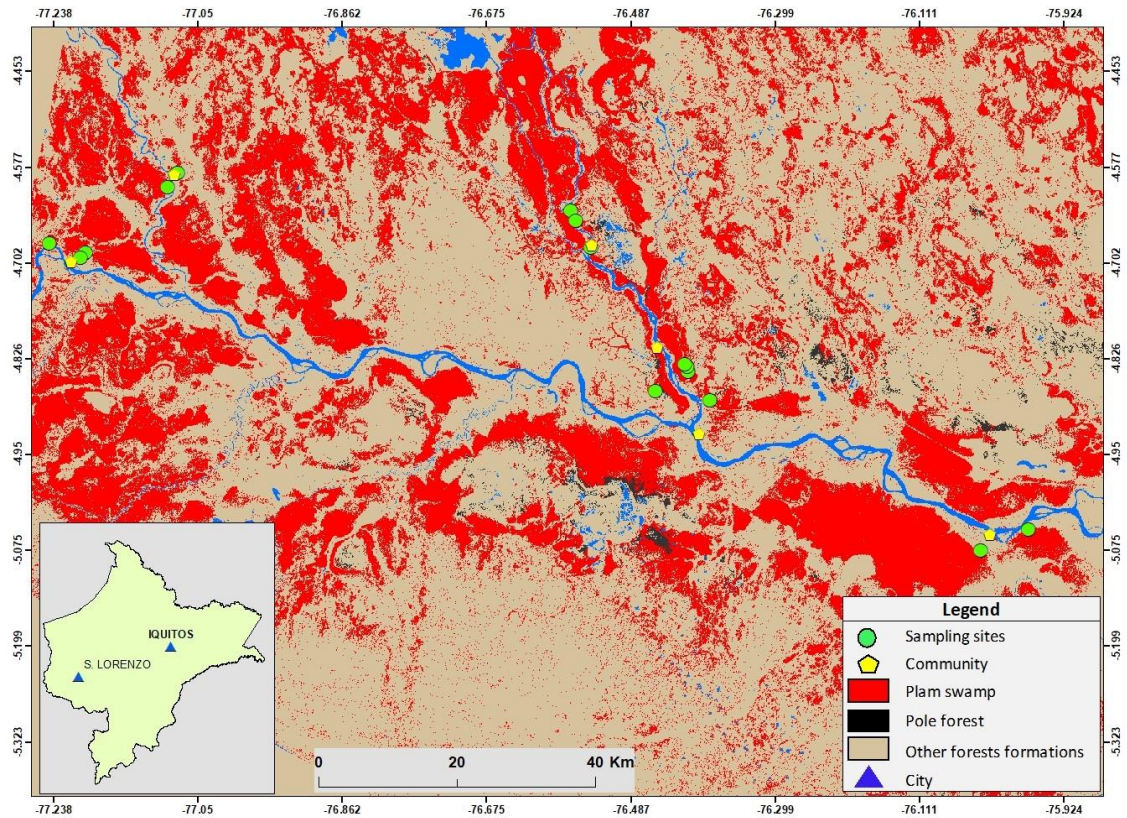


Appendix 2. Map of watersheds assessed in this study

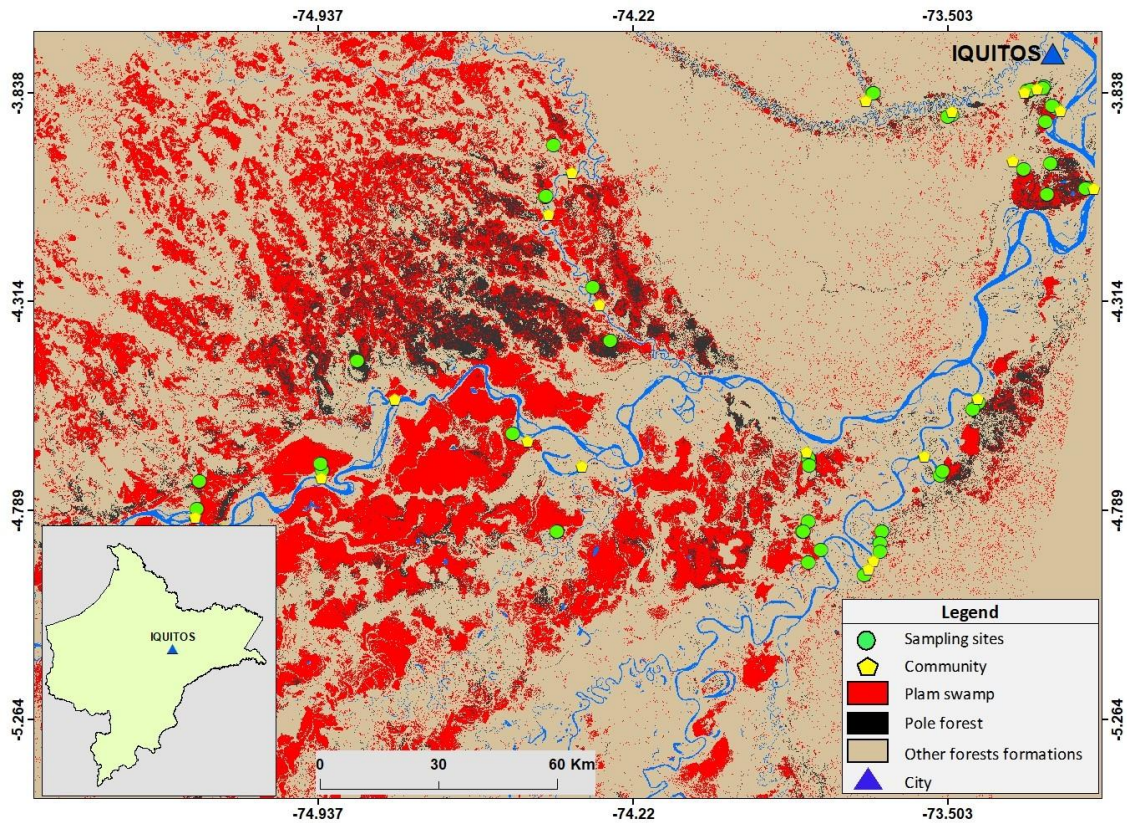


The map shows the zone (red ellipsoid) where the sampling sites were located.

Appendix 3a. Distribution of sampling sites within Datum de Marañon province in the western part of the study region.



Appendix 3b. Distribution of sampling sites close to Iquitos.

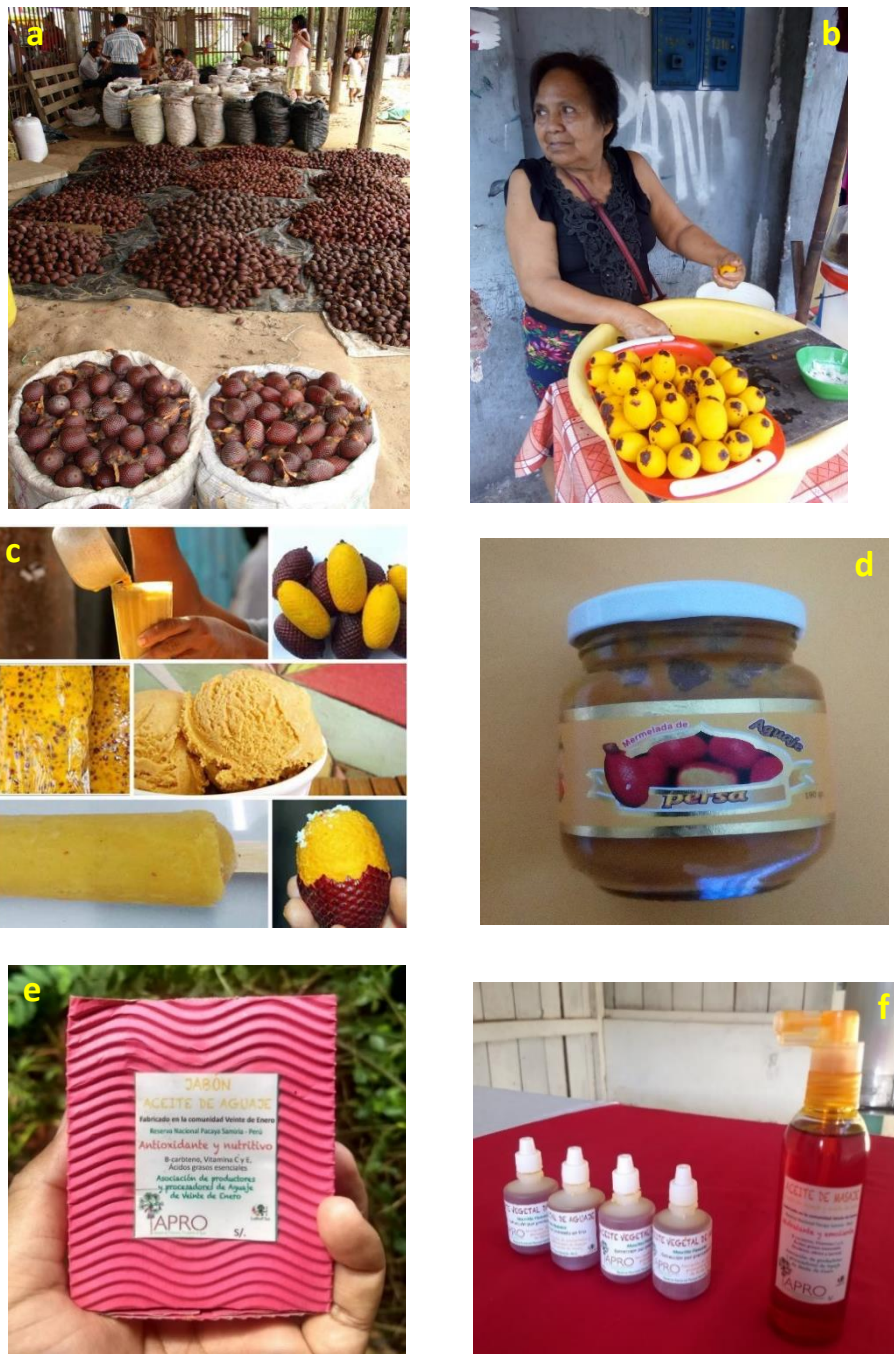


Appendix 4. Sampling sites list according to the allocation by watershed category and river basin as well as the route to reach to the *M. flexuosa* stands

Site code	Watershed	River	Access Stand	Site code	Watershed	River	Access Stand
REQ-01	Big river	Ucayali	BP	LIM-2	Small river	Itaya	BP
REQ-04	Big river	Ucayali	BP	LIM-3	Small river	Itaya	BP
REQ-05	Big river	Ucayali	BP	SJR-1	Small river	Nanay	BP
IRIC 2	Big river	Ucayali	BP	SJR-2	Small river	Nanay	BP
JEN-14	Big river	Ucayali	BP	PUMA	Big river	Ucayali	BP
JEN-15	Big river	Ucayali	BP	CAPT	Big river	Ucayali	P
SAPN	Big river	Ucayali	BP	Req-13B	Big river	Ucayali	P
AUCA	Big river	Tigre	BP	VEN-03	Big river	Marañón	P
PIUR	Big river	Tigre	BP	VEN-01	Big river	Marañón	P
PIU-02	Big river	Tigre	BP	VEN-02	Big river	Marañón	P
OLLN	Big river	Marañón	BP	VEN-04	Big river	Marañón	P
IRIC 1	Big river	Ucayali	BP	V-ENE	Big river	Marañón	P
SAMI	Big river	Marañón	BP	VEN-05	Big river	Marañón	P
SAM-01	Big river	Marañón	BP	P. DIAZ-1	Big river	Marañón	P
PARN	Big river	Marañón	BP	N. MIL-2	Big river	Marañón	P
PRN-01	Big river	Marañón	BP	N. MIL-3	Big river	Marañón	P
P.IND-1	Big river	Marañón	BP	P. LIM-1	Big river	Marañón	P
P.IND-2	Big river	Marañón	BP	P. LIM-2	Big river	Marañón	P
S. ANA-1	Big river	Marañón	BP	IDP-2	Big river	Marañón	P
S. ANA-2	Big river	Marañón	BP	SAR-1	Big river	Marañón	P
S. ANA-3	Big river	Marañón	BP	SAR-2	Big river	Marañón	P
P. DIAZ-2	Big river	Marañón	BP	SAN-1	Big river	Marañón	P
P. DIAZ-3	Big river	Marañón	BP	SAN-2	Big river	Marañón	P
N. MIL-1	Big river	Marañón	BP	PMIG-1	Big river	Ucayali	P
P. LIM-3	Big river	Marañón	BP	DDM-1	Big river	Amazonas	P
IDP-1	Big river	Marañón	BP	DDM-3	Big river	Amazonas	P
CUN-1	Big river	Marañón	BP	SJOR-1	Big river	Amazonas	P
CUN-2	Big river	Marañón	BP	SJOR-2	Big river	Amazonas	P
CLA-1	Big river	Ucayali	BP	QCH-1	Small river	Itaya	P
CLA-2	Big river	Ucayali	BP	QCH-2	Small river	Itaya	P
PMIG-2	Big river	Ucayali	BP	QCH-3	Small river	Itaya	P
DDM-2	Big river	Amazonas	BP	PTA-1	Small river	Itaya	P
NYK-1	Big river	Tigre	BP	PTA-2	Small river	Itaya	P
NYK-2	Big river	Tigre	BP	MSH-1	Small river	Nanay	P
LIM-1	Small river	Itaya	BP	MSH-2	Small river	Nanay	P

BP: access by boat and walking by path. P: access only by path within the forest.

Appendix 5. Commercialisation of aguaje fruit in Iquitos.



Source: **Panel a:** Baker, T. **Panels b,c,d,e,f:** this study

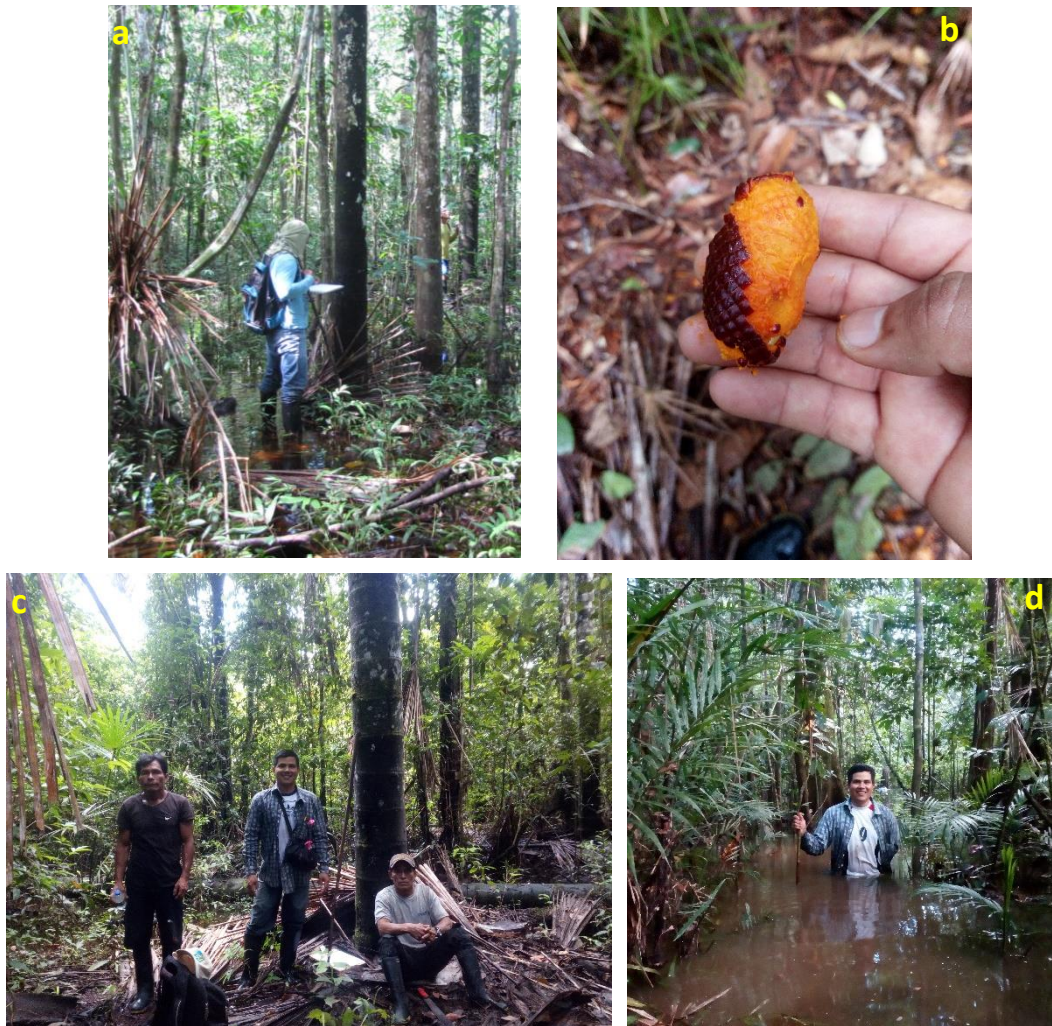
Panel a shows the sale of aguaje fruit a high scale in Iquitos, the fruit is sold in sacks mainly to intermediary sellers. A volume of approximately 22 – 23 ton/day is sold per day in Iquitos (Gonzales and Torres, 2010; Casanova and Pacaya, 2016). **Panels b, c** show the main way of consumption in the Amazonian communities. **Panel c** shows a semi-manufactured (jam). **Panels e, f** show new products such as soap and oil that have the potential to be commercialised in international markets.

Appendix 6. List of companies that industrialise the aguaje fruit.

Company	Product	Country	Link
D'Souza	Massage oil and Powder	Perú	
Inkanatura WorldPeru Export SAC	Powder capsules Oil	Perú	http://www.inkanatural.com
Grupo de manejo Yanaycu-Pucate - RNPS	Massage oil Soap	Perú	http://www.sernanp.gob.pe/jabon-aguaje
Inkanatura World Peru Export SAC	Capsule and Massage oil	Perú	http://www.inkanatural.com
Madre Nature	Powder capsules	Perú	https://madrenature.com
Rainforest Pharmacy	Powder capsules	Perú	https://www.rainpharm.com
Minvita	Powder	UK	https://minvita.co.uk
Aroma do Corpo	Oil	Brasil	http://www.aromadocorpo.com.br
Amazon Andes	Powder capsules	-	http://amazon-andes.com
Dove	Shampoo	USA	https://www.dove.com/us

Source: ITP-CITE (2018)

Appendix 7. Field data collection process.



Source: this study.

Panels a, b show the data collection process and the determination of the gender based on the presence of floral organs. **Panels c, d** show the characteristics of the forest of some of the palm swamps (Panel **c**: Puerto Miguel – P.MIG-1, Panel **d**: San Juan – SJR-1)

Appendix 8. Harvesting techniques practised in the study area.



Source: **Panels a, b:** this study, **Panels c, d:** IIAP.

Panels **a** and **b** show female trees felled as a result of the non-sustainable technique employed by harvesters. Palm tree in panel **a** was felled 1 – 2 years ago approximately, whilst palm in panel **b** was harvested in a recent fruiting season. Panels **c** and **d** show the climbing technique used to harvest 20 % of the stands sampled.