Global Ecology and Conservation 10 (2017) 70–92

Contents lists available at ScienceDirect

Global Ecology and Conservation

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

Review Paper

Ecology, livelihoods, and management of the *Mauritia flexuosa* palm in South America

Arika Virapongse[a,b,*], Bryan A. Endress[c], Michael P. Gilmore[d], Christa Horn[e], Chelsie Romulo[f]

[a] *Tropical Conservation and Development Program, Center for Latin American Studies, University of Florida, Gainesville, FL 32611, United States*
[b] *The Ronin Institute for Independent Scholarship, Boulder, CO 80303, United States*
[c] *Eastern Oregon Agriculture and Natural Resource Program, Oregon State University, La Grande, OR 97850, United States*
[d] *School of Integrative Studies, George Mason University, Fairfax, VA 22030, United States*
[e] *Institute for Conservation Research, San Diego Zoo Global, Escondido, CA 92027, United States*
[f] *Environmental Science and Policy, George Mason University, Fairfax, VA 22030, United States*

ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form 17 December 2016
Accepted 17 December 2016
Available online 20 February 2017

Keywords:
Aguaje
Buriti
Amazon Basin
Arecaceae
Non-timber forest products
Management

ABSTRACT

Mauritia flexuosa is a key ecological and economic palm found throughout tropical South America. To inform improved management of *M. flexuosa*, we conducted a systematic review of published information about the ecology, livelihoods, and management of *M. flexuosa*, synthesized the information and identified knowledge gaps, and analyzed the spatial distribution of publications. A total of 143 documents (primary research, literature reviews, and grey literature) were reviewed. Most published information originates from Peru and Brazil, with a disproportionate number of documents based in the Loreto Department of Peru. Significant geographical gaps in published information exist, especially in the northern portion of the species range. Existing literature emphasizes *M. flexuosa* fruit, although leaves, oil, and other products play important roles economically. To improve *M. flexuosa* management, we recommend that future research focuses on: (1) *M. flexuosa* availability; (2) harvest and cultivation; (3) development of consistent methods and standards; (4) landscape-level issues like land use change; (5) *M. flexuosa* within broader systems; (6) spatial gaps in research; (7) long-term research; and (8) multi- and interdisciplinary approaches.

Contents

* Corresponding author at: Tropical Conservation and Development Program, Center for Latin American Studies, University of Florida, Gainesville, FL 32611, United States

E-mail address: avirapongse@gmail.com (A. Virapongse).

http://dx.doi.org/10.1016/j.gecco.2016.12.005
2351-9894/

1. Introduction

The *Mauritia flexuosa* palm is distributed widely across South America, where it plays a major role in ecology, economics, and culture throughout most areas of its occurrence. Ecologically, *M. flexuosa* provides key habitat and food resources to a wide range of wildlife (Bodmer, 1991; Brightsmith, 2005). *Mauritia flexuosa* swamps store carbon in thick layers of decaying organic matter, which are increasingly regarded as important sources for carbon sequestration and exchange (Lähteenoja et al., 2009; Draper et al., 2014). Almost all parts of *M. flexuosa* are useful, and some products have developed high market value. Destructive harvesting of *M. flexuosa* for valuable products, such as fruit in the Peruvian Amazon (Ruiz et al., 2001a), has been a conservation concern since the late 1980s (Kahn, 1988; Padoch, 1988) and continues today (Mesa and Galeano, 2013). Other *M. flexuosa* products, such as young leaves and oil, are increasing in value and potentially present management challenges (Sampaio et al., 2008; Abreu et al., 2014). Despite these concerns, gaps in basic knowledge about *M. flexuosa* continue to hinder development of effective sustainable management strategies of this important species.

Because of *M. flexuosa's* socioeconomic and ecological importance, a range of research studies and species-specific management efforts have been conducted. As is common among research and management for a species, however, these publications and plans are often restricted to case studies within disciplinary boundaries. Although in-depth case studies are crucial for developing fundamental knowledge (Courchamp et al., 2015), research bound by sociopolitical boundaries can also limit understanding and management initiatives (Vargas et al., 2012). Discipline-focused research on *M. flexuosa* restricts advancement of theoretical and practical understanding of how different factors interrelate, interact, and influence resource management and conservation efforts.

Sustainable management of natural resources is inherently a product of complex interactions between ecological, cultural, economic, and political components (Virapongse et al., 2016). Finding solutions to management issues, such as overharvesting, requires a multidisciplinary approach that includes such aspects as species population assessment and evaluation of human harvesting behaviors (Ticktin, 2004). Multidisciplinary examinations and cross-comparisons of information about *M. flexuosa* can help reduce redundancy of problem solving efforts and more efficiently direct resources towards filling knowledge gaps. Aggregating knowledge and identifying spatial and thematic gaps is essential for advancing both scientific domains (Callaway, 2015) and sustainable development initiatives (McKinnon et al., 2015).

To assess the status of current information about *M. flexuosa*, we combined a systematic review approach with qualitative and spatial analyses. Our objectives were to: (1) synthesize existing information about the ecology, livelihoods, and management of *M. flexuosa* and its associated ecosystems (e.g., palm swamps, floodplain forests, gallery forests of savannas), and (2) identify information gaps to target areas for research and improved sustainable management of the species. The systematic review approach used in this study can be applied by scholars and managers who seek to improve management of other broadly distributed and economically useful species with sustainable management concerns.

2. Methods

2.1. Species description and distribution

Mauritia flexuosa is both abundant and widely distributed throughout South America. Its range extends north to Venezuela, including the island of Trinidad (Henderson, 1995; Goulding and Smith, 2007), and south to the gallery forests along streams and rivers that course through the savannas (cerrados) of central Brazil. With an estimated 1.5 billion individuals, *M. flexuosa* is considered 'hyperdominant' and ranked as the 22nd most abundant tree species in the Amazon Basin and Guinean Shield (ter Steege et al., 2013).

Mauritia flexuosa is a long-lived, single-stemmed, dioecious palm that can reach 30–40 m in height. The species grows in aquatic and swamp habitats throughout its distribution, occurring in the flood plains of rivers and streams or in poorly drained shallow depressions. Seedlings lack a visible aboveground stem (acaulescent), with persistent petiole bases masking the formation of a soft trunk. As the palm grows, a smooth, hard trunk is exposed as the petiole bases fall. Stem diameter can reach up to 60 cm in adults. Leaves are costapalmate, with 8–20 leaves per adult, and can measure up to 2.5 m long and 4.5 m wide. Inflorescences up to 2 m in length emerge between petioles and support 25–40 branches of flowers (Henderson et al., 1995). One male inflorescence can contain over 100,000 staminate flowers, while female inflorescences may have up to 6,000 pistillate flowers (Khorsand Rosa and Koptur, 2013). In females, the inflorescences become pendulous with fruit, often hanging with 4–5 dead leaves that may persist on the palm (Henderson et al., 1995). Fruit are approximately 2.5×4.5 cm in size and single-seeded with an epicarp composed of reddish-brown scales.

2.2. Search strategy

A systematic review was used to collate, filter, and synthesize documents containing information about *M. flexuosa*. Systematic reviews are a replicable methodology that reduces bias in assessments of existing information. In contrast to standard literature reviews that often lack explicit methodological guidelines, a systematic review provides a rigorous and consistent format to search, analyze, and report the literature. Our systematic review protocol was adapted from Pullin et al. (2009).

The systematic review was conducted during 2015 by using three search engines that specialize in peer-reviewed documents (Google Scholar, Web of Science, and Science Direct), and 23 websites managed by organizations and networks that are regionally relevant and address natural resource management and use (Table 1). For each search engine, we reviewed the first 100 returns generated from (1) each main search term, and (2) the search qualifiers that were added to the main search terms (Table 2). For the 23 organizational websites, we reviewed all returns generated by the main search terms only.

2.3. Study inclusion criteria

Our review targeted the themes of ecology, livelihoods, and management of *M. flexuosa* and *M. flexuosa* dominated habitats in South America. Ecology was defined as the study of the processes and factors that influence the distribution and abundance of *M. flexuosa*, as well as interactions between *M. flexuosa* and other organisms. Excluded from this review were paleo-ecological or geomorphological studies and general plant community or floristic research that did not focus on *M. flexuosa* explicitly. Livelihoods was defined as the role of *M. flexuosa* for direct use, cultural value, and livelihood sustainability among local and regional people. Excluded from this review were documents focused on formal education pedagogy, archaeological studies, industrialization of *M. flexuosa* products, nutritional studies unrelated to direct use, and ethnobotanical inventories that did not address *M. flexuosa* specifically. Management was defined as procedures or policies

Table 1
Websites searched to identify publications or reports with a focus on *Mauritia flexuosa*.

Organization	Website
Empresa Brasileira de Pesquisa Agropecuária	www.embrapa.br
Center for International Forestry Research	www.cifor.org
Center for People and Forests	www.recoftc.org
Community Forestry International	www.communityforestryinternational.org
Conservation International	www.conservation.org
Consultative Group on International Agricultural Research	www.cgiar.org
Consultative Group on International Agricultural Research—Collective Action and Property Rights	www.capri.cgiar.org
European Tropical Forest Research Network	www.etfrn.org
Food and Agriculture Organization	www.fao.org
Forest, Trees, and People Program	www.cof.orst.edu/org/istf/ftpp.htm
Instituto de Investigaciones de la Amazonía Peruana	www.iiap.org.pe
International Fund for Agricultural Development	www.ifad.org
International Institute for Environment and Development	www.iied.org
International Union for Conservation of Nature—Palm Conservation	www.iucn.org
Natural Resources Canada	www.nrcan.gc.ca
Overseas Development Institute	www.odi.org
Rainforest Portal	www.rainforestportal.org
Tropenbos International	www.tropenbos.nl
Tropical Agricultural Research and Higher Education Center	www.catie.ac.cr
US Agency for International Development	www.usaid.gov
Wildlife Conservation Society	www.wcs.org
World Agroforestry Centre	www.worldagroforestry.org
World Wide Fund for Nature	www.wwf.panda.org

Table 2
Main search terms and search qualifiers by theme. Main search terms were used for all themes. Search qualifiers were added to main search terms to identify literature specific to each theme.

Theme	Main search terms	Search qualifiers
Ecology		Ecology, Natural history, Biology, Botany
Livelihoods	*Mauritia flexuosa*, Aguaje, Buriti, Amazon palm swamp	Socioeconomic, Market, Livelihood
Management		Conservation, Manage[a], Sustainable

[a] Denotes a search using alternative word endings.

designed to maintain *M. flexuosa* and its habitats in a particular state for wildlife, ecosystem goods and services, and/or human use. Excluded from this review were natural resource management reviews that listed but did not discuss *M. flexuosa*.

Documents were included in the study if: (1) main search terms and search qualifiers were evident in the initial description of the document; (2) abstract, document summary, or the entire document (in the absence of an abstract or document summary) demonstrated relevancy to our research goals; and (3) full papers were available online or via co-author affiliated university library resources. Documents that listed *M. flexuosa* as part of a survey and included little contextual information about the species were not included in our study. Our database of citations was stored and managed using Zotero (v. 4.0.23, 2014). The complete bibliography resulting from the systematic review is presented in the Appendix (Bibliography).

2.4. Analysis

A qualitative approach was used to synthesize literature. Within each theme (ecology, livelihoods, management), citations were coded to identify dominant topics. Literature was grouped together by these codes, and each group of literature was reviewed to synthesize information about each topic. All documents were categorized as literature review, primary research, or grey literature. Literature review and primary research were defined as documents from peer-reviewed scientific journals; if the methods did not indicate that original data were collected and used, documents were classified as literature review. Grey literature was defined as documents from sources other than peer-reviewed scientific journals (i.e., not controlled by commercial publishers; Alberani et al., 1990).

A spatial assessment of the literature was conducted using only primary research and grey literature; not included were documents without administrative-specific location information and papers classified as literature reviews. Of the documents included, the first level administrative boundary or boundaries (e.g., state or department) where research occurred was identified. Spatial distribution of publications was assessed by theme (ecology, livelihoods, management). Publications coded by multiple themes or administrative boundaries were counted toward each theme or boundary total. A coarse species distribution map of *M. flexuosa* was built using a combination of: (1) a description of *M. flexuosa* river basin and elevation distribution from Smith (2015) that consisted of the Amazon and Orinoco river basins and elevations below 300

Table 3
Descriptive statistics of results from the systematic review across themes (ecology, livelihoods, management). Each document could be categorized in more than one country and more than one theme, so "Total unique publications" (column) does not always equal the summation across rows. In contrast, documents were categorized as only one "Type of paper" within each column. Percentages are based on "Total documents reviewed" within each column.

	Total unique publications	Ecology	Livelihoods	Management
Total Documents Reviewed	143	77	51	41
Type of paper				
Primary research	90	67	21	14
% of total documents	(63%)	(87%)	(41%)	(34%)
Grey literature	39	4	24	20
% of total documents	(27%)	(5%)	(47%)	(49%)
Literature review	14	6	6	7
% of total documents	(10%)	(8%)	(12%)	(17%)
Country				
Peru	61	29	23	26
Brazil	54	28	24	9
Colombia	14	6	7	4
Ecuador	9	6	3	2
Venezuela	5	2	3	0
Bolivia	5	3	2	1
Trinidad & Tobago	2	2	0	0
Suriname	2	1	1	0
Guyana	2	1	1	0
French Guiana	1	1	0	0

m but up to 1000 m in the foothills of the Andes[1]; (2) current occurrence records (Lima et al., 2014); and (3) previous maps (Goulding and Smith, 2007). Watersheds (Lehner and Grill, 2013) that met the elevation (USGS, 1996) criteria from Smith (2015) or had known occurrence data described in Lima et al. (2014) were included. There were a total of 109 administrative regions where *M. flexuosa* is found. The research distribution was overlaid onto the generalized species distribution map of *M. flexuosa* to produce the resulting maps used in this study.

3. Results

A total of 143 documents were reviewed (Table 3), and all of the results herein are based on these documents. Overall, the search strategy and selection criteria returned more primary research documents (63%) than grey literature (27%) and literature reviews (10%). The ecology theme was dominated by primary research (87%), however, both livelihoods and management themed documents mostly came from grey literature at 47% and 49%, respectively. Identified documents were published between 1966 and 2015 (Fig. 1).

3.1. Distribution patterns of published literature

There were 117 documents classified as primary or grey literature with sufficient location information to assign them to one or more administrative regions (Fig. 2). Of these, 8 publications crossed one or more administrative boundaries. Most administrative regions where *M. flexuosa* is found did not have any studies (75 regions; 69% out of the 109 administrative regions). Where research did occur (34 administrative regions), most included only 1 or 2 publications, with only 9 locations in Brazil, Colombia, and Peru containing more than 2 studies within a theme. The maximum number of studies for a region was 16 within a theme and 35 for total unique documents. It must be noted, however, that administrative regions varied greatly in size, and research within each region was often focused on a very small area. A similar number of ecology and livelihoods studies have been conducted in both Peru and Brazil, while a great majority of the management documents were focused on Peru (Fig. 2, Table 3). Overall, little research was reported in Guyana, Suriname, French Guiana, or Bolivia.

3.2. Literature review: ecology

We reviewed a total of 77 documents focused on *M. flexuosa* ecology (Table 3). Two primary topics dominated the literature: *M. flexuosa* natural history and population ecology (48%), and wildlife interactions (43%). The remaining documents (9%) covered a range of topics that focused mostly on *M. flexuosa* community and ecosystem ecology. Photos depicting *M. flexuosa* ecology are included in the Appendix (Photos).

[1] Beginning with watershed boundaries outlined by the United States Geological Survey (USGS) HydroShed (Lehner and Grill, 2013), Amazon and Orinoco watersheds were clipped out. When combined with occurrence information provided by Lima et al. (2014) and Goulding and Smith (2007), it was found that many palm habitats occur at elevations between 500 and 1000 m. Although Smith (2015) describes *M. flexuosa* as more common at elevations below 300 m elevation, the occurrence data suggests that removing elevations above 300 m would be inconsistent with reported data, especially in southern Brazil. As such, the elevation limit for this map was set at 1000 m. Given this 1000 m limit, watershed areas were reduced by removing areas above 1000 m using a 30 arc-second Digital Elevation Model (DEM) of South America created by USGS (1996).

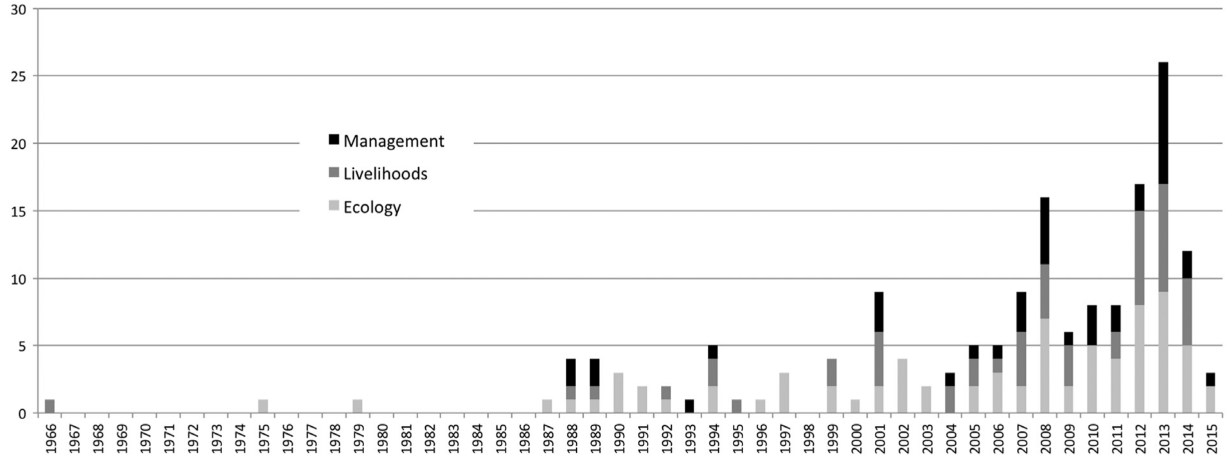

Fig. 1. Number of *Mauritia flexuosa* publications per year, by theme, for 142 documents (1 document about management was not included because it had no publication date). Papers that fit multiple themes were counted for each theme, so the total for each histogram bar may be higher than the total number of unique papers published each year.

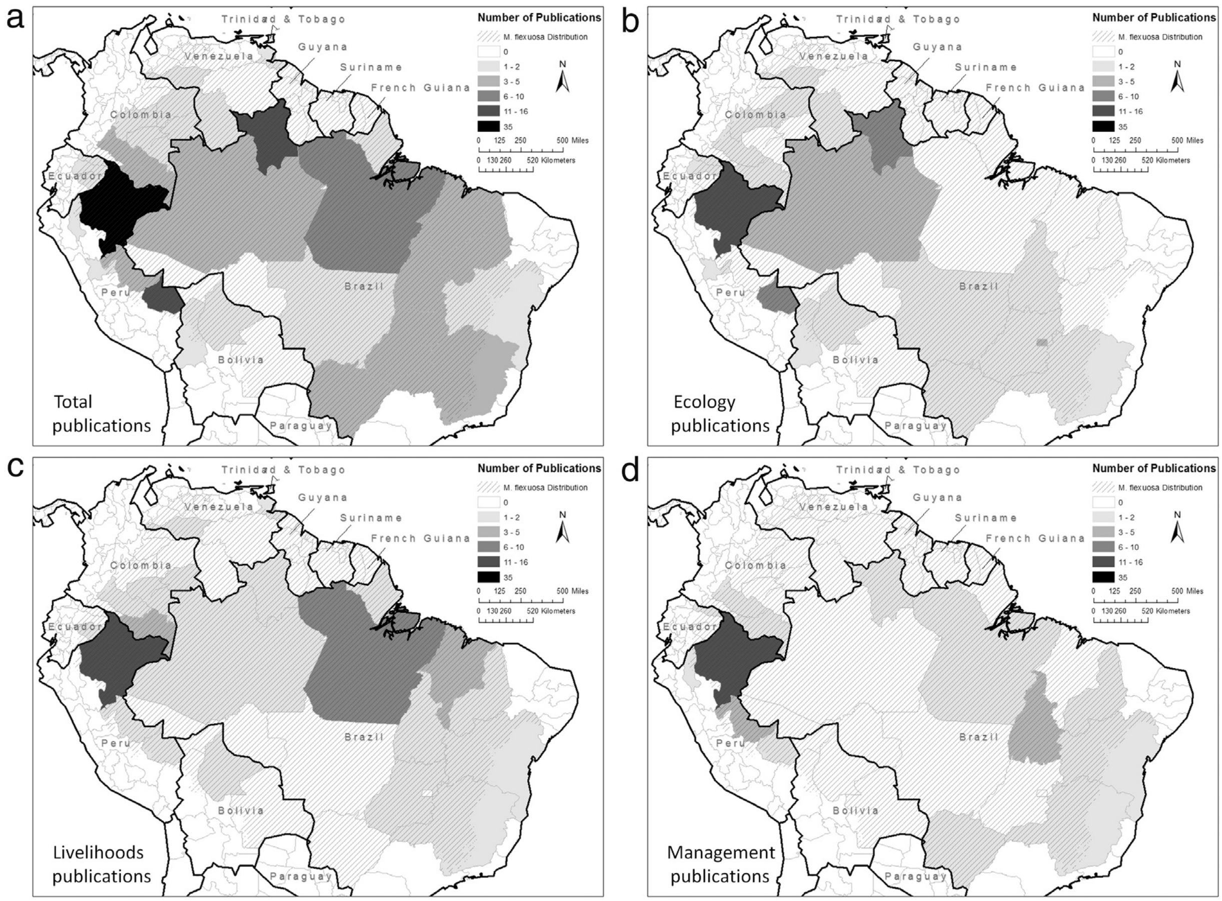

Fig. 2. Distribution of 117 documents reviewed in our study, according to total number (a) and theme (b–d), highlighting the disproportionate number of documents based in the Loreto Department of Peru for all themes (ecology, livelihoods, management).

3.2.1. Natural history and population ecology

Research suggests conflicting accounts of the species pollination syndrome. Knudsen et al. (2001) suggested *M. flexuosa* was pollinated by beetles due to the presence of chemical compounds in flowers that attract beetles. Khorsand Rosa and

Koptur (2013) tested this hypothesis by conducting a manipulative experiment, and found that despite frequent floral visitors, *M. flexuosa* is wind-pollinated. There was no evidence of pollen-limitation, though this remains poorly studied, as most females studied were within 12 m of a male.

Flowering and fruiting phenology was described by studies that reported synchronous flowering and fruiting (Giraldo, 1987; Peres, 1994; Bowler and Bodmer, 2011). Despite the pronounced seasonality of reproduction within a population, a small proportion of adults flower or fruit in any given month. Khorsand Rosa et al. (2013) found that flowering peaked at the wet season/dry season interface as floodwaters recede. In contrast, peak fruiting occurred during the rainy season. Additionally, not all females reproduced in a given year. Just 20% of females produced fruit in consecutive years. No differences were found in flowering phenology between forest or forest-savanna ecotone habitats in Brazil. Delgado and Couturier (2003) found that inflorescence and fruit production can be negatively impacted by larvae from the moth *Eupalamides cyparissias* in the Peruvian Amazon.

Due to the importance of *M. flexuosa* fruit economically and ecologically, many studies measured fruit production. However, methods and measurements vary substantially across publications, making comparisons difficult. For example, studies report fruit production by weight (Khorsand Rosa et al., 2014), per raceme (Barbosa et al., 2010), per female (Delgado et al., 2007), or per hectare (Giraldo, 1987; Peters et al., 1989). In general, adult females can produce over 1000 fruit/year with population production estimates ranging from 6.10 to 9.07 metric tons/ha/year (Giraldo, 1987; Peters et al., 1989; Hada et al., 2013). Soil moisture during the rainy season was identified as the best predictor of seed mass and number (Khorsand Rosa et al., 2014). Khorsand Rosa et al. (2014) also found that total leaf number, diameter at breast height, and palm height were accurate predictors of fruit production. Beyond this, research on factors influencing fruit production is sparse.

Like many species in the wet tropics, seeds of *M. flexuosa* are recalcitrant (Spera et al., 2001; Silva et al., 2014), but exhibit pronounced dormancy. Delayed germination and low germination rates have been observed in both natural and agricultural settings (Spera et al., 2001), and may be caused by a thick operculum and ridged endosperm that restrict embryo growth (Silva et al., 2014). Physical removal of the operculum results in high germination rates (>80% germination; Spera et al., 2001; Silva et al., 2014). Silva et al. (2014) hypothesized that because *M. flexuosa* has seasonably variable fruiting patterns, occurs in constant humid environments, and produces recalcitrant seeds with a low potential for seed bank formation, these adaptations support animal-mediated seed dispersal.

Seed dispersal and predation are well documented. Ungulates act as both seed predators and seed dispersers (Bodmer, 1991; Beck, 2006). Deer, peccary, and tapir consume fruit and can disperse seeds short distances by spitting them out during mastication. Tapir act as important long-distance dispersers, as they are large enough to swallow fruit whole (Bodmer, 1991; Fragoso and Huffman, 2000; Tobler et al., 2010), and this behavior can increase seed-survival rates (Manuel and Fragoso, 1999). Although collared and white-lipped peccary can act as short-distance dispersers, they are the only known mammals able to crack *M. flexuosa* seeds, and thus kill a large proportion of consumed seeds (Beck, 2006). Peccaries also browse seedlings, potentially affecting seedling survival and growth rates (Beck, 2006). Other mammals act as short-distance dispersers, including a wide range of primates (Defler, 1979; Boubli, 1999; Bowler and Bodmer, 2011; Palminteri et al., 2012; Bowler et al., 2013; Astwood et al., 2014) and rodents such as agouti (*Dasyprocta punctata*) and paca (*Cuniculus paca*; Mendieta-Aguilar et al., 2015). Large birds, such as macaw and parrot species, that consume *M. flexuosa* fruit are also dispersers (Lees and Peres, 2008; Motta-Junior et al., 2010; Rodrigues et al., 2012). We are aware of other research noting that fish also consume *M. flexuosa* fruit and disperse seeds (Gottsberger, 1978; Goulding, 1980), though these studies did not appear in our systematic search.

Population metrics for a number of *M. flexuosa* habitats have been reported (Table 4). Populations show a reverse J-shaped structure in both savanna and palm swamp ecosystems (Sampaio et al., 2008; Horn et al., 2012; Resende et al., 2012). Estimates of adult densities per hectare vary widely with reported ranges of 35–735 (Table 4). Horn et al. (2012) reported adult densities ranging from 50 to 160 adults/ha in over-exploited palm swamps in Loreto, Peru. Moreover, just 9% of adults were female, and stands with low female densities exhibited lower densities of seedlings. Varying sampling methodologies confound comparisons between studies on population structure and abundance. Categorization and classification of seedlings, juveniles and adults vary considerably across studies, making it difficult to synthesize findings. A handful of studies have also estimated sex ratios, with two studies finding populations highly biased towards males (Kahn, 1988; Horn et al., 2012; Table 4). Both studies occurred in regions of the Peruvian Amazon with a history of intense destructive harvesting of females for fruit, highlighting the effect of destructive harvest of females for fruit on male-biased sex ratios of populations.

Evaluations of demographic rates or population dynamics are largely lacking in the literature beyond Holm et al. (2008), Sampaio et al. (2008), and Galeano et al. (2015). Holm et al. (2008) tracked *M. flexuosa* demography for two years in palm swamps in Ecuador and found that seedling survival rates were approximately 50%, while palms >1 m height had survival rates >85%, resulting in a positive population growth rate. Additionally, Holm et al. (2008) used a population matrix modeling approach to simulate how different female felling rates affect long-term population dynamics. They estimated that harvesting 22.5% of females every 20 years was sustainable, and higher harvest intensities would likely result in declining populations. Galeano et al. (2015) explored environmental factors that influence *M. flexuosa* regeneration in a 1-ha plot in *M. flexuosa* forests of Colombia. They found that seedling survival was greater in areas of poorly drained soil with high levels of organic matter and low pore-water pH than in microsites with moderately well drained soils. Moreover, seedling survival was lower in years with low levels of precipitation and flooding. Sampaio et al. (2008) tested the effects of leaf harvest on growth, survival and leaf production on juvenile *M. flexuosa* individuals (0.5–4 m height) in palm forests in the Brazilian

Table 4
Summary of sex ratio and adult density estimates for *Mauritia flexuosa*.

Sex ratio (M:F)	Adult density (#/ha)	Country	Habitat	Notes	Citation
1 : 1	–	Brazil	Swamp forest	Unharvested	Khorsand Rosa et al., 2013
1 : 1	–	Brazil	Savanna	Unharvested	Khorsand Rosa et al., 2013
Female-biased	–	Brazil	Forest–Savanna Ecotone	Unharvested	Khorsand Rosa et al., 2013
3.5 : 1	93	Peru	Swamp forest	Adult stem harvest	Horn et al., 2012
1.3 : 1	80	Ecuador	Swamp forest	Adult stem harvest	Holm et al., 2008
3.2 : 1	114	Peru	Swamp forest	Adult stem harvest	Kahn, 1988
–	138	Peru	Swamp forest		Peters et al., 1989
–	190	Peru	Swamp forest		Kahn, 1991
–	300–667	Brazil	Savanna	Juvenile leaf harvest	Sampaio et al., 2008
–	35	Peru	Swamp forest		Rivadeneyra, 1975
–	735	Colombia	Swamp forest		Galeano et al., 2015

savanna. They found that current harvest practices had no impact on demographic rates, although the authors highlighted the importance of monitoring the intensity and frequency of harvest, as both are important for other palm species.

Research on population genetics show that, like many plant species, much of the genetic variation for *M. flexuosa* is at the intrapopulation level with increasing genetic variation among populations as distance between the populations increases (Gomes et al., 2011; Angulo-Quintanilla et al., 2014; Federman et al., 2014). Research on fragmented populations of *M. flexuosa* on the island of Trinidad suggests that genetic diversity can be lost under rapid ecological time scales due to nearest neighbor mating, and habitat fragmentation and isolation of populations associated with land use change, which reduces long distance animal-mediated seed dispersal (Federman et al., 2014). Thus, anthropogenic barriers to gene flow, such as construction of roads and habitat fragmentation, likely have consequences on the genetic variation of *M. flexuosa* populations.

3.2.2. Wildlife interactions

Almost half of the papers addressing *M. flexuosa* ecology focused on interactions between wildlife and *M. flexuosa*. *Mauritia flexuosa's* ability to form dense stands combined with copious production of highly nutritious fruit results in a wide range of wildlife relying on the species as an important food source. Primates include squirrel monkeys (*Saimiri sciureus*; Pontes, 1997; Astwood et al., 2014), uakaries (*Cacajao* spp.; Barnett and Brandon-Jones, 1997; Boubli, 1999; Bowler and Bodmer, 2011; Bowler et al., 2013), capuchins (*Cebus* spp.; Defler, 1979; Pontes, 1997), and spider monkeys (*Ateles* spp.; Pontes, 1997). Many ungulates consume large amounts of *M. flexuosa* fruit, including tapir (Bodmer, 1990; Fragoso and Huffman, 2000; Tobler et al., 2010), red and grey brocket deer (*Mazama* spp.; Bodmer, 1991), and white-lipped (*Tayassu pecari*) and collared (*Pecari tajacu*) peccary (Bodmer, 1991; Manuel and Fragoso, 1999; Beck, 2006). Other mammals that consume *M. flexuosa* fruit include paca (*Cuniculus paca*; Mendieta-Aguilar et al., 2015), agouti (*Dasyprocta punctata*; Mendieta-Aguilar et al., 2015) and olingos (*Bassaricyon* spp.; Pontes and Chivers, 2002).

Avian frugivores feed on *M. flexuosa* fruit. In the Brazilian savannas, numerous bird species consume the fruit, particularly psittacids that consume large quantities (Macedo, 2002; Villalobos and Bagno, 2013). Villalobos and Bagno (2013) suggested that *M. flexuosa* fruit might be a critical food resource for these species during the dry season when other fruits are scarce. Few studies have explored avian frugivory in swamp forests. Avian research primarily focuses on the importance of *M. flexuosa* snags as nesting sites for parrot and macaw species (Renton, 2002; González, 2003; Brightsmith, 2005; Brightsmith and Bravo, 2006; Renton and Brightsmith, 2009). Standing dead trunks of *M. flexuosa* provide critical nesting sites, so their distribution and availability across the landscape are critical for psittacid populations. Additionally, bats create roosting tents in the leaves of the *M. flexuosa* canopy (Kunz and McCracken, 1996).

Reptiles are known consumers of *M. flexuosa* fruit, which was the most common species found in the diet of the turtle *Peltocephalus dumerilianus* in Venezuelan palm swamps (Perez-Eman and Paolillo 1997). In Brazil, *M. flexuosa* fruit comprised 3% of the diet of the turtle *Phrynops rufipes* (Caputo and Vogt, 2008). Tortoises (*Geochelone*) consume both fruit and fallen inflorescences (Moskovits and Bjorndal, 1990). Fish are also known to consume *M. flexuosa* fruit that falls into the water (Gottsberger, 1978; Goulding, 1980).

Other studies have highlighted the high species richness of wildlife associated with *M. flexuosa* habitats. For example, in Venezuela, palm swamps represent the habitat with the greatest species richness of fish at 107 species (Montaña et al., 2008). Macedo (2002) reported that within the Brazilian savanna, *M. flexuosa* forests hosted the greatest richness of frogs and toads.

3.2.3. Community dynamics and ecosystem processes

Community and ecosystem ecology of *M. flexuosa* habitats has been less studied, in comparison to the aforementioned topics. As one of the few studies in this field, Endress et al. (2013) described the structure and composition of *M. flexuosa* palm swamps in the Peruvian Amazon. Marimon et al. (2002, 2010) evaluated factors influencing natural regeneration of gallery forests with *M. flexuosa* in the Brazilian savanna. *Mauritia flexuosa* was more dense in Peruvian Amazon sites than in the Brazilian savanna, but the relative frequency, dominance, density and importance values were similar. In Colombia, Galeano et al. (2015) reported higher density, basal area and importance values than either Endress et al. (2013) or Marimon et al. (2002). Endress et al. (2013) identified a wide range of other plant species that are highly exploited within *M. flexuosa* palm swamps, suggesting that high levels of extraction of many common species may have large implications on stand dynamics and forest succession trajectories. Our literature search, however, revealed no studies that have assessed stand dynamics of *M. flexuosa* ecosystems or how human use may influence forest dynamics.

The role of palm swamps and peatlands dominated by *M. flexuosa* on ecosystem processes is poorly studied despite their hyperdominance within the Amazon Basin. A study on peatlands in the Peruvian Amazon by Householder et al. (2012) concluded that *M. flexuosa* contributes significantly to high rates of carbon accumulation due to its extensive underground root system and hyperdominance in waterlogged substrates; therefore, *M. flexuosa* is likely a dominant producer of peat in the Amazon. Measurements of carbon stocks and accumulation rates in Amazonian peatlands that are often dominated by *M. flexuosa* were comparable to Indonesian tropical peatlands (Lähteenoja et al., 2009). As such, carbon stocks and fluxes in Amazonian peatlands are of global significance. Additional work has been conducted on peatlands, but most studies do not separate *M. flexuosa* dominated peatlands from other peatland systems in the Amazon (e.g. Vegas-Vilarrúbia et al., 2010; Lähteenoja et al., 2012), making it difficult to explicitly discuss the role of *M. flexuosa* in the carbon cycle.

3.3. Literature review: livelihoods

We reviewed a total of 51 documents that focused on the role of *M. flexuosa* in livelihoods (Table 3). Studies addressed the primary topics of commercialization and markets (51%), subsistence and traditional uses (36%), and harvest, cultivation, and access (20%). Some documents covered more than one topic of livelihoods. Photos depicting the role of *M. flexuosa* in livelihoods are included in the Appendix (Photos).

3.3.1. Commercialization and markets

Most literature focused on the role of *M. flexuosa* products as an income generator, particularly for local households. *Mauritia flexuosa* markets provide primary and supplemental income sources for people in regions where income is scarce, and particularly for vulnerable demographic groups, such as land-poor families. Studies on commercialization focused on many different types of *M. flexuosa* products, such as fruit (Loreto, Peru; Coomes et al., 2004), handicrafts made from young leaf fiber (Maranhao, Brazil; Virapongse et al., 2014), toys made from pith (Pará, Brazil; da Silva et al., 2013), and porridge made from fruit (Pará, Brazil; Barros and da Silva, 2013).

Although fruit extraction is often an important income source, it rarely provided the main income for a household because *M. flexuosa* does not fruit year-round. Regardless, the sale of *M. flexuosa* fruit can bring in more than four times the Brazilian minimum wage on a seasonal basis (Sampaio et al., 2012) and contribute 15% of the annual income for a Peruvian community (Manzi and Coomes, 2009). A livelihood survey of 578 households in Ucayali, Peru found that *M. flexuosa* fruit was the most commonly collected forest product (after firewood), and 75% of the collected fruit was typically sold (Porro et al., 2014). Households in this study generated 40% of their income from forest products, and *M. flexuosa* fruit was the 14th highest source of income generated from forest products for households. *Mauritia flexuosa* handicrafts have been reported as providing artisans 17%–66% of the monthly Brazilian minimum wage in Maranhão, Brazil (Saraiva and Sawyer, 2007). In Abaetetuba, Pará, Brazil, a study showed that 60% of interviewees sold *M. flexuosa* fruit, 67% of interviewees sold products made from leaves, and all interviewees used leaf products for subsistence purposes (dos Santos Silva and Coelho-Ferreira, 2012). In some cases, *M. flexuosa* forests were used to establish more reliable income sources, such as agriculture and livestock farming, rather than for their direct products (Sampaio et al., 2012). Among the Maijuna in Peru, for example, *M. flexuosa* fruit contributed little (5%) primary income (Horn et al., 2012), while *M. flexuosa* palm swamps provided additional income and subsistence through game that fed on *M. flexuosa* fruit (Gilmore et al., 2013). These examples demonstrate the important role that *M. flexuosa* plays as part of a larger livelihood system.

The type of *M. flexuosa* products demanded by markets varied by region. For example, commercial demand for fruit in Peru is very high, while it is low in Brazil (Hada et al., 2013). In contrast, young leaf fiber markets were growing quickly in Brazil, but do not exist in other countries. Most markets for *M. flexuosa* were oriented towards local consumers (fruit in Iquitos, Peru; Brokamp et al., 2011), but young leaf fiber handicrafts (Central Brazil; Sampaio et al., 2008; Maranhao, Brazil; Virapongse et al., 2014) and fruit oil for cosmetics in the Brazilian Amazon (Abreu et al., 2014) have been reaching national and global markets. Overall, markets for fruit, young leaf fiber, and oil have been growing rapidly in demand, volume, and price, and they are projected to increase each year. In contrast, *M. flexuosa* markets for such items as petiole baskets in Belem, Brazil (dos Santos Silva and Coelho-Ferreira, 2011) and mature leaves for thatching in Maranhão, Brazil (Virapongse, 2013) are being out-competed by new industrial substitutes. As with many forest product markets, it is difficult to accurately determine the volume and monetary value of *M. flexuosa* (Brokamp et al., 2011), but estimates have been offered (Table 5). Variations in fruit volume estimates are discussed in more detail in the Management review.

Surprisingly, there is still little information regarding trade values and value chains of *M. flexuosa* (Brokamp et al., 2011). For such a regionally-important commercial species, understanding value chain dynamics is important for improving how benefits are distributed across socioeconomically and demographically diverse communities (Delgado et al., 2007; Saraiva and Sawyer, 2007), and for developing management plans based on projections of *M. flexuosa* consumption and production (Marín, 2008). *Mauritia flexuosa* products, such as fruit in Peru (Marín, 2008) and fiber for handicrafts in Brazil (Virapongse et al., 2014), are often brought from forest to market through complex value chains that include primary collectors, intermediaries, wholesalers, street vendors, and retailers (Brokamp et al., 2011). Intermediaries and individuals at the market end of the chain often play necessary roles in the healthy functioning of a market (Padoch, 1988; Virapongse et al., 2014). As is common for many forest product markets, women figure prominently in these markets. Less common, however, is the presence of women with powerful social and economic positions (i.e., the most profitable) in the value chain, such as in the fruit market in Peru (Padoch, 1988; Ruiz et al., 2001b).

Table 5
Economic statistics of *M. flexuosa* products cited in the literature. Estimates of volume vary widely within the literature; this table offers the most recent estimates available in different regions.

Product	Ethnobotanical use	Volume	Monetary value of raw material	Drivers of use and market
Mature leaves	Subsistence for construction (e.g., thatching)	Pume in Venezuela: 13,500 leaves harvested every 2–3 years (Gragson, 1995)	• Maranhão, Brazil: US$50 per 100 leaves (Virapongse et al., 2014)	Local markets; subsistence use
Young leaves (fiber)	Commercialized for handicrafts (e.g., textiles in Maranhão, Brazil; baskets and jewelry in Tocantins, Brazil); Subsistence for construction in many regions	Maranhão, Brazil: 95–125 metric tons of fiber/year from 2004 to 2012 in Barreirinhas (IBGE, 2012) A palm produces 781 grams of fiber/year (assuming 50% of leaves harvested) in Paulino Neves (Saraiva, 2009)	• Maranhão Brazil: US$5200 per metric ton of fiber in 2011 in Barreirinhas (IBGE, 2012); US$11/kg of fiber (Virapongse et al., 2014) US$8.8–66/kg of fiber in Paulino Neves (Saraiva, 2009)	Tourism; local, regional, national, and international markets
Fruit	Commercialized for consumption (e.g., fruit, ice cream, sweets, porridge in the Brazilian Amazon)	See Table 6	• Iquitos, Loreto, Peru: US$749/metric ton of fruit in 2005 (Afonso and Ângelo, 2009); US$0.5–1.2/kg of fruit (Brokamp et al., 2011); Total fruit trade worth US$ 550,000/year (Brokamp et al., 2011) • Roraima, Brazil: US$ 0.1/kg of fruit in wet season and US$ 0.28/kg of fruit in dry season in 2011 (Khorsand Rosa, unpublished data) • Colombia: US$0.5/kg (Brokamp et al., 2011) • Bolivia: US$0.28/kg (Brokamp et al., 2011)	Local, regional markets
Oil (processed from the fruit)	Commercialized (e.g., cosmetics in Brazil); Subsistence in most regions	Bolivia: 30 kg of fruit produces 1 liter of oil (Brokamp et al., 2011)	• Brazil: US$22–24/g of oil wholesale; US$166/kg retail (Brokamp et al., 2011) • Europe: US$/130–210/kg retail (Brokamp et al., 2011)	Local, regional, national, and international markets
Petiole	Commercialized for large baskets (Pará, Brazil and Loreto, Peru) Subsistence for construction in most regions	-	-	Local market; subsistence use
Pith from petiole	Commercialized and subsistence for carvings and toys in Pará, Brazil	-	• Pará, Brazil: US$56 for 100 dried petioles (Santos and Coelho-Ferreira, 2011)	Local and regional markets

3.3.2. Subsistence and traditional uses

In the absence or near absence of markets, *M. flexuosa* serves primarily as a subsistence source for local people. A literature review of palms in South America found that *M. flexuosa* is used for the greatest diversity of purposes among all palm species, particularly within indigenous communities (Isaza et al., 2013). Indigenous people use *M. flexuosa* fruit pulp, oil, fiber, leaves, petioles, larvae found in the decomposing trunk, sap, palm heart, seeds, and roots for food, cultural activities, construction material, medicine, and domestic items (Castaño-Arboleda, 2007). Across communities, fruit and leaves are often the most important plant parts collected and used for subsistence (Martins et al., 2012). High in nutritional qualities such as β-carotene, *M. flexuosa* fruit is an important part of the Amazonian diet (Carrera, 1999; Delgado et al., 2007), and has been promoted as a means to improve regional nutrition (e.g., Amapá, Brazil; Filho and Lima, 2001). Mature leaves of *M. flexuosa* are commonly used as an important thatching material, such as among the Pume in Venezuela (Gragson, 1995) and in Roraima, Brazil (Hada et al., 2013). A study of two regions in Amazonas, Colombia found that most people (61%) used *M. flexuosa* products only for subsistence purposes, while the remaining number of people engaged in commercialization of fruit and handicrafts (Castaño-Arboleda, 2007). In addition to the individual palms themselves, *M. flexuosa* palm swamps offered great value to communities through cattle and pig rearing and agriculture in Central Brazil (Sampaio et al., 2012), and as a source for game and fish (Gilmore et al., 2013). A literature review demonstrated that *M. flexuosa* was one of the top ten most important palm species known by indigenous people in the Colombian Amazon (Mesa and Galeano, 2013). A study across the Amazon, Andes, and Choco regions of northwestern South America demonstrated that *M. flexuosa* is one of the most useful species across these regions, due to its morphological characteristics of being a tall-stemmed, large-leafed plant (Cámara-Leret et al., 2014).

Some studies reviewed considered the transmission and existence of knowledge about the use of *M. flexuosa*. As a species with a long and crucial role in local people's lives, *M. flexuosa* has often been depicted in art and used as a mode of learning to transfer cultural knowledge. In Pará, Brazil, symbolic figurines and toys made from *M. flexuosa* pith are used in religious festivals as valuable tools for teaching younger generations about Amazonian culture (da Silva and Carvalho, 2012) and the local environment (Santos and da Silva, 2012; Barros and Silva, 2013).

Although current uses of *M. flexuosa* are important for determining conservation and development goals, potential uses of *M. flexuosa* maintained through local knowledge should not be overlooked. For example, fiber from young leaves of *M. flexuosa* in Tocantins, Brazil was once important for making traditional household items, but it is no longer used today because of deforestation and replacement by more modern articles. Reviving such cultural values around *M. flexuosa* may help to broaden the species' value beyond simply an economic value. Increased preservation may occur, if the species is viewed as part of the cultural identity for local communities (Sousa and Sousa, 2007). Ethnobotanical surveys have aimed to document and conserve knowledge for potential future use, and such surveys have been conducted in Brazil (Ribeiro et al., 2014; Martins et al., 2012), Peru (Gilmore et al., 2013), and Colombia (Arango, 2012).

3.3.3. Harvest, cultivation, and access

In some regions, such as in Loreto, Peru and Maranhão, Brazil, *M. flexuosa* products have reached high commercial value, and this is sometimes coupled with over-exploitation issues. Increased market access has been correlated to intensity of *M. flexuosa* fruit harvesting (Sampaio et al., 2012). Although traditional management practices for sustainable harvest are often known by local harvesters, they are not consistently practiced, resulting in continued degradation of *M. flexuosa* habitats, such as in palm forests in the Brazilian savanna (Hada et al., 2013). *Mauritia flexuosa* is mostly used at small household scales and products are collected from wild grown individuals. Most *M. flexuosa* habitats are managed as de facto open access, common property, or privately owned land by smallholders (Sampaio et al., 2012), where palms are often unharvested for long periods until *M. flexuosa* products (e.g., fruit, leaves) are needed.

The majority of literature on cultivation focused on Loreto, Peru, where cultivation is being explored as a solution to meet the growing market demand for fruit. Despite the alarming rate of *M. flexuosa* felling around the city of Iquitos in Loreto, Peru, there are few local initiatives to cultivate *M. flexuosa*. For cultivation to be a possibility, considerable extension effort is likely needed, as cultivation of *M. flexuosa* is not typical among smallholders (Penn, 1999). However, aside from monocropping, other cultivation options exist, such as multicropping with food crops like banana or rice (Padoch, 1992) and agroforestry (Penn, 1999). Mechanisms for encouraging cultivation and sustainable harvesting of *M. flexuosa* include nondestructive harvesting techniques (Delgado et al., 2007), providing internationally recognized certification for *M. flexuosa* products (Abreu et al., 2014), appropriate land property arrangements (e.g., Conservation Units in Brazil; Abreu et al., 2014), pest and biological controllers to improve viability of commercial cultivation (Torres et al., 2006), and experimenting with different palm varieties. A dwarf variety has high potential for cultivation because its early fructification and short stem facilitates fruit collection (Delgado et al., 2007).

In an effort to identify strategies to encourage *M. flexuosa* cultivation by smallholders, studies on decision-making, socioeconomics, and preferences of landowners, managers, and end users have been conducted. In Loreto, Peru, farmers cultivating *M. flexuosa* often did so as a long-term investment and complementary income source. Households that planted *M. flexuosa* tended to be more financially stable, younger, and have a larger land base (Penn, 1999). Adoption of new palm climbing techniques for the collection of fruit, which is a proposed substitute for felling of palms, is also important for the cultivation and sustainable management of *M. flexuosa* (Manzi and Coomes, 2009). Active engagement with small landowners and farmers, who often have specific preferences for *M. flexuosa* products, such as different fruit varieties (Torres et al., 2006; Delgado et al., 2007), is crucial for commercial success of cultivation initiatives (Rutger, 2008).

3.4. Literature review: management

We reviewed 41 documents addressing management of *M. flexuosa* and its habitats (Table 3). Documents addressed management of wild fruit harvest (71%), but also covered leaf harvest (22%) and ecosystem services (24%), including carbon sequestration, wildlife habitat, hunting grounds, and other non-timber forest product resources; some documents addressed more than one topic. Documents fell into four stages of resource management: (1) awareness of a conservation or management problem that is documented empirically (24%); (2) a situational analysis conducted to better understand the problem and/or identify potential solutions (51%); (3) implementation of management solutions (17%); and (4) evaluation of implemented management plans and conservation measures (7%). Some documents presented information on multiple stages. Categorizations were based on the furthest stage in the management progression covered by the document. Photos depicting management of *M. flexuosa* are included in the Appendix (Photos).

Given the usefulness of *M. flexuosa*, as outlined in the Livelihoods review, most publications with conservation concerns focused on overharvesting, specifically regarding fruit harvest. Though recent papers address fruit harvest in Brazil for consumption and the burgeoning fruit oil market (Hada et al., 2013; Sampaio and dos Santos, 2015), Peru has a large regional fruit market where demand and destructive fruit harvest dominates the literature. Overharvesting of leaves for thatch and handicrafts is also a resource management concern (Sampaio et al., 2008; Ribeiro, 2010). Additionally, there is growing concern for the overall decline of *M. flexuosa* dominated forests given their importance to wildlife, for carbon storage, and as a special habitat type providing services for local people (Gilmore et al., 2013; Janovec et al., 2013).

Table 6
Summary of estimates of *Mauritia flexuosa* fruits and trees harvested for the market in Iquitos, Peru.

Fruits harvested (metric tons/year)	Trees harvested (trees/year)	Base figures	Notes	Citation
46	–	–	Estimate from the Ministerio de Agricultura of Peru—unknown methods used to calculate estimate.	Peters et al. (1989)
1,810	>24,000	124 sacks of fruit/day; 40 kg/sack	Aguiar et al. (1980) is cited as the source of estimates yet this information is not found there. Instead, we believe estimates come from Ruiz et al. (2001b), which are based on original research via market interviews, but were cited incorrectly by the authors.	Delgado et al. (2007)
5,475	–	15 metric tons/day	Estimate based on original research—interviews and observations.	Padoch (1988)
7,300	–	20 metric tons/day	No sources or explanation of methods given to support estimate provided.	Penn (2008)
7,526	158,045	20.62 metric tons/day; 433 trees harvested/day	Estimates based on original research—consumer interviews.	Mauricio and Arevalo (2001)
10,950	–	30 metric tons/day	Estimate based on unofficial information and unknown methods from the Ministerio de Agricultura of Peru.	COMAPA "Veinte de Enero" et al. (2005)
1,825–10,950	24,000–200,000[a]	5–30 metric tons/day	Fruits harvested estimated from COMAPA "Veinte de Enero" et al. (2005), Delgado et al. (2007), and Mauricio and Arevalo (2001). No sources or explanation of methods given to support estimate of palms harvested.	Brokamp et al. (2011)
7,300–18,250	17,000[a]	20 metric tons/day; 50 metric tons/day	Provides two different and conflicting estimates for metric tons of fruits harvested per day. No sources or explanation of methods provided.	Torres et al. (2006)

[a] Estimate only includes trees cut down and not climbed.

3.4.1. Awareness and alarm

Early alarm papers report the decline of *M. flexuosa* near Iquitos, Peru, and discuss the problem of destructive harvest and need to manage *M. flexuosa* as a resource (Kahn, 1988; Padoch, 1988). Padoch's (1988) evidence resulted from a socioeconomic study of the importance of *M. flexuosa* in the urban economy. Kahn (1988) reported ecological data on uneven sex ratios in *M. flexuosa* dominated swamps under heavy fruit harvest. With accumulating evidence, the alarm of mismanagement has been repeated in literature reviews through to 2013 (Mesa and Galeano, 2013).

Several papers attempt to highlight the scope of the conservation challenge by estimating the amount of fruits and trees harvested to satisfy market demand in Iquitos, Peru (Table 6). These estimates are generated from daily or monthly demand estimates, and are often taken secondarily from other sources (Brokamp et al., 2011; Delgado et al., 2007; Torres et al., 2006; Peters et al., 1989). Padoch (1988) and Mauricio and Arevalo (2001) offered estimates based on results from interviews to determine fruit demand. Overall, estimates ranged widely from 46 metric tons/year to 18,250 metric tons/year (Table 6). Different assumptions of the average amount of fruit harvested from individual trees further clouds assessments of the impact of high fruit demand on conservation of the species. For example, Delgado et al., (2007) bases his calculation of harvested palms on an individual palm providing around 4000 fruit at harvest, while Mauricio and Arevalo (2001) assumed only 999 fruit per palm. Documents did not attempt to determine the proportion of trees destructively harvested; many assume that most trees are felled or make no comment on harvest technique. No estimates were based on actual supply (i.e., the amount of fruit harvested or being sold).

Overharvesting of leaves is a possibility (Sampaio et al., 2008), but there has been minimal alarm raised about this activity. No documents fall in the alarm category for leaf harvest. In fact, in Brazil, where leaf harvest is more prevalent, the loss of *M. flexuosa* dominated habitats is of greater concern. Work in Brazil highlights the economic value of intact *M. flexuosa* habitats and need for broad management strategies (Sampaio et al., 2012), largely to oppose recent threats of conversion to other land uses. Although the impact of fruit harvesting on the overall health of *M. flexuosa* ecosystems has been a concern since the first wave of alarm papers in the late 1980s, the loss of these key habitats and their conservation impacts has only been recently documented in Peru (Gilmore et al., 2013; Endress et al., 2013). Beyond harvesting, Janovec et al. (2013) reported habitat loss due to mining and Willink et al. (2000) warn of the impacts of other land use conversions to *M. flexuosa* habitats. While there are certainly other potential threats to *M. flexuosa* populations (e.g., climate change, changes in hydrology), only overharvesting and habitat destruction have been documented in the literature.

3.4.2. Situational analysis

Most documents reviewed include some level of situational analysis, providing a more thorough discussion of issues and often identifying conservation options and management solutions. Such situational analyses included primary literature that combined social and biological research methods (Ribeiro, 2010; Horn et al., 2012), although many relied on only population biology or ecology research to understand the impacts on the palms.

Regarding sustainable management of fruit harvest, solutions include: new technologies for harvesters to climb female palms, rather than cut them (Peters et al., 1989; Santana et al., 2008; Manzi and Coomes, 2009); promoting cultivation of *M. flexuosa* in agroforestry systems and home gardens (Torres et al., 2006; Delgado et al., 2007; Coral and Reyna, 2010); development of a dwarf variety for cultivation (Torres et al., 2006; Delgado et al., 2007); calculating a sustainable harvest rate for destructive harvesting (Holm et al., 2008); increasing recruitment with selective cutting of male palms to increase light (Horn et al., 2012); and incorporating management measures of other traditional resources and ecosystem services of harvested areas (Endress et al., 2013; Gilmore et al., 2013). Economic sustainability of management is often the focus of situational analyses and solutions. Common problems that must be addressed to improve implementation of solutions for successful management include limited market access (Horn et al., 2012); lack of incentives, such as a premium pricing for sustainable practices (Goulding and Smith, 2007; Marín, 2008); lack of interest in agroforestry due to labor demands (Penn, 2008); and degradation of the resource stock, which affects availability (Horn et al., 2012) and genetic quality (Delgado et al., 2007). Leaf harvest has not yet been documented to negatively affect *M. flexuosa*. Situational analyses for leaf harvest focused mainly on the effects of traditional harvest methods on the individual palms and highlighted practices likely to be sustainable, while ultimately recommending long-term studies to further understand the sustainability of leaf harvest (Sampaio et al., 2008; Hada et al., 2013).

Degradation or destruction of *M. flexuosa* habitats for agriculture or mining reduces the possibility that non-timber forest products and carbon sequestered within these forests can be used as sources of revenue or a conservation tool (Sampaio et al., 2012; Janovec et al., 2013; Fraser, 2014). This point highlights the limitations of using non-timber forest products as a tropical forest conservation tool due to the socioeconomic and ecological complexities in sustaining such enterprises (Richards, 1993; Penn, 2008; Brokamp et al., 2011).

3.4.3. Implementation

The third stage of resource management consisted entirely of grey literature published since 2004. We found two management plans for sustainable fruit harvest, each involving some level of situational analysis (e.g., conducting a resource inventory at a minimum), development of a *M. flexuosa* committee for management activities, incorporation of climbing training and home gardens, improvement of natural recruitment (through moving seedlings or selective silvicultural techniques), and monitoring natural stand recovery (COMAPA ''Veinte de Enero'' et al., 2005; Sánchez, 2004).

Other implementation material focused on fruit harvesting included a report on a training workshop to enhance management (AIDER, 2013a) and education or outreach documents on how to climb or cultivate *M. flexuosa* (Coral and Reyna, 2010; AIDER, 2013b). The only document in this category addressing leaf harvest was an outreach booklet for local harvesters to share traditional management practices (Sampaio et al., 2010). We found no documents beyond the situational analysis stage for efforts to manage *M. flexuosa* forests holistically or for carbon sequestration.

3.4.4. Evaluation

All documents evaluating management strategies focused on fruit harvest, with both Brazil and Peru represented. Evaluation research has been biological (evaluating effects of harvest on palm populations) or social (examining factors promoting or hindering management initiatives). Noting the trend for destructive overharvest in Peru, Sampaio and dos Santos (2015) evaluated existing harvest practices (ground collection and some climbing) for commercial use within Brazil, and found them sustainable. During a situational analysis of the ecological and socioeconomic factors affecting *M. flexuosa* harvest, Horn et al. (2012) evaluated previous conservation measures enacted by a local non-governmental organization (e.g., climbing training and establishment of management committees) within two indigenous communities in Peru. While efforts to establish a management plan had community support, there was insufficient training in climbing and administration, inadequate equipment, and failure to conduct a full situational analysis to understand other factors that affect implementation, such as market access, degraded resource stock, and lack of incentives. Also in Peru, Manzi and Coomes (2009) identified factors influencing adoption of management tools within a harvesting community and made observations on the effectiveness of the implemented management plan. Large land holdings, a youthful household, an extended kin network, and extensive forest knowledge contributed to a household's ready adoption of climbing harnesses, while the availability of household labor paired with observing the effectiveness of climbing harnesses prompted household cultivation of *M. flexuosa*. Manzi and Coomes (2009) concluded that a perception of scarcity, reliance on the resource, secured land tenure, and help from a trusted non-governmental organization helped create the broad community commitment needed for sustained implementation of management strategies.

Table 7
Gaps and recommendations for future *Mauritia flexuosa*-centered research.

Gaps and recommendations	Ecology	Livelihoods	Management
Mauritia flexuosa availability	• Life history and demography research that is directly relevant to sustainable harvest, especially regarding sex ratios. • Effects of specific harvest practices on vital rates and population dynamics.	• Evaluation of product volume along *M. flexuosa* value chains.	• Quantity of resources harvested (e.g., fruits, leaves), resource extraction methods used, and locations of harvest on regional and local scales.
Role of harvest and cultivation	• Life history and demography research relevant to sustainable harvest of the species, especially regarding sex ratios.	• Understanding harvest and cultivation from the collector/producer's perspective, including techniques, preferences, and land tenure.	• Rigorous evaluation of management strategies, including cultivation, with emphasis on factors influencing success or failure and why cultivation is rarely implemented.
Development of standards and approaches	• Standardized methods to measure and monitor demography and stand dynamics.	• Standards for product quality assessment and assurance. • Systems approaches to assess the role of *M. flexuosa* in livelihoods.	• Rigorous evaluation of management plans and strategies with emphasis on their positive and negative effects, and factors leading to success or failure.
Land use change decisions and effects	• Effects of fragmentation on palm pollination, dispersal, and genetics.	• Effect of land tenure on access to *M. flexuosa* products among different socioeconomic user groups.	• Extent and distribution of threats to *M. flexuosa* habitats.
Mauritia flexuosa within broader systems and scales	• Understanding community-level dynamics, including effects of degradation on stand dynamics, recovery rates, and loss of seed dispersers. • Effects of fruit decline (from overharvesting) on wildlife. • Importance to global carbon cycle.	• Holistic understanding of the role of *M. flexuosa* as a source for subsistence, income, and safety net within livelihoods. • Change/transfer of knowledge across generations in regards to sustainable harvesting and use.	• Development of multi-use management plans on local, regional, and continental scales.
Spatial gaps	• Fill in spatial gaps for each of the topic areas (ecology, livelihoods, and management), particularly for the countries of Bolivia, Guyana, Suriname, and French Guiana, where very few studies have been published on *M. flexuosa*; Compare and contrast across different regions and ecosystems supporting *M. flexuosa* in regards to uses and threats; Determine where knowledge transfer across the continent is appropriate.		
Long-term research	• Initiate long-term efforts to document temporal changes in ecological, social, and economic factors that influence social–ecological systems and their management.		
Multi- & inter-disciplinary approaches	• Increase number of studies integrating social and ecological research to better understand the role of *M. flexuosa* within and between natural and human systems, and develop more comprehensive and integrative management approaches.		

4. Discussion

Table 7 summarizes our discipline-specific gaps and recommendations for future research efforts according to eight topic areas, grouped by the Ecology, Livelihoods, and Management themes. Based on our review, these are critical recommendations for advancing research and sustainable management of *M. flexuosa* and its associated habitats. This discussion details the gaps and recommendations according to each theme, and then those that cut across the different themes.

4.1. Gaps and recommendations: ecology

There remains much to be learned about the biology *of M. flexuosa* and its ecosystem interactions, as well as the effects of anthropogenic changes on these interactions. We recommend the following:

4.1.1. Research on M. flexuosa life history and demography that is directly relevant to conservation and sustainable harvest of the species

Despite the hyperdominance of *M. flexuosa* and its ecological, economic, and cultural importance, major gaps exist in our knowledge of *M. flexuosa* life history and demography, and these hinder development of sustainable harvest and management practices. For example, it is still unknown how long it takes for the species to reach reproductive age in either natural or agroforestry situations. In agroforestry settings in the Peruvian Amazon, palms are reported to reach maturity in 7–8 years (Delgado et al., 2007); however, the basis for this conclusion is largely anecdotal or from various unpublished reports. There is a complete lack of information about natural stands, making it difficult to estimate recovery rates of degraded stands among other natural resources issues. Additionally, basic information on seed germination, seedling establishment and recruitment rates, as well as palm growth and survival is surprisingly sparse. Research by Galeano et al. (2015), Holm et al. (2008), and Sampaio et al. (2008) represent the few studies that measured *M. flexuosa* demographic performance the longest, and these studies only tracked individuals for 2 years. For such an ecologically, culturally, and economically important long-lived species, this time period is insufficient. Further investigation is needed on *M. flexuosa* demography and the environmental, biological, and management factors that influence vital rates in natural, managed, and agroforestry stands. Additionally, because of *M. flexuosa*'s broad distribution, comparative studies examining demography across sites are needed.

Additional research on potential pollen-limitation and how male density influences pollination rates and subsequent fruit production of *M. flexuosa* is also recommended. In wild or agricultural situations where palms are managed for fruit production, the goal is often to create female-biased stands; however, the male densities or spatial configurations required to ensure fruit production are still unknown. A number of published management plans and reports recommend cutting males in natural palm swamps and other habitats ostensibly to create female-biased stands to boost fruit production (Hiraoka, 1999; Bejarano and Piana, 2002; Bernal et al., 2011; AIDER, 2013b). Moreover, Horn et al. (2012) suggested that recovery of overexploited, heavily male-biased palm swamps may be facilitated by thinning males to create space in the canopy for juvenile *M. flexuosa* recruits (assuming half would be female). Thinning actions may speed recovery of palm swamps to a 1:1 sex ratio or shift the stand towards female-bias. Yet, no research has sought to evaluate management of sex ratios.

4.1.2. Development of standardized methods to measure and monitor demography and population dynamics

Research that standardizes the measurement, categorization, and classification of *M. flexuosa* life history stages would greatly advance our ability to integrate and synthesize data across studies. There is no consensus about how to categorize size classes of *M. flexuosa*, particularly for palms without an exposed trunk ("juveniles"). While most studies classify seedlings as individuals <1 m in height (Kahn, 1988; Holm et al., 2008; Horn et al., 2012; Galeano et al., 2015), palms >1 m in height that are too small to measure diameter at breast height (DBH) have been categorized in many different ways. This is primarily because the aboveground stem of these palms is not visible due to persistent petiole bases, and the size range of these individuals can vary greatly, making consistent, repeatable measurements difficult. Yet, these individuals may be critical to influencing population dynamics (Holm et al., 2008). Kahn (1988) divided these palms into two groups: acaulescent juveniles and stemmed juveniles (with stem too short to allow for a measurement of DBH); others simply divided populations into height categories (Holm et al., 2008; Horn et al., 2012; Resende et al., 2012). More information on the growth, development, and survival of these juvenile palms would greatly advance our understanding of palm demography and population ecology. Developing consistent, standardized methods for categorizing and measuring these individuals would facilitate comparative analysis. To a lesser degree, this is also an issue when measuring adult palms; some studies categorize adults by height (Holm et al., 2008; Horn et al., 2012), while others by DBH (Galeano et al., 2015). Both DBH and height are helpful for predicting fruit production (Khorsand Rosa et al., 2014), so future research should report both measurements. An alternative measurement of Diameter at Root Crown (DRC) may also be warranted due to the persistent petioles of certain juveniles/small adults. Research is needed to identify efficient measurements that are both ecologically and economically meaningful.

4.1.3. Research evaluating effects of specific harvest practices on individual plant vital rates and population dynamics

While numerous publications express concern about the impacts of overexploitation (see Awareness and Alarm section of the Management review), just three of the 77 publications reviewed sought to evaluate the effects of harvest on vital rates or palm population dynamics (Holm et al., 2008; Sampaio et al., 2008; Sampaio and dos Santos, 2015), and these studies only contained two years of demographic data. The wide range of uses and harvest techniques across the species range make this research question a challenging task. However, the effects of harvest techniques on palm populations have been studied for a wide range of other palms, including *Brahea aculeata, Chamadorea radicalis*, *Geonoma deversa*, and *Sabal* spp. (Endress et al., 2006; Zuidema et al., 2007; Lopez-Toledo et al., 2012; Martínez-Ballesté and Martorell, 2015), and these studies could guide and inform research on *M. flexuosa* and the effects of different harvest strategies on population dynamics. Establishment of long-term comparative studies across numerous sites focused on *M. flexuosa* population dynamics would greatly inform conservation, harvest, and management efforts.

4.1.4. Community-level dynamics of M. flexuosa habitats, effects of degradation and prospects for recovery

Degradation of *M. flexuosa* stands due to felling of females to harvest fruit has been recognized for over 25 years (Kahn, 1988; Peters et al., 1989). Little is known, however, of the effects of this destructive harvest on plant community dynamics and associated wildlife that are also ecologically, culturally, and economically important (Gilmore et al., 2013; Endress et al., 2013). Large tracts of *M. flexuosa* palm stands are male-dominated due to extraction of adult females for fruit harvest (Kahn, 1988; Horn et al., 2012), particularly in Loreto, Peru. Drastic reduction in females eventually leads to declines in overall *M. flexuosa* recruitment (Holm et al., 2008). Destructive harvest of *M. flexuosa* and subsequent reduction of palms in the overstory may cause a shift in stand composition to more woody species (Endress et al., 2013), which can influence a wide range of ecological patterns and processes from wildlife-palm interactions to carbon storage. Research on the rate of recovery of degraded palm populations is a valuable research direction as no reviewed studies explored this critically important topic, which has implications for conservation, management, and restoration.

4.1.5. Effects of declining abundance of seed dispersers, land use change and fragmentation

Mauritia flexuosa relies on a wide range of species to disperse seeds. Large declines in wildlife are well documented in South America. Manuel and Fragoso (1999) found that long-distance dispersal by tapir increased seedling survival rates. Beyond this study, however, the implications of declining seed dispersers on seedling establishment and *M. flexuosa* regeneration remain poorly studied. Additionally, the Amazon Basin is undergoing rapid land use transformation from development projects (e.g., road, rail, and hydroelectric dam construction), extractive activities (e.g., mining, fossil fuel extraction), and commercial agriculture (e.g., palm oil plantations). These changes are likely to have profound impacts on the abundance and distribution of seed dispersers, particularly on large game mammals such as tapir, peccaries, and deer. Results from Federman et al. (2014) suggest that *M. flexuosa* may be particularly susceptible to rapid changes in population genetic structure resulting from loss of long-distance seed dispersers and land use-land cover change. Additional validation beyond the research by Khorsand Rosa and Koptur (2013) that *M. flexuosa* is not insect pollinated but rather exclusively wind pollinated is also warranted, as issues of fragmentation and land cover change would affect pollination rates and gene flow. With limited information available, it remains difficult to evaluate the implications of these factors on *M. flexuosa* populations.

Simultaneously, we know very little about how large declines in fruit production and availability across landscapes due to overharvesting of females may affect already-stressed wildlife populations. The concomitant region-wide stressors of overharvesting wildlife that are key dispersers of *M. flexuosa* and over-exploitation of *M. flexuosa* stands that are important food sources for many wildlife species may only further accelerate degradation of these ecosystems.

4.1.6. Role of M. flexuosa habitats on the global carbon cycle

Understanding the role of *M. flexuosa* in carbon sequestration and nutrient cycling requires more investigation. A growing body of literature highlights the importance of South American peatlands, many of which are dominated by *M. flexuosa*, as an important global carbon sink (Lähteenoja et al., 2009; Householder et al., 2012; Draper et al., 2014). Research explicitly on *M. flexuosa* habitats would clarify their role in carbon accumulation and storage, and may provide additional avenues to promote the maintenance, conservation, and sustainable use of *M. flexuosa* forests, including financial mechanisms associated with United Nations Reducing Emissions from Deforestation and Forest Degradation (REDD+) efforts, which provides financial incentives for developing countries to reduce emissions from their forested land (UN-REDD, 2016). Based on the emerging research, it appears that *M. flexuosa*'s value goes well beyond its importance to local wildlife and people, as it is likely to play an important role in global carbon cycles.

4.2. Gaps and recommendations: livelihoods

Examining the role of *M. flexuosa* in livelihoods is important because it: (1) demonstrates a more comprehensive value for *M. flexuosa* as a resource, (2) can be applied towards improved socioeconomic equity across users, and (3) can help to develop a more sustainable and resilient social–environmental system. We recommend the following:

4.2.1. Better understanding of the effects of cultivation on M. flexuosa access and use, and the relationship between property arrangements on harvesting, agroforestry, and cultivation

Available information on cultivation addresses primarily the potential for *M. flexuosa* cultivation to increase access to *M. flexuosa* fruit for commercial purposes. More studies are still needed on decision-making about harvesting and cultivation from the perspective of the land user (Penn, 1999), establishment of land tenure, and people's perception of land ownership. Being able to access *M. flexuosa* to fulfill livelihood needs depends greatly on property rights (Castillo, 2005). Up-to-date information linking harvesting techniques, economic viability of cultivation, and sustainable forest management is also lacking.

Most studies on cultivation and agroforestry have been conducted in Peru, where degradation of *M. flexuosa* stands is well recognized. However, some regions of Brazil (e.g., states of Maranhão and Tocantins) are experiencing increased demand for *M. flexuosa* products that are at risk for overexploitation (e.g., young leaves; Sampaio et al., 2008; Virapongse, 2013) and tightening restrictions on property rights' arrangements, so cultivation of *M. flexuosa* may be seen as an option in the near future. There was little mention in the literature of cultivation of *M. flexuosa* for leaves or young leaf fiber, which are often sold in the local market and emerging external markets.

It is recommended that studies on different cultivation techniques, such as agroforestry, multicropping, and low density planting, be conducted to enhance sustainability of *M. flexuosa* and its habitats, ensure access to *M. flexuosa* products, and support livelihood systems. Indeed, livelihood studies have shown that agriculture and forest use are often tightly integrated among smallholders (Porro et al., 2014). Up-to-date economic analyses of cultivation of *M. flexuosa* in different regions, including labor, maintenance, and harvesting costs, are also direly needed, as the most recent analysis was provided by Carrera in 1999. Carefully targeting and tailoring conservation and development efforts to specific contexts by integrating smallholder perspectives into *M. flexuosa* management plans can help identify and overcome obstacles to implementing cultivation and sustainable harvesting (Coomes et al., 2004). Development of sustainable harvesting techniques (e.g., reduction of felling) and habitat restoration and protection must also occur in tandem with cultivation to address sustainable management of the species.

4.2.2. Development of a systems approach for assessing the role of M. flexuosa in livelihoods

A systems framework must be developed to include the role of *M. flexuosa* in livelihoods as a part of a broader and more integrated social–ecological system. With such a framework, components of a system are viewed as linked through interdependencies and feedbacks within a dynamic, web-like structure, which is influenced by direct and indirect drivers at different temporal and spatial scales (Liu et al., 2007). In most regions where *M. flexuosa* studies have occurred, studies often emphasize the primary role of *M. flexuosa* as an income generator (da Silva et al., 2013). Although it is evident that *M. flexuosa* plays a much more complex role within livelihoods even in areas where the palm has commercial value, there are few studies that highlight the role of *M. flexuosa* as an income generator with respect to other household income sources; however, some exceptions are Coomes et al. (2004), Horn et al. (2012), and Porro et al. (2014). Even rarer still are studies that provide a comprehensive picture of both the income and subsistence roles played by *M. flexuosa* within a household system, such as the work by Gilmore et al. (2013). Similar to many other forest products, *M. flexuosa* products provide an important safety net during unanticipated crises by providing alternative economic resources as part of a coping mechanism (Shackleton and Shackleton, 2004). The subsistence and "potential" (not currently used) value of *M. flexuosa* is difficult to assess, but these valuations are needed to more effectively justify conservation and sustainable management of the species.

Complementary information must be used to understand the demographics of people who use *M. flexuosa* in different ways, and how these uses shift over time as people change within their lifetime or over generations. Studies on socioeconomics and social demographics associated with *M. flexuosa* as an income generator are important for developing conservation and development targets (Coomes et al., 2004). Sustainable management efforts must consider the larger ecosystem associated with *M. flexuosa* and the ecosystem services that these forests provide, and not simply the individual species and its specific commercial value (Gilmore et al., 2013; Sampaio et al., 2012). Overall, *M. flexuosa* must be considered for its value to produce multiple products and services, and its high value to provide a safety net for vulnerable people in times of crises. A more holistic approach to management of *M. flexuosa* is needed.

4.2.3. More accurate estimates of volume, price, and drivers along the market value chain, identified locations of harvested M. flexuosa individuals, and developed standards for quality assessment and assurance of M. flexuosa products

Valuation of volume and price at all points along value chains is needed in all regions. Most estimates vary widely, so it still remains very difficult to manage markets sustainably and in an informed way. For example, little is known about where products are harvested as well as how much raw material is currently available and may be available in the future. Likewise, sustainable harvesting perceptions among extractors can vary widely; science-based information that is region and product-specific is needed to support more informed harvesting. Tracking the price inputs/outputs at different points in the value chain is key for managing for equality among different actors in the value chain (e.g., livelihood and value chain sustainability) and identifying key points of contrasting market demand/product availability. Additionally, quality assessment and assurance (e.g., for fruit and oil; Brokamp et al., 2011) is needed, particularly for products being marketed outside of the local market. Improved technologies for better preservation and mechanical equipment to process fruits (Ruiz et al., 2001b) are needed, as processing of products is still crude (Brokamp et al., 2011). Community organization and lack of technical assistance have proven to be limiting factors for development of *M. flexuosa* activities, increase in harvester and artisan incomes, and the production arrangement as a whole (Saraiva, 2009; Virapongse et al., 2014). Studies are needed to develop strategies for sustainable use of fiber palms, particularly when palm fiber extraction is promoted by governments and non-governmental organizations as a 'sustainable' means to improve welfare (Isaza et al., 2013).

4.2.4. Better understanding of the change/transfer of knowledge across generations in regards to sustainable harvesting and use of M. flexuosa

Knowledge about biological productivity and sustainable harvesting of *M. flexuosa* varies widely among users and examining the change and transfer of knowledge across generations is critical. This is particularly important because as markets grow to demand more products, the user base can include people who do not have sustainable harvesting knowledge about the species including how much and when to harvest. Maintenance of traditional knowledge is key for community and ecosystem resilience in the case of leaner times. More macro studies are needed to analyze knowledge and use patterns on a spatial scale, and the drivers that stimulate change. Given the richness and abundance of palms and the cultural diversity that is present in the Amazon, it is important to understand how palms are used by local people for the purpose of supporting management, conservation and development plans (Mesa and Galeano, 2013).

4.3. Gaps and recommendations: management

Effective management requires a good understanding of the various threats facing *M. flexuosa* and its habitats, and effective management solutions to address those threats. Many of the gaps and recommendations already described in the Ecology and Livelihood sections also apply to the Management theme. Here, we identify additional knowledge gaps and recommendations to improve the conservation and management of *M. flexuosa* and its habitats.

4.3.1. Research to more effectively document the quantity of resources harvested from M. flexuosa (e.g., fruits, leaves), resource extraction methods used (e.g., climbing vs. cutting), and locations of harvest on local and regional scales

The degree and location of extracted *M. flexuosa* products must be more rigorously documented and understood throughout its range. For example, over a quarter of a century has passed since Kahn (1988) and Padoch (1988) first sounded the alarm about the destructive harvest of *M. flexuosa* fruit and its effects in the region surrounding Iquitos, Peru, yet estimates of the amount of fruit consumed in Iquitos and number of trees harvested to meet this demand vary widely and remain unknown. For trees that are harvested, the proportion that is destructively harvested (cut) versus climbed is unknown. Detailed studies regarding extraction locations in the region surrounding Iquitos would not only strengthen our understanding of markets and current (and potential) impacts on livelihoods, but also allow for the possibility of targeting conservation and management efforts on communities that are hotspots for extraction. This type of information is also lacking for other *M. flexuosa* products beyond fruit, such as leaves. Understanding the degree and scope of the conservation challenges in a spatially explicit way helps prioritize and focus management efforts.

4.3.2. Research into the extent and distribution of threats to M. flexuosa forests from mega-development projects, extractive activities, and commercial agriculture and plantations

There is growing concern about the destruction and degradation of *M. flexuosa* dominated forests resulting from changing land use patterns, especially as pressure grows to connect the Amazon basin to the global economy. Little is known about the potential effects of mega-development projects (e.g., road and rail projects, dam construction), extractive activities (e.g., mining, fossil fuel extraction), and commercial agriculture (e.g., oil palm plantations) on *M. flexuosa* and its habitats, although the potential for far-reaching and sometimes unforeseen ecological consequences on forests, their resources, and the ecosystem services that they provide are great. Janovec et al. (2013) documented the impact of gold mining on *M. flexuosa* palm swamps and the extent of this threat in one part of Peru, but more threat analysis is needed throughout the palm's range to better understand the extent, distribution, and potential impact of land use changes.

4.3.3. More integrative and holistic situational analyses and development of multi-use management plans on local, regional, and continental-wide scales

Although conservation and management of *M. flexuosa* and its habitats has been of concern since the late 1980s, documenting the implementation of conservation and management solutions has only occurred since 2004. Since that time, few management plans have been made widely available. Our review identified only two management plans (COMAPA "Veinte de Enero" et al., 2005 and Sánchez, 2004), both at the community level, to manage fruit harvest and one guide for developing community plans (AIDER, 2013b). These low numbers could be due to limitations in our search methods combined with a lack of diffusion of local management plans to broader audiences. However, the fact remains that there is a dearth of management plans and initiatives throughout the palm's range, particularly given the scope and scale of the conservation challenge and importance of *M. flexuosa* and its habitats.

Perhaps even more alarming is a lack of any semblance of coordinated management on a regional, national and continental-wide scale. There is an urgent need for policy level intervention to tackle this critical conservation challenge, and a need for easily transferable and replicable community-based management plans that can be implemented throughout the Amazon basin. Any management prescriptions developed, whether on a policy level or on-the-ground in communities, should be holistic in nature and include not only concern for commercial forest products (e.g., fruit and/or fiber) and ecosystem services (e.g., carbon sequestration), but also the wide range of non-market cultural, economic, and subsistence goods and services provided by this palm and its associated habitats to local communities (Endress et al., 2013; Gilmore et al., 2013). Most of the situational analysis studies that we reviewed focused on developing a better understanding of only one aspect of the conservation challenge (e.g., social or biological). Situational analyses must be interdisciplinary and include both social and biological aspects to develop more effective and holistic management interventions and prescriptions for *M. flexuosa* and its habitats.

4.3.4. Rigorous evaluation of management plans and strategies with emphasis on their positive and negative effects, as well as factors leading to success or failure

The need for effective and rigorous evaluation of management plans is highlighted by the fact that our systematic review only identified three documents with this focus. This may reflect a limitation of our search methods, the possibility that management plans are not being properly evaluated, and/or the evaluation results are not being broadly shared. Regardless, rigorous evaluation of management plans, along with broad sharing of results to create a strong feedback loop, is absolutely critical if management and conservation of *M. flexuosa* and its habitats is to improve over time. Numerous reviews mention efforts to promote sustainable wild harvest and/or cultivation, as well as the limited impact and spread of these efforts. Understanding and addressing factors limiting sustainable management efforts is needed to increase impact and address problems on broader spatial scales. Management efforts and their evaluation must be shared more broadly, both within and beyond academic documentation. Without properly evaluating the positive and negative effects of management, as well as the factors leading to success or failure, communities, governmental agencies, and conservation organizations are less likely to learn from past challenges and mistakes.

4.4. Crosscutting themes

Results of our systematic review reveal that progress has been made in documenting and understanding the ecological, social, and conservation-related factors associated with *M. flexuosa* harvest and management. Despite this progress, however, significant discipline-specific gaps remain, hindering the ability to understand and develop best practices for sustainable management of the species. Overall, basic information regarding the ecology, livelihoods, and management of the species remains lacking. Table 7 summarizes the discipline-specific gaps and recommendations for future research efforts, as well as highlights the transcending nature of the different gaps. These unifying topics are: (1) *M. flexuosa* availability; (2) role of harvest and cultivation; (3) development of standards and approaches; (4) land use change decisions and effects; (5) *M. flexuosa* within broader systems and scales; (6) spatial gaps; (7) long-term research; and (8) multidisciplinary approaches.

Most research efforts have been short-term (less than 2 years) and restricted spatially to a handful of regions, such as northern Peru and northern Brazil. These represent significant challenges when confronted with a long-lived species that is spatially distributed across an enormous area and spans a broad range of ecological, geographical, political, economic and cultural contexts. The degree to which we can make informed, wide-ranging inferences about the sustainable management of this species and its ecosystems based on the existing research remains unclear. When inferences are to be made, they must be made with caution, recognizing the limitations of our knowledge, and the complex and diverse social–ecological systems of the region.

Of the 143 *M. flexuosa*-focused publications identified in this review, only 22 (15%) addressed more than one of our three broad themes of Ecology, Livelihoods, and Management (Appendix I). Only four of these publications included all three themes: Delgado et al. (2007), Hada et al. (2013), Horn et al. (2012), and Peters et al. (1989). The findings from these papers demonstrate the need for multi- and interdisciplinary efforts that more holistically focus on *M. flexuosa* systems and highlight the interconnectedness of *M. flexuosa* abundance, yield, market access, value chains, harvest techniques, land tenure and more. Given the complex nature of social–ecological systems, integrated research that examines the interplay between ecology, livelihoods, and management is critically important to develop appropriate best management practices that are based on the ecological, political, economic and cultural conditions of a given area (Virapongse et al., 2016). Long-term multi- and interdisciplinary research is needed for sustainable management of natural resources (Janssen and Goldsworthy, 1996) and non-timber forest products (Ticktin and Shackleton, 2011), including *M. flexuosa*. Given the broad distribution of this species and the diverse social–ecological systems associated with its use and management, a concerted effort across disciplines by using a systems approach is needed to advance research and understanding of *M. flexuosa* and its ecosystems.

It is worth noting that systematic reviews are not comprehensive reviews, and are designed to reduce bias associated with traditional review papers that often lack explicit methodological guidelines (Pullin et al., 2009). Systematic reviews are based upon the key words selected, search engines used, and institutional websites examined to produce an informative picture of the status of a review topic. Systematic reviews are also highly dependent on the algorithms of the search engines and accessibility of the content on websites. As a result, peer-reviewed papers in highly visible and well-promoted journals are more easily identified, while local literature from non-peer reviewed manuscripts could be overlooked. We are aware that a small number of research papers were missed in our systematic search. Examples include research on *M. flexuosa* ecotones by San-José et al. (2010) and the work by Ervik (1993) and Storti (1993) on pollination biology. Despite these shortcomings of the systematic review approach, based on the collective expertise and on-the-ground experience of the co-authors, we feel confident that this review captures the vast majority of significant literature associated with *M. flexuosa*, and thoroughly documents and synthesizes the most important information available about the ecology, livelihoods, and management of this species.

5. Conclusion

Using a systematic review approach, we demonstrate that there is a large body of research available on *M. flexuosa,* although most of these studies are region-specific and restricted to one discipline. *Mauritia flexuosa* offers an appropriate topic for a systematic review because the species is broadly distributed across the South American continent, and it is an important species in regards to both ecology and livelihoods in all areas of its occurrence. Destructive harvesting and overexploitation of *M. flexuosa* is a risk to the species, its ecosystems, and the wildlife and people that depend on its products, especially considering that markets are often unpredictable and there is a lack of baseline information regarding the availability of *M. flexuosa* palms and products. Knowledge generation and better solutions for sustainable management of *M. flexuosa* are needed. Such novel solutions for management challenges can be developed through cross-comparisons of geographical regions, as well as through multi- and interdisciplinary research and the use of a social–ecological systems framework. The research approach presented here provides a model for how knowledge synthesis can be conducted to support sustainable management and conservation efforts of other broadly distributed and economically valuable species. Results of this study can be useful for researchers, managers, government agencies, NGOs, and policy makers that seek to improve management and sustainable livelihoods associated with *M. flexuosa* and its ecosystem services. For researchers, the study highlights gaps in knowledge that need more attention. For managers, government agencies, NGOs, and policy makers, our results summarize current information about harvesting, management, and income generation that can be used to guide conservation and sustainable development efforts.

Acknowledgments

We thank all of the researchers, fieldworkers, Amazonian communities, and organizations whose publications and knowledge are synthesized in this review paper. We are grateful to the individuals and communities that we have worked with and learned from over the years during our *Mauritia flexuosa*-related work. In Peru, we thank the Maijuna indigenous communities of Sucusari, Nueva Vida, Puerto Huamán, and San Pablo de Totolla; Victor Vargas Paredes; Heraclides Flores Simon; Hemilton Flores Simon; Einsten Flores Simon; Elvis Valderrama Sandoval; the Cocama community of Parinari; Cecilia Lesly Ballón Falcón; Delia Yolanda Moreno Gutierrez; and Anthony Franco Rojas Flores. In Brazil, we thank the communities of Barreirinhas, Maranhão and particularly Atins and Laranjeirias; Rita de Souza; Alcino Ramos Diniz and Jocilene Almeida Brasil; and Luis Carlos da Luz Brasil. Publication of this article was funded in part by the George Mason University Libraries Open Access Publishing Fund, Oregon State University, and San Diego Zoo Global.

Appendix. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.gecco.2016.12.005.

References

Abreu, Y.V., Ávila, R.G., Gonçalves, T.S., 2014. The buriti agro extractivism: an alternative for the development of the Brazilian Amazon Region. Int. J. Soc. Sci. Entrepreneurship 1, 189–197.

Afonso, S.R., Ângelo, H., 2009. Market of non-wood forest products from brazilian savanna. Ciência Florestal 19, 317–328.

Aguiar, J.P.L., Marinho, H.A., Rebelo, Y.S., Shrimpton, R., 1980. Aspectos nutritivos de alguns frutos da Amazonia. Acta Amazon. 10 (4), 755–758.

AIDER, 2013a. Apoyo a la implementación de actividades productivas sostenibles en las comunidades nativas nuevo saposoa, Patria Nueva y Callería, Ucayali. Asociacion Para la Investigacion y Desarrollo Integral—AIDER.

AIDER, 2013b. Guia para el manejo y aprovechamiento de aguaje (*Mauritia flexuosa*) Pucallpa-Region Ucayali. Asociacion Para la Investigacion y Desarrollo Integral–AIDER.

Alberani, V., Pietrangeli, P.D.C., Mazza, A.M., 1990. The use of grey literature in health sciences: a preliminary survey. Bull. Med. Libr. Assoc. 78, 358.

Angulo-Quintanilla, J., Marapara-Del Águila, J., Rengifo-Trigoso, D., Adrianzén-Julca, P., Ramírez-Arévalo, F., Braga-Vela, J., Castro-Gómez, J., 2014. Diversidad genética y filogenia molecular de poblaciones de *Mauritia flexuosa* L.f. "aguaje" de la Amazonía Peruana. Ciencia Amazónica (Iquitos) 4, 22–28.

Arango, S.L.F., 2012. Uso De Algunos Productos forestales No Maderables Provenientes De Bosques De *Mauritia Flexuosa* L.f. En cercanías De La Ciudad De Leticia (thesis). Departamento Del Amazonas, Colombia, Universidad Nacional de Colombia, Medellín, Columbia.

Astwood, R., Rodríguez, P., Rodríguez-C, K., 2014. Foraging density for squirrel monkey *Saimiri sciureus* in two forests in Puerto Lopez-Colombia. Rev. MVZ Córdoba 19, 4158–4167.

Barbosa, R.I., Lima, A.D., Junior, M.M., 2010. Biometria de frutos do buriti (*Mauritia flexuosa* L.f. –Arecacaceae): produção de polpa e óleo em uma área de savanna em Roraima. Amazonia: Ciencia & Desenvolvimento 5, 71–85.

Barnett, A.A., Brandon-Jones, D., 1997. The ecology, biogeography, and conservation of the Uakaris, *Cacajao* (Pitheciinae). Folia Primalol 68, 223–235.

Barros, F.B., Silva, D., 2013. Os mingauleiros de miriti: trabalho, sociabilidade e consumo na beira de Abaetetuba, Pará/The mingauleiros de miriti: work, sociability and consumption In "edge" of Abaetetuba municipality, Pará state. Revista FSA (Faculdade Santo Agostinho) 10: 44–66.

Beck, H., 2006. A review of peccary-palm interactions and their ecological ramifications across the neotropics. J. Mammal. 87, 519–530.

Bejarano, P., Piana, R., 2002. Plan de manejo de los aguajales aledaños al caño Parinari. Junglevagt for Amazonas WWF-AIF/DK, Iquitos, Peru.

Bernal, R., Torres, C., Garcia, N., Isaza, C., Navarro, J., Vallejo, M.I., Galeano, G., Balslev, H., 2011. Palm management in South America. Botan. Rev. 77, 607–646. http://dx.doi.org/10.1007/s12229-011-9088-6.

Bodmer, R.E., 1990. Fruit patch size and frugivory in the lowland tapir (*Tapirus terrestris*). J. Zool. 222, 121–128.

Bodmer, R.E., 1991. Strategies of seed dispersal and seed predation in Amazonian ungulates. Biotropica 23, 255.

Boubli, J.P., 1999. Feeding ecology of black-headed uacaris (*Cacajao melanocephalus melanocephalus*) in Pico da Neblina National Park, Brazil. Int. J. Primatol. 20, 719–749.

Bowler, M., Barton, C., McCann-Wood, S., Puertas, P., Bodmer, R., 2013. Annual variation in breeding success and changes in population density of *Cacajao calvus ucayalii* in the Lago Preto Conservation Concession, Peru.

Bowler, M., Bodmer, R.E., 2011. Diet and food choice in peruvian red Uakaris (*Cacajao calvus ucayalii*): selective or opportunistic seed predation? Int. J. Primatology 32, 1109–1122.

Brightsmith, D.J., 2005. Parrot nesting in Southeastern Peru: season patterns and keystone trees. Wilson Bull. 117, 296–305.

Brightsmith, D.J., Bravo, A., 2006. Ecology and management of nesting blue-and-yellow macaws (*Ara ararauna*) in *Mauritia* palm swamps. Biodivers. Conserv. 15, 4271–4287.

Brokamp, G., Valderrama, N., Mittelbach, M., Grandez, C.A., Barfod, A.S., Weigend, M., 2011. Trade in palm products in north-western South America. Bot. Rev. 77, 571–606.

Callaway, E., 2015. Computers read the fossil record. Nature 523, 115–116.

Cámara-Leret, R., Paniagua-Zambrana, N., Balslev, H., Barfod, A., Copete, J.C., Macía, M.J., 2014. Ecological community traits and traditional knowledge shape palm ecosystem services in northwestern South America. Forest Ecol. Manag. 334, 28–42.

Caputo, F.P., Vogt, R.C., 2008. Stomach flushing vs. fecal analysis: The example of *Phrynops rufipes* (Testudines: Chelidae). Copeia 2008, 301–305.

Carrera, L. 1999. Aguaje (*Mauritia flexuosa*) a promising crop of the Peruvian amazon. In: II ISHS Conference on Fruit Production in the Tropics and Subtropics, vol. 531, pp. 229–236.

Castaño-Arboleda, N., Cárdenas, D., Rodriguez, E.O., (Eds.), 2007. Ecología, aprovechamiento y manejo sostenible de nueve especies de plantas del departamento del Amazonas, generadoras de productos maderables y no maderables. Instituto Amazónico de Investigaciones Científicas - SINCHI, Corporación para el Desarrollo Sostenible del Sur de la Amazonia - CORPOAMAZONIA, Ministerio de Ambiente, Vivienda y Desarrollo Territorial, Bogotá, Colombia.

Castillo, W.G. 2005. Propiedad colectiva, zonificación y ordenamiento territorial: estudio de caso en bosques inundables de aguaje (*Mauritia flexuosa*) en la comunidad nativa de Parinari, Loreto, Perú. Instituto de Investigaciones de la Amazonia Peruana, IIAP, Iquitos, Perú.

COMAPA "Veinte de Enero", ProNaturaleza, Dávila, E.G., Pereira, R.R.N., 2005. Plan de Manejo Forestal de *Mauritia flexuosa* "aguaje". COMAPA "Veinte de Enero", Iquitos, Perú.

Coomes, O.T., Barham, B.L., Takasaki, Y., 2004. Targeting conservation–development initiatives in tropical forests: Insights from analyses of rain forest use and economic reliance among Amazonian peasants. Ecol. Econom. 51, 47–64.
Coral, A.G., Reyna, G.M.T. 2010. Manual Cultivo de Aguaje. IIAP, Iquitos, Perú.
Courchamp, F., Dunne, J.A., Le Maho, Y., May, R.M., Thébaud, C., Hochberg, M.E., 2015. Fundamental ecology is fundamental. Trends Ecol. Evol. 30, 9–16.
Defler, T.R., 1979. On the ecology and behavior of *Cebus albifrons* in eastern Colombia: I. Ecology. Primates 20, 475–490.
Delgado, C., Couturier, G., 2003. Relationship between *Mauritia flexuosa* and Eupalamides. Palms 47, 104–106.
Delgado, C., Couturier, G., Mejia, K., 2007. *Mauritia flexuosa* (Arecaceae: Calamoideae), an Amazonian palm with cultivation purposes in Peru. Fruits 62, 157–169.
Draper, F.C., Roucoux, K.H., Lawson, I.T., Mitchard, E.T., Coronado, E.N.H., Lähteenoja, O., Montenegro, LT, Sandoval, EV, Zaráte, R, Baker, TR., 2014. The distribution and amount of carbon in the largest peatland complex in Amazonia. Environ. Res. Lett. 9, 124017.
Endress, B.A., Gorchov, D.L., Berry, E.J., 2006. Sustainability of a non-timber forest product: effects of alternative leaf harvest practices over 6 years on yield and demography of the palm *Chamaedorea radicalis*. Forest Ecol. Manag. 234, 181–191.
Endress, B.A., Horn, C.M., Gilmore, M.P., 2013. Mauritia flexuosa palm swamps: composition, structure and implications for conservation and management. Forest Ecol. Manag. 302, 346–353.
Ervik, F., 1993. Notes on the phenology and pollination of the dioecious palms *Mauritia flexuosa* (Calamoideae) and *Aphandra natalia* (Phytelephantoideae) in Ecuador. Animal–plant interactions in tropical environments 7–12.
Federman, S., Hyseni, C., Clement, W., Oatham, M.P., Caccone, A., 2014. Habitat fragmentation and the genetic structure of the Amazonian palm *Mauritia flexuosa* L.f. (Arecaceae) on the island of Trinidad. Conserv. Genet. 15, 355–362.
Filho, A.B.G., Lima, J.A.de S., 2001. O Buritizeiro (*Mauritia flexuosa* L.) E Seu Potencial de Utilização. Vol. 27. Documentos. Macapá, AP: EMBRAPA.
Fragoso, J., Huffman, J.M., 2000. Seed-dispersal and seedling recruitment patterns by the last neotropical megafaunal element in Amazonia, the tapir. J. Tropical Ecol. 16, 369–385.
Fraser, B. 2014. Project seeks to unlock the mysteries of Peru's peatlands. CIFOR. Forest News. March 11. (Accessed 19 February 2016).
Galeano, A., Urrego, L.E., Sánchez, M., Peñuela, M.C., 2015. Environmental drivers for regeneration of *Mauritia flexuosa* L.f. in Colombian Amazonian swamp forest. Aquatic Botany 123, 47–53.
Gilmore, M.P., Endress, B.A., Horn, C.M., 2013. The socio-cultural importance of *Mauritia flexuosa* palm swamps (aguajales) and implications for multi-use management in two Maijuna communities of the Peruvian Amazon. J. Ethnobiol. Ethnomed. 9, 1–23.
Giraldo, L.E.U., 1987. Estudio preliminar de la fenologia de la canangucha (*Mauritia flexuosa* L.F). Colombia Amazónica 2, 57–81.
Gomes, L.R.P., Lopes, M.T.G., da S. Bentes, J.L., Barros, W.S., Neto, C., de Queiroz, P., Contim, L.A.S., 2011. Genetic diversity in natural populations of Buriti (*Mauritia flexuosa* L.f.). Crop Breeding and Applied Biotechnology 11, 216–223.
González, J.A., 2003. Harvesting, local trade, and conservation of parrots in the northeastern peruvian amazon. Biol. Cons. 114, 437–446.
Gottsberger, G., 1978. Seed dispersal by fish in the inundated regions of Humaitá, Amazônia. Biotropica 10, 170–183.
Goulding, M., 1980. The Fishes and The forest: Exploration in Amazonian Natural History. University of California Press, Los Angeles, USA.
Goulding, M., Smith, N., 2007. Palms: Sentinels for Amazon Conservation. Missouri Botanical Garden Press, St. Louis, Missouri, USA.
Gragson, T.L., 1995. Pume exploitation of *Mauritia flexuosa* (Palmae) in the llanos of Venenzuela. J. Ethnobiology 15, 177–188.
Hada, A.R., Nelson, B.W., Alfaia, S.S., Hess, L.L., de Pinho, R.C., Pedreira, J.L., Perez, I.U. and Miller, R.P. 2013. Resource stock, traditional uses and economic potential of the buriti palm (*Mauritia flexuosa* L.f.) in wetlands of the Araça Indigenous Area, Roraima, Brazil. Published on the Internet: http://wazakaye.com.br (Accessed 9 February 2016).
Henderson, A., 1995. The Palms of the Amazon. Cambridge University Press, New York.
Henderson, A., Galeano-Garces, G., Bernal, R., 1995. Field Guide to the Palms of the Americas. Princeton University Press.
Hiraoka, M. 1999. Miriti (*Mauritia flexuosa*) palms and their uses and management among the ribeirinhos of the Amazon estuary. In: Padoch, C., Ayres, J.M., Pinedo-Vasquez, M., Henderson, A. (Eds), Várzea: Diversity, Development, and Conservation of Amazonia's Whitewater Floodplains. New York Botanical Garden, New York, NY, USA, pp. 169–186.
Holm, J.A., Miller, C.J., Cropper, W.P., 2008. Population dynamics of the dioecious Amazonian palm *Mauritia flexuosa*: simulation analysis of sustainable harvesting. Biotropica 40, 550–558.
Horn, C.M., Gilmore, M.P., Endress, B.A., 2012. Ecological and socio-economic factors influencing aguaje (*Mauritia flexuosa*) resource management in two indigenous communities in the Peruvian Amazon. Forest Ecol. Manag. 267, 93–103.
Householder, J.E., Janovec, J.P., Tobler, M.W., Page, S., Lähteenoja, O., 2012. Peatlands of the madre de dios river of Peru: distribution, geomorphology, and habitat diversity. Wetlands 32, 359–368.
IBGE—Brazilian Institute of Geography and Statistics, 2012. Production of vegetal extraction and silvaculture 2004–2011. IBGE. Available from http://www.ibge.gov.br/estadosat/.
Isaza, C., Bernal, R., Howard, P., 2013. Use, production and conservation of palm fiber in South America: A review. J. Human Ecol. 42 (1), 69–93.
Janovec J.P., Householder E., Tobler M., Valega R., Von May R., Araujo J., Zelski S., Shearer C., Jiménez M., Wells J., Chambi B., Herrara F., de Janovec M.P.Q. 2013. Humedales de Madre de Dios, Perú: Impactos y amenazas en aguajales y cochas. WWF, Lima, Perú.
Janssen, W., Goldsworthy, P., 1996. Multidisciplinary research for natural resource management: conceptual and practical implications. Agricult. Syst. 51, 259–279.
Kahn, F., 1988. Ecology of economically important palms in Peruvian Amazonia. Adv. Econ. Botany 6, 42–49.
Kahn, F., 1991. Palms as key swamp forest resources in Amazonia. Forest Ecol. Manag. 38, 133–142.
Khorsand Rosa, R., Barbosa, R.I., Koptur, S., 2013. How do habitat and climate variation affect phenology of the Amazonian palm, *Mauritia flexuosa*? J. Trop. Ecol. 29, 255–259.
Khorsand Rosa, R., Barbosa, R.I., Koptur, S., 2014. Which factors explain reproductive output of *Mauritia flexuosa* (Arecaceae) in forest and savanna habitats of Northern Amazonia? Int. J. Plant Sci. 175, 307–318.
Khorsand Rosa, R., Koptur, S., 2013. New findings on the pollination biology of *Mauritia flexuosa* (Arecaceae) in Roraima, Brazil: Linking dioecy, wind, and habitat. Am. J. Bot. 100, 13–621.
Knudsen, J.T., Tollsten, L., Ervik, F., 2001. Flower scent and pollination in selected neotropical palms. Plant Biol. 3, 642–653.
Kunz, T.H., McCracken, G.F., 1996. Tents and harems: apparent defense of foliage roosts by tent-making bats. J. Trop. Ecol. 12, 121–137.
Lähteenoja, O., Reátegui, Y.R., Räsänen, M., Torres, D.D.C., Oinonen, M., Page, S., 2012. The large Amazonian peatland carbon sink in the subsiding Pastaza-Marañón foreland basin, Peru. Global Change Biol. 18, 164–178.
Lähteenoja, O., Ruokolainen, K., Schulman, L., Oinonen, M., 2009. Amazonian peatlands: an ignored C sink and potential source. Global Change Biol. 15, 2311–2320.
Lees, A.C., Peres, C.A., 2008. Conservation value of remnant riparian forest corridors of varying quality for Amazonian birds and mammals. Conserv. Biol. 22, 439–449.
Lehner, B., Grill, G., 2013. Global river hydrography and network routing: Baseline data and new approaches to study the world's large river systems. Hydrol. Process. 27, 2171–2186.

de Lima, N.E., Lima-Ribeiro, M.S., Tinoco, C.F., Terribile, L.C., Collevatti, R.G., 2014. Phylogeography and ecological niche modelling, coupled with the fossil pollen record, unravel the demographic history of a Neotropical swamp palm through the Quaternary. J. Biogeogr. 41, 673–686.
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., et al., 2007. Complexity of coupled human and natural systems. Science 317 (5844), 1513e1516.
Lopez-Toledo, L., Anten, N.P., Endress, B.A., Ackerly, D.D., Martínez-Ramos, M., 2012. Resilience to chronic defoliation in a dioecious understorey tropical rain forest palm. J. Ecol. 100, 1245–1256.
Macedo, R.H., 2002. The avifauna: ecology, biogeography, and behavior. In: Oliveira, P.S., Marquis, R.J. (Eds.), The Cerrados of Brazil: Ecology and Natural History of a Neotropical Savanna. Columbia University Press, New York, USA, pp. 242–265.
Manuel, J., Fragoso, V., 1999. Perception of scale and resource partitioning by peccaries: behavioral causes and ecological implications. J. Mammal. 80, 993–1003.
Manzi, M., Coomes, O., 2009. Managing Amazonian palms for community use: a case of aguaje palm (*Mauritia flexuosa*) in Peru. Forest Ecol. Manag. 257 (2), 510–517.
Marimon, B.S., Felfili, J.M., Lima, E.S., 2002. Floristics and phytosociology of the gallery forest of the Bacaba Stream, Nova Xavantina, Mato Grosso, Brazil. Edinb. J. Bot. 59, 303–318.
Marimon, B.S., Felfili, J.M., Lima, E.S., Duarte, W.M.G., Marimon-Júnior, B.H., 2010. Environmental determinants for natural regeneration of gallery forest at the Cerrado/Amazonia boundaries in Brazil. Acta Amazonica 40, 107–118.
Marín, E.A. 2008. Plan de negocio del aguaje comunidad nativa Parinari. IIAP, Iquitos, Perú.
Martínez-Ballesté, A., Martorell, C., 2015. Effects of harvest on the sustainability and leaf productivity of populations of two palm species in maya homegardens. PLoS One 10:e0120666.
Martins, R.C., Filgueiras, T.S., de Albuquerque, U.P., 2012. Ethnobotany of *Mauritia flexuosa* (Arecaceae) in a maroon community in central Brazil. Econ. Bot. 66, 91–98.
Mauricio, A.G., Arevalo, J.J.P., 2001. Diagnóstico de la demanda de *Mauritia flexuosa* L.f. aguaje, en la ciudad de Iquitos. IIAP, Iquitos, Perú.
McKinnon, M.C., Cheng, S.H., Garside, R., Masuda, Y.J., Miller, D.C., 2015. Map the evidence. Nature 528, 185.
Mendieta-Aguilar, G., Pacheco, L.F., Roldán, A.I., 2015. Dispersión de semillas de *Mauritia flexuosa* (Arecaceae) por frugívoros terrestres en Laguna Azul, Beni, Bolivia. Acta Amazonica 45, 45–56.
Mesa, L., Galeano, G., 2013. Palms uses in the Colombian Amazon. Caldasia 35 (2), 351–369.
Montaña, C.G., Layman, C.A., Taphorn, D.C., 2008. Comparison of fish assemblages in two littoral habitats in a neotropical morichal stream in Venezuela. Neotropical Ichthyol. 6, 577–582.
Moskovits, D.K., Bjorndal, K.A., 1990. Diet and food preferences of the tortoises *Geochelone carbonaria* and *G. denticulata* in northwestern Brazil. Herpetologica 207–218.
Motta-Junior, J.C., Granzinolli, M.A.M., Monteiro, A.R., 2010. Miscellaneous ecological notes on brazilian birds of prey and owls. Biota Neotropica 10, 255–259.
Padoch, C., 1988. Aguaje (*Mauritia flexuosa* L.f.) in the economy of Iquitos, Peru. Adv. Econ. Botany 6, 214–224.
Padoch, C., 1992. Marketing of non-timber forest products in western amazonia: General observations and research priorities. In: Nepstad, D., Schwartzman, S. (Eds.), Advances in Economic Botany, Vol. 9. New York Botanical Gardens, New York.
Palminteri, S., Powell, G.V., Peres, C.A., 2012. Advantages of granivory in seasonal environments: feeding ecology of an arboreal seed predator in Amazonian forests. Oikos 121, 1896–1904.
Penn, J.W., 1999. The aguaje palm (*Mauritia flexuosa* L.f.): examining its role as an agroforestry species in a community conservation project (thesis), University of Florida, Gainesville, FL.
Penn, J.W., 2008. Non-timber forest products in Peruvian Amazonia : Changing patterns of economic exploitation. FOCUS on Geography 51 (2), 18–25.
Peres, C.A., 1994. Composition, density, and fruiting phenology of arborescent palms in an Amazonian terra firme forest. Biotropica 26, 285.
Perez-Eman, J.L., Paolillo, O., 1997. Diet of the pelomedusid turtle *Peltocephalus dumerilianus* in the Venezuelan Amazon. J. Herpetology 31, 173.
Peters, C.M., Balick, M.J., Kahn, F., Anderson, A.B., 1989. Oligarchic forests of economic plants in Amazonia : utilization and conservation of an important tropical resource. Conserv. Biol. 3, 341–349.
Pontes, A.R.M., 1997. Habitat partitioning among primates in Maracá Island, Roraima, northern Brazilian Amazonia. Int. J. Primatology 18, 131–157.
Pontes, A.R.M., Chivers, D.J., 2002. Abundance, habitat use and conservation of the olingo Bassaricyon sp. in Maracá ecological station, Roraima, Brazilian Amazonia. Studies on Neotropical Fauna and Environment 37, 105–109.
Porro, R., Lopez-Feldman, A., Vela-Alvarado, J.W., Quiñonez-Ruíz, L., Seijas-Cardenas, Z.P., Vásquez-Macedo, M., Salazar-Arista, C., Núñez-Paredes, V.I., Cardenas-Ruiz, J., 2014. Forest use and agriculture in Ucayali, Peruvian Amazon: Interactions among livelihood strategies, income and environmental outcomes. Tropics 23 (2), 47–62.
Pullin, A., Bowler, D., Buyung-Ali, L., Healey, J., Jones, J., Knight, T., Sinclair, F., 2009. The evidence base for community forest management as a mechanism for supplying global environmental benefits and improving local welfare. CEE protocol 08-011 (SR48). Collaboration for Environmental Evidence: www.environmentalevidence.org/SR48.html.
Renton, K., 2002. Seasonal variation in occurrence of macaws along a rainforest river. J. Field Ornithology 73, 15–19.
Renton, K., Brightsmith, D.J., 2009. Cavity use and reproductive success of nesting macaws in lowland forest of southeast Peru. J. Field Ornithology 80, 1–8.
Resende, I.L.de M., dos Santos, F.P., Chaves, L.J., do Nascimento, J.L., 2012. Estrutura etária de populações de *Mauritia flexuosa* L.f. (Arecaceae) de veredas da região central de Goiás, Brasil. Revista Árvore 36, 103–112.
Ribeiro, A.H., 2010. O buriti (*Mauritia flexuosa* L.f.) na terra indígena Araçá, Roraima: usos tradicionais, manejo e potencial produtivo (Dissertation), Instituto Nacional de Pesquisas da Amazônia, Manaus, Brazil.
Ribeiro, E.M.G.da A., Baptistel, A.C., Neto, E.M.F.L., Monteiro, J.M., 2014. Conhecimento etnobotânico sobre o buriti (*Mauritia flexuosa* L.f.) em comunidades rurais do município de Currais, Sul do Piauí, Brasil. Revista Gaia Scientia, Special Edition Traditional Populations 28–35.
Richards, M., 1993. The potential of non-timber forest products in sustainable natural forest management in Amazonia. Commonwealth Forestry Review 72 (1), 21–27.
Rivadeneyra, M.G., 1975. Estudio sobre la densidad de poblaciones de aguaje (Mauritia sp.) en tingo maria-peru. Revista Forestal del Peru 5, 1–11.
Rodrigues, P., Borges, M., Melo, C., 2012. Riqueza, composición y detectabilidad de los psittacidae (aves) en tres pantanos del cerrado sensu lato en el Brasil central. Rev. Chil Hist. Natural 85, 171–178.
Ruiz, R.R., Jarama, C.F.S., Flores, C.L., Sias, C.R., Vásquez, J.O., Isuiza, V.M., Luque, H., Salinas, J.S.R., Noriega, D.T., de María Panduro, F., 2001a. Industrialización primaria del aguaje (*Mauritia flexuosa* L.f.) en Iquitos (Perú). Folia Amazónica 12 (1–2), 107–121.
Ruiz, R.R., Panduro, G.R., Meléndez, P.R., Salazar, C.F., Jarama, C.R.S., Flores, C.L., Ríos, C.M., Torres, D., Noriega, J.O.V., Alván, W.S., Isuiza, V.M., Salinas, H.L., Gonza, N.V., Fasabi, N.del C., Ruiz, J.S., de Oliveira, R.L., Ruiz, F.de M.P., 2001b. Comercialización de masa y fruto verde de aguaje (*Mauritia flexuosa* L.f.) en Iquitos (Perú). Folia Amazónica 12 (1–2), 15–38.
Rutger, H. 2008. After acai, what is Amazon's next cinderella fruit? National Geographic. Published on the Internet. http://news.nationalgeographic.com/news/2008/10/081014-amazon-fruit-missions.html (Accessed 9 February 2016).

Sampaio, M.B., dos Santos, F.A., 2015. Harvesting of palm fruits can be ecologically sustainable: a case of buriti (*Mauritia flexuosa*; Arecaceae) in Brazil. In: Shackleton, C.M., Pandey, A.K., Ticktin, T. (Eds.), Ecological sustainability for non-timber forest products: dynamics and case studies of harvesting, Routledge, London, England, pp. 73–89.
Sampaio, M.B., Figueiredo, I.B., Sano, P.T., 2010. Boas praticas de manejo para o extrativismo sustentavel do capim-dourado & buriti. Embrapa Recursos Genéticos e Biotecnologia, Brasília, Brazil.
Sampaio, M.B., Schmidt, I.B., Figueiredo, I.B., 2008. Harvesting effects and population ecology of the buriti palm (*Mauritia flexuosa* L.f., Arecaceae) in the Jalapão Region, Central Brazil. Econ. Botany 62, 171–181.
Sampaio, M.B., Ticktin, T., Seixas, C.S., dos Santos, F.A.M., 2012. Effects of socioeconomic conditions on multiple uses of swamp forests in central Brazil. Hum. Ecol. 40 (6), 821–831.
San-José, J., Mazorra, M.A., Mathaly, M., 2010. Heterogeneity of the inland water–land palm ecotones (morichals) in the orinoco lowlands. South Amer. Plant Ecol. 208, 259. http://dx.doi.org/10.1007/s11258-009-9703-3.
Sánchez, A.Y.B. 2004. Plan de manejo del bosque comunal, Comunidad Campesina Roca Fuerte, Río Marañón. Centro para el Desarrollo del Indigena Amazonico (CEDIA), Perú.
Santana, R.F., Ochoa, J.V., Vega, A.A.S., Ponte, M.X., 2008. Manejo de Aguaje (buriti) na Comunidade de Parinari-Reserva Nacional Pacaya Samiria na Região de Loreto no Peru: uma proposta de pagamento por serviço ambiental carbono. In: IV Encontro Nacional Da Anppas, Brasilia, Brazil.
Santos, I.N.L., da Silva, M.de F.V., 2012. Saberes da tradição na produção de brinquedos de miriti-patrimônio cultural. Revista Educação, Cultura e Sociedade 2(2).
Santos, R.da S., Coelho-Ferreira, M., 2011. Artefatos de miriti (*Mauritia flexuosa* L.f.) em Abaetetuba, Pará: da produção à comercialização Miriti artifacts (*Mauritia flexuosa* L.f.) in Abaetetuba, Pará State, Brazil: from production to marketing. Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas 6 (3), 559–571.
Santos, R.da S., Coelho-Ferreira, M., 2012. The ethnobotanical study of *Mauritia flexuosa* L. f.(Arecaceae) in riverine communities of Abaetetuba county, Pará state, Brazil. Acta Amazonica 42 (1), 1–10.
Saraiva N.A., 2009. Manejo sustentável e potencial econômico da extração do Buriti nos Lençóis Maranhenses, Brasil. Thesis, University of Brasilia, Brasilia, Brazil.
Saraiva, N.A., Sawyer, D., 2007. Análise do potencial econômico e socioambiental do artesanato do buriti em comunidades tradicionais nos Lençóis Maranhenses. VII Encontro da Sociedade Brasileira de Economia Ecológica. Fortaleza, CE, Brazil.
Shackleton, C., Shackleton, S., 2004. The importance of non-timber forest products in rural livelihood security and as safety nets: a review of evidence from South Africa. South Afr. J. Sci. 100, 658–664.
Silva, R.S., Ribeiro, L.M., Mercadante-Simões, M.O., Nunes, Y.R.F., Lopes, P.S.N., 2014. Seed structure and germination in buriti (*Mauritia flexuosa*), the Swamp palm. Flora-Morphology, Distribution. Funct. Ecol. Plants 209, 674–685.
da Silva, C.do S.Q., Carvalho, N.C., 2012. A cultura e a educação amazônica na arte dos brinquedos de miriti. Eccos Revista Científica 27 (Jan-Apr), 17–32.
da Silva, L.M., Pontes, A.N., Batalha, S.S.A., da Silva, L.M., 2013. Manifestação cultural no círio de Nazaré, Belém, Pará: A contribuição socioeconômica dos brinquedos de miriti na valorização do artesanato local. Enciclopedia Biosfera 9 (17), 3584–3593.
Smith, N., 2015. *Mauritia flexuosa*. In: Palms and People in the Amazon, Springer, pp. 341–381. Available from http://link.springer.com/chapter/10.1007/978-3-319-05509-1_47 (Accessed 25 October 2014).
Sousa, M.R.S., Sousa, A.J., 2007. Vestígios artesanais na biodiversidade e plasticidade do Buriti. II Congresso de Pesquisa e Inovação da Rede Norte Nordeste de Educação Tecnológica. CONNEPI, João Pessoa, PB, Brazil.
Spera, M.R.N., da Cunha, R., Teixeira, J.B., 2001. Quebra de dormência, viabilidade e conservação de sementes de buriti (*Mauritia flexuosa*). Pesquisa Agropecuária Brasileira 36, 1567–1572.
Storti, E.F., 1993. Biologia floral de *Mauritia flexuosa* Lin. Fil, na região. Acta Amazónica 23, 371–381.
ter Steege, H., et al., 2013. Hyperdominance in the Amazonian tree flora. Science 342, 1243092.
Ticktin, T., 2004. The ecological implications of harvesting non-timber forest products. J. Appl. Ecol. 41, 11–21.
Ticktin, T., Shackleton, C., 2011. Harvesting non-timber forest products sustainably: opportunities and challenges. In: Non-timber forest Products in The Global Context. Springer, pp. 149–169.
Tobler, M.W., Janovec, J.P., Cornejo, F., 2010. Frugivory and seed dispersal by the lowland Tapir *Tapirus terrestris* in the Peruvian Amazon: lowland tapir seed dispersal in Peru. Biotropica 42, 215–222.
Torres, D. del C., Acevedo, E.O., Alvarado, L.F., 2006. Instituto de Investigacion de la Amazonía Peruana. Aguaje: La maravillosa palmera de la Amazonía/Aguaje: The amazing palm tree of the Amazon. Instituto de Investigaciones de la Amazonía Peruana, Loreto, Perú.
UN-REDD, 2016. What Is REDD+? *UN-REDD Programme*. http://www.unredd.net/about/what-is-redd-plus.html (Accessed 24 October 2016).
USGS, 1996. 30 arc-second DEM of South America.
Vargas, R., Loescher, H.W., Arredondo, T., Huber-Sannwald, E., Lara-Lara, R., Yépez, E.A., 2012. Opportunities for advancing carbon cycle science in mexico: toward a continental scale understanding. Environ. Sci. Policy 21, 84–93.
Vegas-Vilarrúbia, T., Baritto, F., López, P., Meleán, G., Ponce, M.E., Mora, L., Gómez, O., 2010. Tropical histosols of the lower orinoco delta, features and preliminary quantification of their carbon storage. Geoderma 155 (3), 280–288.
Villalobos, M.P., Bagno, M.A., 2013. Avian frugivores feeding on *Mauritia flexuosa* (Arecaceae) fruits in Central Brazil. Revista Brasileira de Ornitologia-Brazilian Journal of Ornithology 20, 4.
Virapongse, A., 2013. Forest Products for Subsistence and Markets: Livelihood Systems and Value Chains of Buriti (*Mauritia flexuosa*) in Brazil. University of Florida, Gainesville, FL, USA.
Virapongse, A., Brooks, S., Metcalf, E.C., Zedalis, M., Gosz, J., Kliskey, A., Alessa, L., 2016. A social ecological systems approach for environmental management. Environ. Manag.. http://dx.doi.org/10.1016/j.jenvman.2016.02.028.
Virapongse, A., Schmink, M., Larkin, S., 2014. Value chain dynamics of an emerging palm fiber handicraft market in Maranhão, Brazil. Forests, Trees and Livelihoods 23, 36–53.
Willink, P.W., Chernoff, B., Alonso, L.E., Montambault, J.R., Lourival, R. (Eds.), 2000. A rapid assessment of the aquatic ecosystems of the Pantanal, Mato Grosso do Sul, Brasil. RAP Bulletin of Biological Assessment 18. Conservation International, Washington D.C., USA.
Zuidema, P.A., de Kroon, H., Werger, M.J., 2007. Testing sustainability by prospective and retrospective demographic analyses: evaluation for palm leaf harvest. Ecol. Appl. 17, 118–128.