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RESEARCH ARTICLE

Long-term interventions by conservation and development projects support successful recovery of tropical peatlands in Amazonia

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Abstract

1. Rural communities in Amazonia rely on harvesting *Mauritia flexuosa* fruit, a dominant peatland palm, for their subsistence and income. However, these palms are felled to harvest the fruits, which has led to reduced resource availability due to the pressure exerted by the increasing fruit demand. As a result, climbing has been proposed as a means to harvest the fruits sustainably. However, the long-term ecological and socio-economic impacts of climbing, rather than felling, palms remain unknown.
2. We evaluate whether *M. flexuosa* populations and fruit production in managed peatland palm swamps have recovered within two rural communities in Peru where climbing to harvest palm fruits was adopted between 1999 and 2002. Since then, these communities have been supported by conservation and development projects.
3. We conducted interviews with community members to assess perceptions of change since the introduction of climbing and carried out forest inventories to estimate changes in two socio-economic indicators (volume of harvested *M. flexuosa* fruits and income) and three ecological indicators (pole stem density of *M. flexuosa*, seedling and sapling density, and the sex ratio of adult palms).

4. Our results reveal that the adoption of climbing has improved the health of the forest stands and incomes in both rural communities. Recovery of *M. flexuosa* populations was supported by local perceptions of increases in stand productivity, improved values of most indicators within managed stands compared to reference data from unmanaged stands in the region, and continuous recovery of degraded stands over time following the adoption of climbing by both communities.
5. *Synthesis and applications*. We demonstrate how long-term conservation and development initiatives can lead to successful outcomes for rural communities and peatland ecosystems. However, urgent adoption of sustainable harvesting techniques, such as the palm climbing in our study, is needed across Amazonia to safeguard the ecological integrity of peatlands, below carbon storage, and livelihoods. This transition will require long-term collaboration among different stakeholders, affordable management plans, and fair prices for sustainable management for peatland resources.

KEYWORDS
forest management, livelihoods, natural regeneration, non-timber forest products, Parinari, Veinte de Enero

1 | INTRODUCTION

In Amazonia, the most extensive and continuous tropical peatland occurs in the Pastaza-Marañón Foreland Basin (PMFB) in northern Peru, in palm swamps dominated by *Mauritia flexuosa* L.f. (Draper et al., 2014; Hastie et al., 2022; Lähteenoja et al., 2012). Conserving the 43,617 km^2 of peatlands in this region is important because of the ecosystem services that they provide, including high peat carbon storage (4.07 Pg C), unique biological and cultural diversity, and resources that support rural communities (Draper et al., 2014; Gilmore et al., 2013; Hastie et al., 2022; Lähteenoja et al., 2012; Schulz et al., 2019a). However, the increasing regional demand for *M. flexuosa* fruits, which are harvested by felling female palms (Horn et al., 2018), is putting pressure on these peatlands (Delgado et al., 2007; Vasquez & Gentry, 1989). While the permanently waterlogged conditions of palm swamps make them difficult to access and walk on, felling *M. flexuosa* is relatively easy because of its smooth, straight, unbranched stem, and the large racemes of fruit at the top. This widespread practice reduces the economic potential of stands over time because, as overharvested stands become dominated by unproductive male individuals, harvesters are forced to seek productive stands at increasingly greater distances from community centres (Hidalgo Pizango et al., 2022; Horn et al., 2012).

Intensive felling of *M. flexuosa* also leads to a loss of biomass and peat decomposition, converting the carbon sink of these peatland ecosystems into a net carbon source (Hergoualc'h et al., 2023), while also affecting animals that feed on the fruits or nest in dead palm stems (Kahn, 1991; Peters, 1992). A modelling study demonstrated that felling all female palms is not ecologically sustainable; a maximum harvest intensity of 22.5% every 20 years could be maintained in stands with a minimum of 20 female palms in Ecuador (Holm et al., 2008), which is far less intensive than common practice in these ecosystems. Thus, because felling puts pressure on palm populations, peatland carbon sequestration, and local livelihoods, palm climbing has been suggested as an alternative technique for harvesting fruits. Climbing has the dual benefit of protecting peatland ecosystem functions by contributing to the mitigation of climate change and the protection of biodiversity while maintaining long-term fruit production and local livelihoods (Baker et al., 2019).

A perception of resource scarcity was an incentive for developing new management initiatives for *M. flexuosa*, and this is how local initiatives to use climbing equipment emerged (Falen Horna & Honorio Coronado, 2018; Manzi & Coomes, 2009). A leading example of such an initiative was developed in 1999 by the Flores Simón family in the community of Parinari using climbing equipment that they designed (Flores Simón & Flores Simón, 2001). Conservation-development projects were also launched in the 1990s to protect palm swamps, initially focusing on bans, quotas, i.e. restricting the number of female palms that were harvested in local communities, and promoting the reforestation of *M. flexuosa* (Gaviria & Sabogal, 2013). These projects emerged in response to the decline of productive *M. flexuosa* palm swamps close to populated areas in the PMFB that scientists first observed in the late 1980s (Vasquez & Gentry, 1989). Although the idea of climbing to harvest *M. flexuosa* fruits has since spread throughout the region, only a few communities, such as Parinari and Veinte de Enero, have consistently continued climbing palms over the past two decades (Hidalgo Pizango et al., 2022; Romulo et al., 2022).

To justify the wider use of palm climbing as a harvesting method, there is a need to demonstrate that it leads to long-term benefits for both people and palm swamp ecosystems. This justification is required because climbing equipment and management plans, which are required for implementing legal and sustainable extraction of *M. flexuosa* fruits for commercial use, are costly for rural communities (de la Torre et al., 2011). More broadly, this reflects the need for studies that explore the success or failure of sustainable management of non-timber forest products in Amazonia in terms of both ecological and socio-economic impacts, over decadal timescales and across different governance scenarios (Sampaio et al., 2008; Ticktin, 2004). Within the PMFB, two communities, Parinari and Veinte de Enero, provide a unique opportunity to answer this question. Both communities switched from felling to climbing palms approximately 20 years ago, and all their *M. flexuosa* fruit harvesters today use climbing to harvest the fruits (Romulo et al., 2022).

Since then, these communities have benefited from long-term interventions by conservation and development projects. In Parinari, management areas were divided and assigned to specific families, with the first management plan for *M. flexuosa* established in 2002. Veinte de Enero adopted a community-based approach in which all harvesters collectively managed the designated areas, with their management plan finalised in 2005. These early management plans focused on allowing palm swamps to recover by using climbing equipment that does not destroy productive female palms, combined with surveillance against felling, and implementing management techniques such as producing seedlings in nurseries and protecting regeneration and natural stands (Bejarano & Piana, 2002; Gonzales et al., 2007). Parinari and Veinte de Enero still rely on peatland palm swamps as a crucial source of income and have management plans in place today to harvest *M. flexuosa* fruits by climbing. Therefore, a comparative analysis can shed light on the nature and extent of ecosystem recovery in response to the adoption of climbing after intensive felling, and the effectiveness of contrasting governance systems in ensuring long-term resource sustainability.

Our aim is to assess the recovery potential of *M. flexuosa* populations and fruit production in managed peatland palm swamps in Parinari and Veinte de Enero, where climbing has been adopted for fruit harvesting for two decades following intensive destructive harvesting by felling the palms. We ask (1) whether *M. flexuosa* populations can recover after the introduction of climbing and, if so, (2) whether this recovery benefits communities. To address these questions, we carried out semi-structured interviews with local people and forest inventories of *M. flexuosa* populations to compare the local perceptions of change after the introduction of climbing and the ecological response of the stands. We also calculated five ecological and socio-economic indicators for *M. flexuosa* (SERNANP, 2022) and compared them to independent reference datasets of unmanaged palm swamps in northern Peru, compiled using primary and secondary data.

2 | MATERIALS AND METHODS

2.1 | Study site

We assessed managed palm swamps surrounding the communities of Parinari and Veinte de Enero within the Pacaya Samiria National Reserve in Peru (Figure 1). The area has a tropical climate. According to the National Service of Meteorology and Hydrology of Peru (2001–2014), the mean annual temperature is 26°C, the mean relative humidity is 87%, and the mean annual precipitation is 2570 mm, with the presence of a rainy season from December to March and a dry season from July to September.

2.2 | Management areas

We selected two palm swamp areas under management in Parinari (the *Grupo Esperanza* area administrated by the Flores family and the *Defensores de la Naturaleza* area administrated by the families Mozombite, Tamani, Vela and Isuiza) and three areas in Veinte de Enero (Paima, San Juan, and 31 Diablos), with the help of community members during participatory mapping exercises. The management plans of both communities establish that fruit harvesting is done by climbing and can reach a maximum quota of ca. 5% of the estimated annual fruit production in the area. In Parinari, 52 harvesters are registered as beneficiaries and between 2016 and 2020 were granted an annual harvesting quota per beneficiary of 1175–2184 sacks of fruits (each sack weighs 40 kg) within the 16,396 ha of managed forest (RNPS, 2016), while 35 beneficiaries in Veinte de Enero were granted a harvesting quota per beneficiary of 721 sacks of fruits between 2021 and 2026 within the 6447 ha of managed forest (RNPS, 2021).

2.3 | Socio-economic assessment

We carried out a total of 56 semi-structured interviews using a snowball sampling strategy, beginning with individuals recommended by community leaders and continuing with those suggested by the interviewees. Individual householders were purposely selected to ensure that each informant represented a different household and belonged to all management groups associated with *M. flexuosa* palm harvesting. The interviewees included 38 men and 16 women, ranging in age from 21 to 82 years. These interviews were conducted during mid-August to mid-September 2022 and aimed to gather insights into their activities for subsistence and income, as well as their management practices for *M. flexuosa*, the pressures on peatland palm swamps, and community needs. The interviews discussed a variety of topics including the species used in hunting, fishing, farming, and gathering, management activities, fruit production, and perceptions of forest change after adopting climbing (see Table S1). Additional information about perceived income from economic activities was collected during a second field visit in August 2023. For this, we interviewed a total of 32 individual householders, primarily beneficiaries of palm harvesting—24 men and 8 women— and used a calendar of economic-productive activities in relation to the hydrological and climatic cycles (e.g. high/low river levels and rainy/dry seasons). Income was calculated by multiplying the estimated annual harvest of products annually (e.g. sacks of fruits, tonnes of rice) and the mean sale price provided by community members. Prior informed consent was obtained from participants in 2022 and

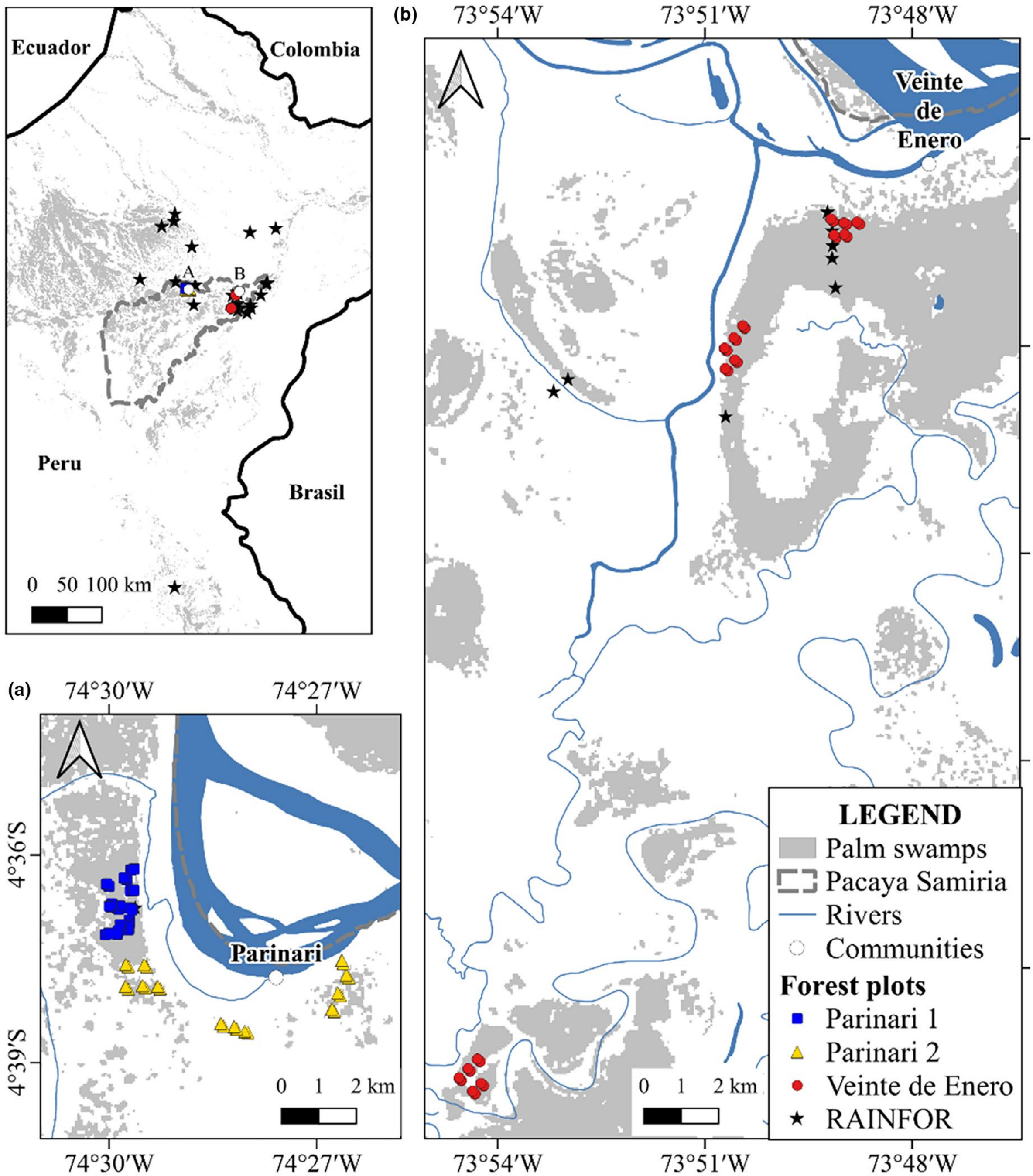

FIGURE 1 Location of the forest plots used in this study, featuring the plots established in (a) Parinari and (b) Veinte de Enero within the Pacaya Samiria National Reserve, Peru. Palm swamp spatial distribution based on Hastie et al. (2022).

2023, and institutional ethical approval was granted by the School of Geography and Sustainable Development Ethics Committee of the University of St Andrews (GG16343) before starting the fieldwork.

2.4 | Ecological assessment

We established 40 forest plots, each 20 m × 100 m, with 5 to 13 plots per management area to quantify the ecological health of each site. Fieldwork was undertaken in August and September 2022 and August 2023. The census was carried out before fruit harvesting, except in San Juan, where fruit harvesting had begun a few days earlier. In each plot, we counted all individuals of *M. flexuosa* ≥0.4 m tall and classified them into three size classes: short saplings (0.4–1.49 m total height), tall saplings (≥1.5 m total height and without stem or with stem height <1.3 m), and pole stems (≥4 m total height and with stem height ≥1.3 m). All seedlings <0.4 m were counted in a subplot of 5 m × 100 m. For each pole stem, we recorded the life stage as juvenile (<15 m total height), subadult (≥15 m total height without flowers or fruits), or male/

female adult (≥15 m total height with inflorescences or infructescences). Total height of saplings was estimated using a stick with marks at 0.4 and 1.5 m, while the total height of pole stems was measured using a clinometer. The sex of each adult was assessed by observing reproductive structures either on the palms using binoculars or on the ground around the base of the stem. We counted the number of racemes with fruits for each female adult individual. Peat thickness was measured in the centre of each plot using a stick. Peat was identified in the field as a substrate consisting of predominantly wet, partially decomposed organic matter of mid to dark brown colour and at least 30 cm thick (Hastie et al., 2022).

2.5 | Data analysis

To account for the differences in management governance, we categorized the data into three groups for analysis: (a) Parinari 1, which includes the 504-ha management area assigned to the Flores family of the *Grupo Esperanza* management group; (b) Parinari 2, which includes the 15,892-ha area assigned to each family of the *Defensores de la Naturaleza* management group; (c) Veinte de Enero, which encompasses all management areas (6447 ha) used by the ACORENA and *Asociación Las Palmeras* management groups.

For each of the three groups, we calculated the mean and standard error of five ecological and socio-economic indicators for *M. flexuosa*: (1) stem density, expressed as density of pole stems per hectare, (2) natural regeneration, expressed as the density of seedlings and saplings per hectare, (3) sex ratio of adult palms, expressed as the number of males per female, (4) volume of harvested fruits, expressed as the number of 40-kg fruit sacks harvested per year by all beneficiaries, and (5) income, expressed as the gross annual income generated from fruit harvesting by each community. While indicators (1), (2), and (3) were estimated using the new field datasets, indicator (4) was estimated using the volume of harvested fruits recorded by SERNANP between 2018 and 2021 in Parinari 1 and between 2018 and 2022 in Veinte de Enero. We assumed that Parinari 2 harvested a similar number of sacks to Parinari 1 based on the interviews. Indicator (5) was estimated by multiplying the volume by US$ 10.53 (Endress et al., 2018), which represents the average price per sack stated by interviewees in Nuevos Soles (S/. 40) and converted to USD using the average exchange rate for 2022.

To assess the potential recovery of palm swamps, we tested whether the mean values of the indicators of each group (i.e. managed palm swamps with resource extraction by climbing the palms) were significantly different from the mean values of the reference datasets (i.e. unmanaged palm swamps where resource extraction has involved cutting down the palms and with no management plan) using Kruskal–Wallis and Dunn tests and employing a Bonferroni corrected p-value (residuals among groups were not normally distributed; Shapiro test, $p < 0.05$). Both managed and unmanaged palm swamps occur in similar ecological conditions, with the same climate and permanently waterlogged soils. The reference datasets for indicators (1) to (3) include an independent dataset of 31 RAINFOR forest plots downloaded from the Forestplots.net database (ForestPlots.net, 2022; Lopez-Gonzalez et al., 2011) that represent unmanaged palm swamps with different levels of past resource extraction based on the sex ratio of adult *M. flexuosa* palms. The sex ratio is typically close to 1 in intact stands; however, as rates of felling the (female) fruit-bearing palms rise, stands become increasingly dominated by male stems (Hidalgo Pizango et al., 2022). Rates of past resource extraction were defined as low (0.5–1.9 males per female), medium (2.0–3.9 males per female) and high (≥4 males per female; Table S2). Peat thickness was measured using a Russian corer at 3–5 points inside each forest plot. The reference dataset for indicators (4) and (5) was taken from the literature and includes the number of sacks of harvested fruits arriving in Iquitos from 271 communities between April 2012 and March 2013 and the corresponding gross income estimated by multiplying the volume by US$ 10.53 (Endress et al., 2018). Historical records of the same indicators were also obtained from previous *M. flexuosa* inventories carried out in Parinari and Veinte de Enero between 1995 and 2022 (ForestPlots.net, 2022; Freitas, 1995, 2000; Freitas & Flores, 2015; Gonzales et al., 2007) and from reports of the volume of fruit extraction in Parinari (2011–2021) and Veinte de Enero (2001–2003, 2013, 2015–2022) available in the management plans or provided by SERNANP.

Variation in the ecological indicators was analysed in relation to two variables representing waterlogging (peat thickness) and vegetation density (Normalized Difference Vegetation Index—NDVI). In Amazonia, peat forms where *M. flexuosa* generally dominates, on permanently waterlogged substrates, causing the carbon input (palm litterfall and root mortality) to exceed losses from decomposition (soil respiration; Dargie et al., 2024; Hergoualc'h et al., 2023). The felling of *M. flexuosa* palms for fruit harvesting affects peat accumulation, and palm abundance may be positively correlated to peat thickness. NDVI is a measure of vegetation greenness, with high values indicating high canopy density; the abundance of palms should be negatively correlated with NDVI because of their low canopy density compared to stands dominated by trees (E. Honorio, pers. obs.). PlanetScope Surface Reflectance Mosaics with 5-m resolution from August 2022 were provided through Level 1 access of the NICFI data program and used to calculate the mean NDVI for each plot area in Google Earth Engine (Gorelick et al., 2017).

3 | RESULTS

3.1 | Socio-economic assessment

Our interviews showed that community members in Parinari and Veinte de Enero engage in various activities to sustain their livelihoods and generate income. The most common activities include fishing, hunting, farming, and forest resource extraction, while other less common activities include animal husbandry, plantations, and tourism. Fishing and hunting are carried out throughout the year. The most frequently named fish species is *boquichico* (*Prochilodus nigricans*), while hunting targets large animals such as capybara (*Hydrochoerus hydrochaeri*), peccary (*Pecari tajacu*) and deer (*Mazama* sp.), as well as smaller species like monkeys, tortoises and birds. Farming is carried out mainly in secondary seasonally flooded forests and river beaches primarily for subsistence, with planting occurring during low river levels. However, some crops, such as plantains, cassava, rice and corn, are cultivated for income generation (Table 1).

Mauritia flexuosa fruits are harvested in managed areas by community members (harvesters) registered in management groups. In Parinari, the *Grupo Esperanza* management group has used climbing since 1999 and currently manages approximately 5000 female palms, while the *Defensores de la Naturaleza* group manages between 50 and 200 female palms per family, with management starting in 2002. In Veinte de Enero, the ACORENA and *Asociación Las Palmeras* management groups have carried out management since 2002 in nearby areas such as Paima and since the 2010s in additional areas such as San Juan and 31 Diablos. *Mauritia flexuosa* fruit extraction is an economically important extractive activity that represents 46% and 89% of the total income per household in Parinari and Veinte de Enero, respectively. Mean community income from fruit harvesting was lower in Parinari (US$ 2613 ± 1100) than in Veinte de Enero (US$ 4059 ± 483), while other economic activities contributed more in Parinari (US$ 1403 ± 840) than in Veinte de Enero (US$ 447 ± 202; Table 1).

Both communities describe similar management practices in accordance with their management plans, including the use of surveillance, harvesting by climbing, trail maintenance and reforestation. The primary distinguishing factor between these communities lies in their resource management governance systems. Management areas in Parinari are assigned to individual families, and the application of management practices relies on the effort of each family. This requires individuals to inhabit the village permanently, and thus, 79% of the interviewees were born locally or migrated from nearby communities. In contrast, management areas in Veinte de Enero are assigned to the community, and practices are based on a community effort, with only 25% of the interviewees born locally and 75% who have migrated from other communities in the regions of Loreto, San Martín, and Ucayali. These different management governance systems have implications for resource management and community dynamics. In Parinari, family-based governance promotes individual responsibility and long-term investment in sustainable management and building business capacity, as livelihoods are directly tied to the land they manage (e.g. the *Grupo Esperanza* management group). In contrast, the community-based governance system in Veinte de Enero promotes collective management efforts and has created greater pressure to expand management activities into previously unharvested stands (e.g. San Juan and 31 Diablos harvested since 2010s). Both systems still rely on the support of NGOs and SERNANP to update the management plans and to develop a fair value chain.

Notably, all individuals that were interviewed reported an increase in fruit production over time, beginning at least 5 to 7 years after implementing climbing techniques. Climbing *M. flexuosa* palms is considered risky, especially when equipment is improperly used or the climber encounters animals at the top of the palm such as venomous snakes or tarantulas. The harvested fruits are sold directly to companies and intermediaries in Nauta, Iquitos and Yurimaguas, and sometimes to intermediaries who travel to the communities, at prices typically ranging from US$ 7 to 26 per sack, but reaching up to US$ 32 per sack for the larger, so-called *shambo*, fruit variety and when fruits are scarce. Within Parinari, the group *Defensores de la Naturaleza* also sells fruits to *Grupo Esperanza* for oil production at market prices that fluctuate markedly (US$ 7–26 per sack). Veinte de Enero additionally sells the fruits through the NGO Naturaleza y Cultura Internacional to AJE, which is a Peruvian multinational beverage company, at a fixed price of US$ 9 per sack. Both communities rely on intermediaries in Iquitos and Lima for exporting locally produced *M. flexuosa* oil to France, which is sold at US$ 24 per litre. The income generated from these sales is primarily used to buy household items such as soap, sugar, and rice, as well as to pay for higher education for children, petrol, and healthcare. During the period of high fruit production, some individuals also spend money on alcohol and gambling. Among the various pressures on palm swamps, members of both communities mentioned that periods of cold weather in June, known locally as *friajes*, pose a significant risk to fruit production. Some responders reported that these events have increased in recent years and have been observed to cause unripe fruits to drop (Table 1).

3.2 | Ecological assessment

A total of 19,675 *M. flexuosa* individuals were sampled across the 40 forest plots (Table S3). Among these individuals, 2% were seedlings, 84% were short saplings, 6% were tall saplings, and 9% were poles. In Parinari 1, the mean (±standard error) densities of seedlings (374 ± 171 ind/ha) and short saplings (4448 ± 855 ind/ha) were significantly higher than in Parinari 2 (33 ± 7 ind/ha and 712 ± 156 ind/ha, respectively) and Veinte de Enero (95 ± 39 ind/ha and 1056 ± 298 ind/ha). The density of tall saplings was similar among the groups, with values varying from 69 to 214 ind/ha. Pole density was higher in Parinari 1 (229 ± 13 ind/ha) and Veinte de Enero (268 ± 33 ind/ha) than in Parinari 2 (120 ± 14 ind/ha; Figure S1A). In terms of pole stems, the densities of juveniles and subadults were mostly not significantly different among groups, while the density of male and female adults in Parinari 1 (105 ± 6 ind/ha and 58 ± 6 ind/ha, respectively) and Veinte de Enero (100 ± 12 ind/ha and 62 ± 8 ind/ha, respectively) was higher than in Parinari 2 (55 ± 8 ind/ha and 30 ± 4 ind/ha, respectively; Figure S1B). In addition, the density of males was nearly double the density of females in the stands. Most female individuals were observed with fruits, with a mean production of 113 ± 16 sacks/ha in Parinari 1, 85 ± 10 sacks/ha in Parinari 2, and 64 ± 21 sacks/ha in Veinte de Enero.

TABLE 1 Socio-economic assessment of local people in Parinari and Veinte de Enero.

Topics	Subtopics	Parinari 1 and 2 (*n* = 29 interviews)	Veinte de Enero (*n* = 25 interviews)
1. Activities for subsistence and income			
Fishing[a]		Each month in rivers and streams, resource abundance from April to May and August to September. Species: boquichico (*Prochilodus nigricans*), sábalo (*Brycon* sp.), shuyo (*Hoplerythrinus unitaeniatus*), sardina (*Triportheus* sp.), zúngaro (*Brachyplatystoma juruense*), gamitana (*Colossoma macropomum*), paiche (*Arapaima gigas*), lisa (Anostomidae), bujurqui (Cichlidae), acarahuazu (*Astronotus ocellatus*), doncella (*Pseudoplatystoma punctifer*), pez torre (*Phractocephalus hemioliopterus*), carachama (Loricariidae), arahuana (*Osteoglossum bicirrhosum*)	Each month in rivers and streams, resource abundance from February to July. Species: boquichico (*Prochilodus nigricans*), acarahuazú (*Astronotus ocellatus*), bujurqui (Cichlidae), palometa (Serrasalmidae), carachama (Loricariidae), sardina (*Triportheus* sp.), fasaco (*Hoplias malabaricus*), lisa (Anostomidae)
Hunting[a]		Each month in seasonally flooded forests and swamps, resource abundance from January to April. Species: ronsoco (*Hydrochoerus hydrochaeri*), majaz (*Cuniculus paca*), añuje (*Dasyprocta fuliginosa*), motelo (*Chelonoidis denticulata*), carachupa (*Dasypus* sp.), achuni (*Nasua nasua*), coto mono (*Alouatta seniculus*), mono choro (*Lagothrix lagotricha*), maquisapa (*Ateles* sp.), huapo (*Pithecia* sp.)	Each month in seasonally flooded forests and swamps, resource abundance from November to April. Species: majaz (*Cuniculus paca*), añuje (*Dasyprocta fuliginosa*), sajino (*Pecari tajacu*), huangana (*Tayassu pecari*), venado (*Mazama* sp.), achuni (*Nasua nasua*), ronsoco (*Hydrochoerus hydrochaeri*), perdiz (*Tinamus major*), carachupa (*Dasypus* sp.)
Farming[a]		Planting from May to July. Species: plantain (*Musa* sp. harvested after 12 months), manioc (*Manihot esculenta* harvested after 6 months), corn (*Zea mays* after 4 months), rice (*Oryza sativa* after 3 months), vegetables, fruit trees	Planting from May to July. Species: plantain (*Musa* sp. harvested after 12 months), watermelon (*Citrullus lanatus* harvested after 3–4 months), manioc (*Manihot esculenta* harvested after 6 months), corn (*Zea mays* after 4 months), rice (*Oryza sativa* after 3 months), vegetables, fruit trees
Resource extraction		Aguaje fruit harvesting, timber for house and boat construction	Aguaje fruit harvesting, timber for house and boat construction
Other activities		Animal husbandry, forest and fruit tree plantations, aguaje oil production	Animal husbandry, tourism, handicrafts, forest plantations, aguaje oil and soap production, essential store, carpentry
2. *Mauritia flexuosa* management practices			
Governance		Family management	Community management
Management groups		Grupo Esperanza & Defensores de la naturaleza	ACORENA & Asociación COMAPA Las Palmeras
Beneficiaries		52 harvesters	35 harvesters
Fruit harvesting		From September to March	From April to January
Fruit production		Increased over time with climbing techniques	Increased over time with climbing techniques
Buyers		Intermediaries in Parinari and Nauta, Grupo Esperanza, Shambo ice-cream company (fruits), intermediaries in Lima to export to France (oil)	Intermediaries in Nauta, Iquitos, Yurimaguas, AJE beverage company (fruits), intermediaries in Iquitos to export to France (oil), local tourists (soap)
Agreements		Surveillance, trail maintenance, climbing, reforestation	Surveillance, trail maintenance, climbing, mature fruits, reforestation
3. Pressures on palm swamps		Oil spills, *friajes*, shortage of natural resources, river erosion, offenders	*Friajes*, severe drought and flooding, offenders
4. Community needs		Drinking water, electricity, medical centre, pedestrian sidewalk, better school infrastructure, capacity training for producing oil related products	Medical centre, drinking water, electricity, better school infrastructure, bridge, new oil production plant aligned with national regulations
		(*n* = 15 interviews)	(*n* = 17 interviews)
5. Annual gross income per householder			
Fruit harvesting		Mean ± SE: US$ 1210 ± 645 Minimum: US$ 0 Maximum: US$ 9895	Mean ± SE: US$ 3611 ± 559 Minimum: US$ 0 Maximum: US$ 7368

(Continues)

TABLE 1 (Continued)

	($n = 15$ interviews)	($n = 17$ interviews)
Other economic activities	Mean ± SE: US$ 1403 ± 840 Minimum: US$ 0 Maximum: US$ 12,105	Mean ± SE: US$ 447 ± 202 Minimum: US$ 0 Maximum: US$ 3421
Total income	Mean ± SE: US$ 2613 ± 1100 Minimum: US$ 16 Maximum: US$ 14,736	Mean ± SE: US$ 4059 ± 483 Minimum: US$ 79 Maximum: US$ 7493

[a]Names of species ordered from most to least frequently cited by community members.

3.3 | Ecological and socio-economic indicators relative to reference data

The mean values of all ecological and socio-economic indicators within most managed stands were greater than the reference dataset of unmanaged stands with intense use in the region (Table 2). Pole density was significantly higher in Parinari 1 (229 ± 13 ind/ha) and Veinte de Enero (268 ± 33 ind/ha) than in the reference dataset with intense use (137 ± 23 ind/ha), and lower in Parinari 2 (120 ± 14 ind/ha). Seedling and sapling density was higher in Parinari 1 (5036 ± 995 ind/ha) compared to Parinari 2 (815 ± 165 ind/ha), Veinte de Enero (1314 ± 328 ind/ha) and the reference datasets with medium (499 ± 253 ind/ha) and intense (179 ± 60 ind/ha) uses. The sex ratio was around 2 males per female in all managed sites compared to >9 males per female in the unmanaged sites with intense use (Figure 2). When comparing these ecological indicators with NDVI and peat thickness, we found that pole density was negatively correlated with NDVI ($r = -0.37$, $p < 0.01$; Figure 3a) and positively correlated with peat thickness ($r = 0.43$, $p < 0.001$; Figure 3b), indicating that *M. flexuosa* was more abundant in areas with thick peat and low NDVI. The male-to-female sex ratio was positively correlated only with NDVI ($r = 0.32$, $p < 0.01$; Figure 3c), indicating that sites with more intense use have high canopy density due to the replacement of dominant palms by trees, while seedling and sapling density was correlated only with peat thickness ($r = 0.49$, $p < 0.001$; Figure 3d). Moreover, NDVI and peat thickness were also correlated ($r = -0.50$, $p < 0.001$; Figure 3e), while the other indicators were not correlated with these variables (Figure S1). The volume of harvested fruits was significantly greater in managed sites (8470 ± 2011 sacks in Veinte de Enero and 1683 ± 503 sacks in both Parinari sites) than in the unmanaged sites (816 ± 158 sacks). Gross annual income per community was also higher in Parinari (US$ 35,444 ± 10,593) and Veinte de Enero (US$ 89,189 ± 21,175) compared to US$ 8592 ± 1664 for the unmanaged sites (Table 2).

The time series graphs reveal a recovery in most of the ecological and socio-economic indicators over time. This improvement is shown by a slight (but not statistically significant) decrease in the male: female ratio of adult palms (Wilcox text comparing the periods 2000–2011 and 2012–2023, $p = 0.05$), and significant increases in the density of female palms and the volume of harvested fruits following a decade of implementation of the management plans (Wilcox test, both $p < 0.05$; Figure 4).

4 | DISCUSSION

4.1 | Recovery of *M. flexuosa* stands after the adoption of climbing techniques

Our results demonstrate that both family and community management governance systems, accompanied by the consistent use of climbing, can have positive effects on enhancing the health of intensively harvested *M. flexuosa* stands. The recovery of *M. flexuosa* was observed across most indicators, as evidenced by improved values within managed stands compared to unmanaged stands in the region. These results align with the local perception of increased stand productivity following the adoption of climbing techniques, with indicators significantly improving during the second decade of implementation of management plans (Figure 4). Influential champions have played an important role in enabling this transition in both communities (Romulo et al., 2022), as well as the long-term interventions by conservation and development projects. For example, the *Programa Integral de Desarrollo y Conservación Pacaya Samiria* funded by the World Wildlife Fund and Danish AIF was implemented in Parinari from 1992 to 2003 (Junglevagt for Amazonas, 1995), while the Employment and Natural Resource Sustainability Project funded by the USAID and TNC was implemented in Veinte de Enero from 1991 to 1999, with extended collaboration until 2012 (Gaviria & Sabogal, 2013). The involvement of these projects might have also contributed to the success, as interviewees acknowledged the technical support provided for the development of management plans and the enforcement of management activities.

Previous studies examining the ecological effects of harvesting non-timber forest products have primarily focused on short-term data and have rarely included reference information from unmanaged sites (Hall & Bawa, 1993; Ticktin, 2004). In contrast, our study benefits from the analysis of long-term data and incorporates reference data that reflect the regional context of *M. flexuosa* populations. Although there is clear evidence that recovery is underway, the stands are not yet fully recovered; that is, they have not reached a sex ratio of one male per female as observed

TABLE 2 Mean and standard error of the ecological and socio-economic indicators. Comparisons of the significance difference among the groups representing unmanaged (A, B, C) and managed (D, E, F) sampled sites are provided.

Indicator	Group	Mean ± SE	*n*	B	C	D	E	F
Pole density (ind/ha)	A intense use	137 ± 23	9	ns	ns	*	ns	*
	B medium use	156 ± 16	11		ns	ns	ns	ns
	C low use	216 ± 28	11			ns	ns	ns
	D Parinari 1	229 ± 13	13				**	ns
	E Parinari 2	120 ± 14	12					**
	F Veinte de Enero	268 ± 33	15					
Sex ratio (males per female)	A intense use	9.8 ± 1.6	9	*	***	**	**	***
	B medium use	2.9 ± 0.2	11		*	ns	ns	ns
	C low use	1.2 ± 0.1	11			ns	ns	ns
	D Parinari 1	2.2 ± 0.4	13				ns	ns
	E Parinari 2	2.1 ± 0.4	12					ns
	F Veinte de Enero	2.0 ± 0.4	15					
Seedling and sapling density (ind/ha)	A intense use	179 ± 60	4	ns	ns	**	ns	ns
	B medium use	499 ± 253	3		ns	*	ns	ns
	C low use	602 ± 178	4			ns	ns	ns
	D Parinari 1	5036 ± 995	13				**	**
	E Parinari 2	815 ± 165	12					ns
	F Veinte de Enero	1314 ± 328	15					
Volume of harvested fruits (# sacks/year)	A intense use	816 ± 158	271					
	B medium use					*	*	***
	C low use							
	D Parinari 1	1683 ± 503	4				ns	ns
	E Parinari 2	1683 ± 503	4					ns
	F Veinte de Enero	8470 ± 2011	5					
Gross annual income per community (US$)	A intense use	8592 ± 1664	271					
	B medium use					*		***
	C low use							
	D Parinari 1	35,444 ± 10,593	4					ns
	E Parinari 2							
	F Veinte de Enero	89,189 ± 21,175	5					

Abbreviation: ns, not significant.
*$p < 0.05$. **$p < 0.01$. ***$p < 0.001$.

in natural stands (Kahn & de Granville, 1992). Moreover, while our study demonstrates the feasibility of long-term sustainable resource harvesting in tropical peatland forests based on ecological and socio-economic indicators for *M. flexuosa*, further investigation is required to evaluate the effectiveness of long-term conservation and development projects in other Amazonian communities (Choquet, pers. comm.). Field data are also required to assess the changes in other components of the ecosystem, such as species diversity and composition of managed stands (e.g. Freitas et al., 2021) and the fauna that rely on *M. flexuosa* fruit consumption, such as ungulates, rodents, and primates (Bodmer et al., 1999).

The recovery of *M. flexuosa* populations could be linked to the status of the stands before climbing and management plans were implemented. For example, the pole density of *M. flexuosa* is still low in Parinari 2, resembling that of unmanaged sites, and this low density could be due to the proximity of these stands to the Marañón river, which would be expected to have been harvested more intensively than more distant, less accessible sites (Hidalgo Pizango et al., 2022). The recovery of the stands could also be affected by the implementation of management practices by each family or community. For example, thinning by cutting trees was carried out at the study sites (e.g. Parinari 1) but increasing light penetration through the canopy dried the soil, changing the naturally wet habitat that is preferred by *M. flexuosa* (Interviewees, pers. comm.). Tree thinning has not been used in Parinari 2, resulting in higher NDVI (i.e. high canopy density) in these sites compared to Parinari 1. The benefits of pruning and thinning of competing

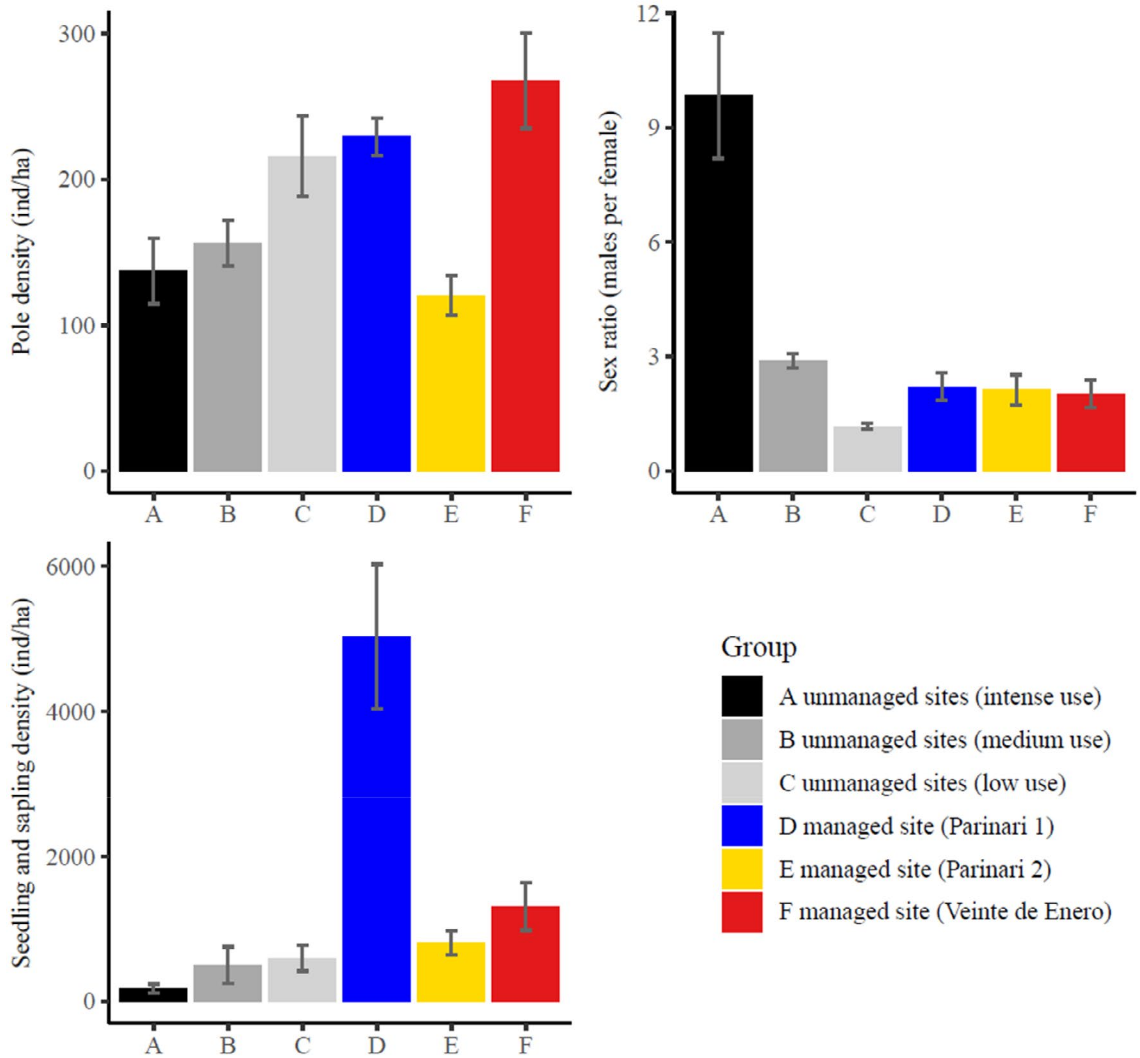

FIGURE 2 Comparison of the ecological indicators of *Mauritia flexuosa* populations (pole density, sex ratio and seedling and sapling density) among unmanaged and managed sampled sites. Error bars indicate standard error of the mean. Comparisons of the significant differences among groups are provided in Table 2.

tree species have been demonstrated elsewhere; for example, in *Euterpe oleracea* stands near the city of Belem in Brazil, resulting in an increase in palm density and fruit yield (Anderson, 1988). However, it is important to note that the intensification of management practices to favour target species can negatively impact overall forest structure and community composition in the long term, as observed in another study of *E. oleracea* stands in the same areas in eastern Brazil (Freitas et al., 2021). Additionally, enhancing light penetration in palm swamps may not necessarily facilitate the long-term establishment of new individuals of the desired palm species. This view is supported by the similar densities of tall saplings and juveniles found in Parinari 1, Parinari 2, and Veinte de Enero, despite the variation in canopy density among these sites. This is consistent with findings from Ecuador, where eight arborescent palm species, including *M. flexuosa*, did not rely on gaps for recruitment or exhibit an increasing demand for light during the survival and growth of seedlings, saplings, and juveniles (Svenning, 1999). Transferring knowledge about the management from one species to another without careful consideration of the specific ecological requirements, such as the low light tolerance of target species, may pose risks to the long-term sustainable management and recovery of naturally abundant species.

4.2 | Socio-economic benefits to rural communities of sustainable fruit harvesting

The sustainable management of *M. flexuosa* for palm fruit harvesting has yielded significant socio-economic benefits to the communities of Parinari and Veinte de Enero that extend beyond the immediate increase in fruit production. Our interview data indicate that management techniques, including climbing, have contributed to the overall well-being of communities by providing a source of income, supporting essential needs, and improving access to education and healthcare.

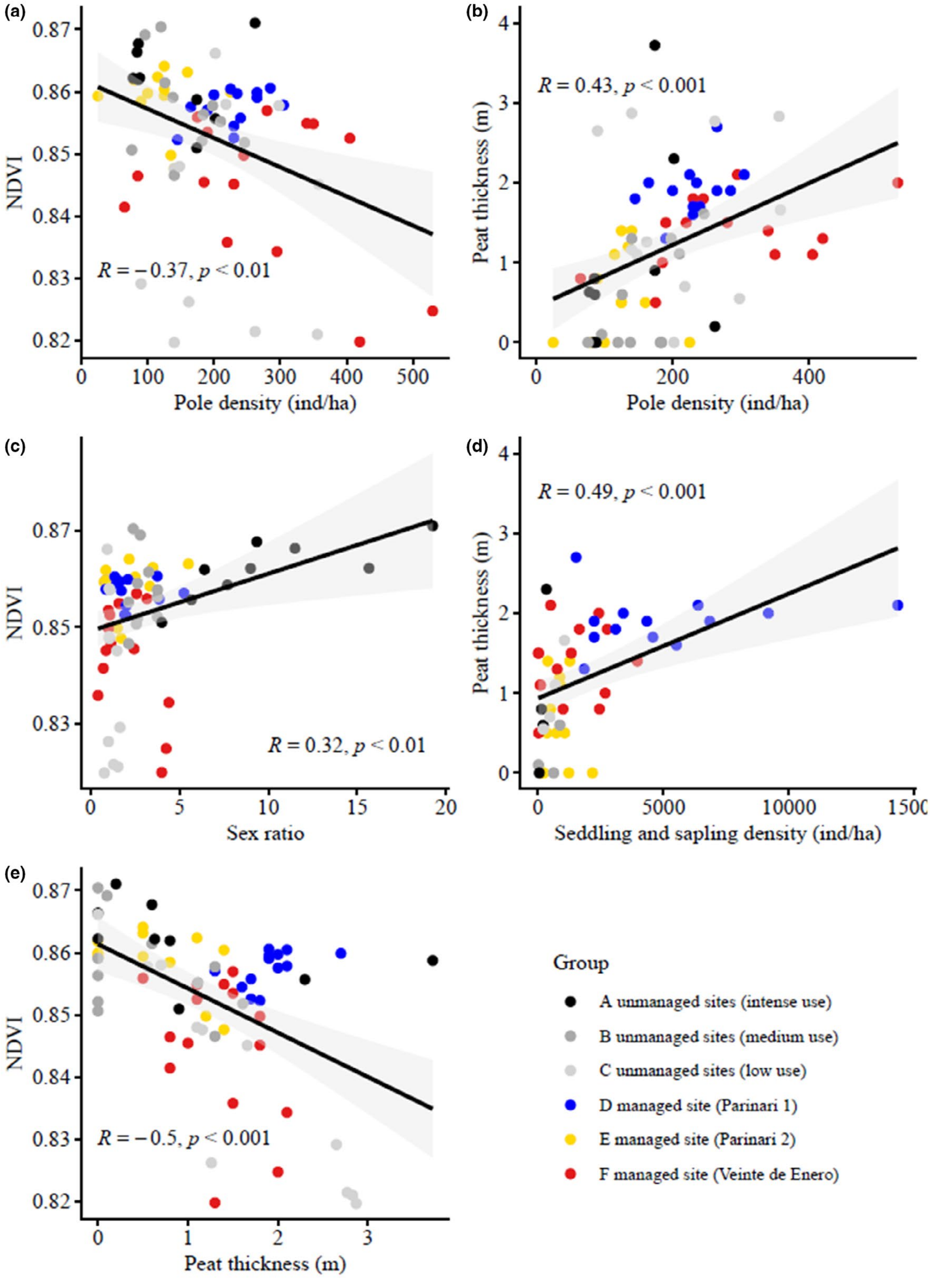

FIGURE 3 (a–e) Relationship between variables (peat thickness and Normalized Difference Vegetation Index [NDVI]) and ecological indicators (pole density and seedling and sapling density) including linear regression line in black, 95% confidence interval in grey, Pearson correlation and *p*-values.

The extraction of *M. flexuosa* fruits remains the most economically important activity for families in these communities. In 1997, fruit harvesting generated an average of US$ 230 (i.e., S/. 285 Nuevos Soles adjusted to the 2022 values using the World Bank consumer price index) per family in the Parinari community, equivalent to 15% of their annual income from other extractive activities (Bejarano &

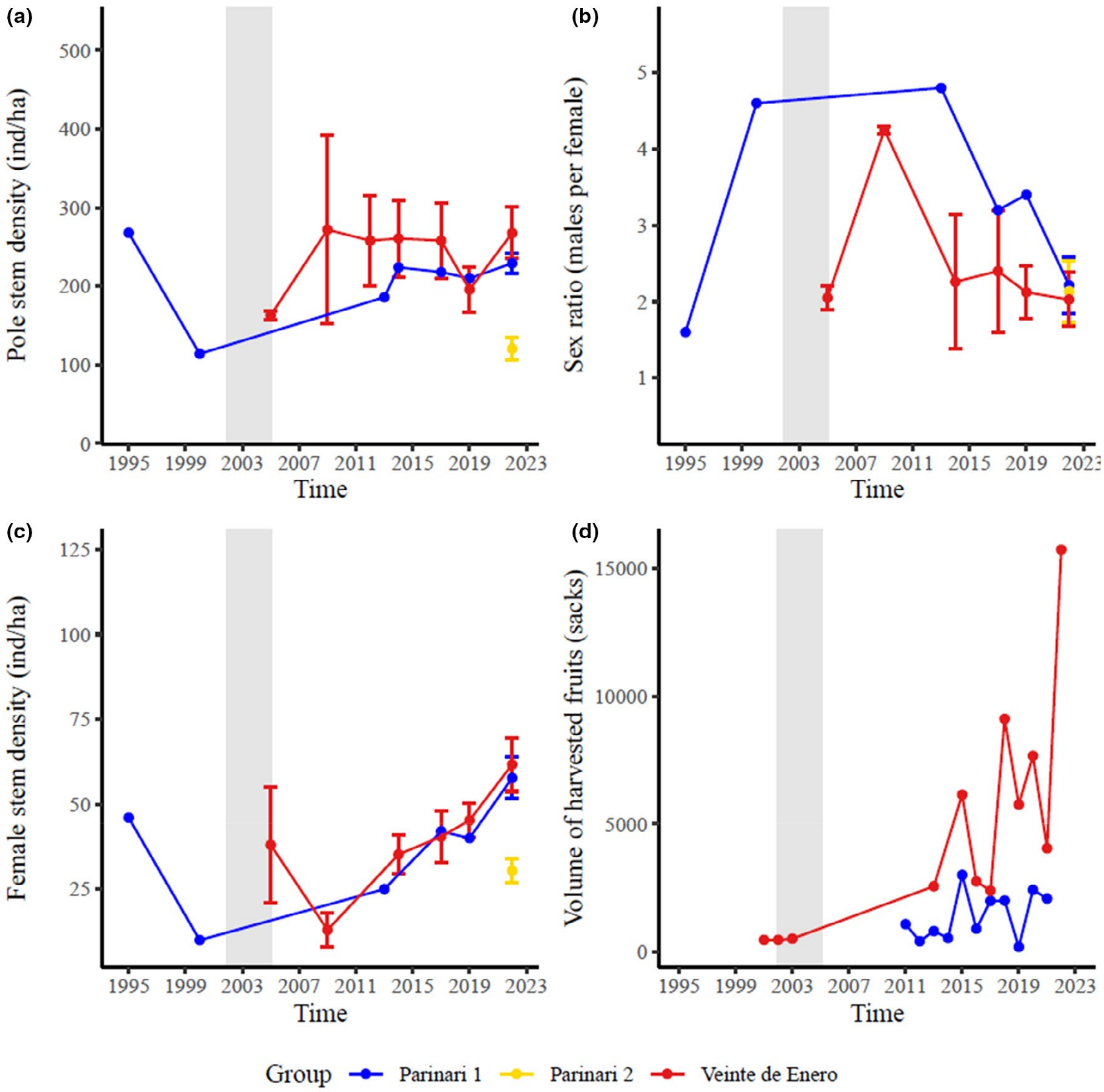

FIGURE 4 Variation of the ecological indicators of *Mauritia flexuosa* populations through time: (a) pole stem density, (b) sex ratio of adult palms, (c) female density, and (d) volume of harvested fruits. Standard error was estimated when two or more values were available. The grey area represents the period when management plans were introduced.

Piana, 2002). Currently, families generate an overall average of US$ 2486 annually through *M. flexuosa* fruit harvesting, representing 71% of their annual gross income. This increase in community income is explained mainly by the high fruit availability, short distances to productive stands, and the increasing demand for palm fruits rather than the change in the price per sack of fruits (from S/. 20 in 2005 to S/. 40 Nuevos Soles in 2023 which solely reflects national inflation rates). Our study therefore aligns with previous research that highlights the socio-economic importance of palm resource extraction as a livelihood strategy for rural communities (Carney et al., 1998; Horn et al., 2012). Therefore, promoting palm climbing to harvest fruits as a central plank of management plans not only serves to increase the long-term sustainability of this livelihood strategy but also generates greater benefits to communities.

Interestingly, income is not the sole motivator that supports sustainable resource management in either Veinte de Enero or Parinari, as interviewees constantly also emphasize the benefits of maintaining their livelihoods and welfare in rural communities. The possible reasons for this finding include that income from fruit harvesting can drop due to sudden periods of very low fruit production (e.g. in 2021) and the challenges faced in setting fair contracts with private companies (e.g. secure production volumes and prices). In addition to income, the management plans, including sustainable harvesting techniques, have formalized the commercial extraction of *M. flexuosa* fruits and empowered the inhabitants of both communities to take responsibility for the care and sustainable use of resources. The management groups coordinate with relevant authorities and sectors such as SERNANP, regional government, academia, NGOs, and private companies, who actively involve community members in decision-making processes related to resource management (Gockel & Gray, 2009). Although fruit harvesting is commonly carried out by men, the women who were interviewed said that they are becoming increasingly involved in fruit processing due to the current management system.

Community members in Parinari and Veinte de Enero identified themselves as descendants of the kukama kukamiria indigenous group; however, traditional practices (e.g. native language) are no longer in use and therefore they resemble mestizo communities. Indigenous and mestizo communities can both cut *M. flexuosa* palms (Gilmore et al., 2013); however, indigenous communities have traditional practices that limit the use of natural resources that are generally lacking among mestizos. For example, among the Urarina indigenous group of the Chambira river, a tributary of the Marañón River, there is a tradition of changing the location of their communities every 30–40 years, which allows for the regeneration of the local ecosystem. In mestizo communities, there is a greater need to adopt new practices in the use and management of these resources such as climbing, since they do not share these traditions (Schulz et al., 2019b). The adoption of climbing protects *M. flexuosa* populations and benefits communities in the face of increasing regional and international demand for its fruits; however, other technologies and traditional uses of *M. flexuosa* swamps should be promoted throughout the region to ensure the maintenance of sociocultural values and, if necessary, the diversification and transformation of resources that are potentially profitable (e.g. textiles, honey and *M. flexuosa* oil production). Further studies should focus on how the adoption of climbing equipment and management plans to harvest *M. flexuosa* fruits can affect the permanence of traditional technologies and practices across indigenous and mestizo communities.

4.3 | Recommendations for sustainable palm management

Despite the positive ecological outcomes observed in the recovery of *M. flexuosa* stands and the socio-economic benefits to communities of adopting sustainable management, there are several considerations that need to be addressed for long-term sustainable resource use and peatland conservation. Firstly, our data support calls for the urgent adoption of climbing as a harvesting method in northern Peru and beyond to ensure restoration of degraded peatlands and avoid degradation of newly managed peatland areas. In the last two decades, few communities in Loreto have adopted climbing, either through their own initiative or by participating in new conservation projects (Hidalgo Pizango et al., 2022), indicating that either (i) the economic and ecological benefits shown by our study may not apply everywhere, (ii) the potential benefits are still not widely known across the region, and/or (iii) other factors prevent the widespread, sustained adoption of climbing techniques. The presence of peat (0.5–2.7 m thick) in most managed stands could be an incentive to value these forests, and climbing would prevent CO_2 emissions due to loss of biomass and peat decomposition caused by intensive felling of *M. flexuosa* (Hergoualc'h et al., 2023). During the interviews, community members also recalled the challenges faced during the adoption of climbing techniques and recognized the need for long-term support from projects to achieve the positive and transformative change observed in Parinari and Veinte de Enero. Therefore, efforts to introduce sustainable harvesting techniques should focus on long-term interventions with communities to tackle limitations by raising awareness, providing training, creating management incentives, and ensuring access to the necessary equipment for communities to transition from felling to climbing (Falen Horna & Honorio Coronado, 2018; Romulo et al., 2022).

Another challenge for establishing sustainable palm management is the financial burden associated with conducting forest inventories, which are required for management plans for commercial fruit extraction according to the current Forestry and Wildlife Law in Peru. While forest inventories are led by SERNANP inside protected areas, rural communities outside protected areas often lack the resources to afford these inventories; therefore, there is no interest in developing management plans, which leads to illegal commercial extraction and little investment in sustainable harvesting practices. Local and regional governments should explore alternative approaches and support mechanisms to make forest inventory more accessible and affordable for communities. Simplified management plans, such as the declaration of management for the use of palm resources (DEMAs; SERFOR, 2017), are a step in the right direction but should be accompanied by adequate financial support and enforcement (Dykstra et al., 2002). Long-term collaboration between various stakeholders, including companies, academia, NGOs, and communities, is also crucial for success and can be facilitated through monitoring the use and impacts of sustainable harvesting techniques and participatory research with harvesters (Ticktin, 2004).

Thirdly, a fair-trade market for sustainably harvested resources is not yet well developed within Peru. There is a lack of knowledge about, and a lack of interest from, the public and companies in paying a premium price for sustainably harvested *M. flexuosa* fruits. Currently, as a free market, the price per fruit sack fluctuates throughout the year from US$ 3.95 per sack when the resource is naturally abundant to more than US$ 26.32 during periods of scarcity (Delgado et al., 2007). Our interviews indicated that scarcity in the regional market favours the communities of Parinari and Veinte de Enero because they have abundant *M. flexuosa* palms close to the villages and therefore experience less scarcity than other communities. However, an over-abundance of fruits presents a significant challenge because, at these times, the resource is sold at a very low price, making the sustainable harvesting of palm fruits unprofitable. The extraction of oil from *M. flexuosa* fruits and the production of soap in Parinari and Veinte de Enero generate greater profits compared to selling fruits, and therefore, the search for more companies interested in these products is underway in both communities. These processed products enhance the resilience of fruit harvesting as an income stream by allowing communities to take greater advantage of periods when fruit is abundant and maintain incomes during periods of scarcity. However, more long-term technical support and infrastructure are required to fulfil the national and international standards for human use and export of these products.

AUTHOR CONTRIBUTIONS

Eurídice N. Honorio Coronado conceived the ideas behind this study; Eurídice N. Honorio Coronado, Timothy R. Baker, Eva Loja Aleman, Jacqueline Ramirez Chávez, Estela P. Martinez Gonzales, Emiliana Isasi-Catalá, Manuel Martín Brañas, and Margarita del Aguila Villacorta designed the methodology; Eurídice N. Honorio Coronado, Julio Grández Ríos, Jhon del Águila Pasquel, Gerardo Flores Llampazo, Cesar J. Córdoba Oroche, José Reyna Huaymacari, C. Gabriel Hidalgo Pizango, Luis Freitas Alvarado, Ulises Pipa Murayari, Gonzalo Isla Reátegui, Chris López Álvarez, Eva Loja Aleman, Emiliana Isasi-Catalá, Joaquín Gutierrez-Sotelo, and Frederick C. Draper collected the data; Eurídice N. Honorio Coronado analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

Our study brings together authors from different countries, including scientists based in the country where the study was carried out. All authors were engaged early on with the research and study design to ensure that the diverse sets of perspectives they represent were considered from the onset. Whenever relevant, literature published by scientists from the region was cited; efforts were made to consider relevant work published in the local language.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets used in the analysis in the current study are available within the article and Supporting Information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Density of *Mauritia flexuosa* by (A) class sizes of all sampled individuals and (B) life stages of pole stems.

Figure S2. Correlations between explanatory variables and ecological indicators.

Table S1. Topic and subtopics guiding the questions in the semi-structured interviews to householders of Parinari and Veinte de Enero, Peru.

Table S2. Details of the location, area, census year, ecological indicators and past resource extraction for each RAINFOR forest plot used as reference dataset in this study.

Table S3. Ecological assessment of managed palm swamps in Parinari and Veinte de Enero, Peru.

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