



ELSEVIER

Forest Ecology and Management 167 (2002) 251–262

Forest Ecology  
and  
Management

www.elsevier.com/locate/foreco

# Harvesting of *Geonoma macrostachys* Mart. leaves for thatch: an exploration of sustainability

Jens-Christian Svenning<sup>a,\*</sup>, Manuel J. Macía<sup>b</sup>

<sup>a</sup>Department of Systematic Botany, University of Aarhus, Nordlandsvej 68, DK-8240 Risskov, Denmark

<sup>b</sup>Real Jardín Botánico, Plaza de Murillo 2, E-28014 Madrid, Spain

Received 4 April 2001; accepted 5 August 2001

## Abstract

Palm leaves are an important source of roof thatch for rural communities in many parts of the tropics. Often leaves are harvested from wild populations, and as a non-timber forest product may promote local commitment to forest conservation. Nevertheless, reports suggest that at least some wild populations are declining due to over-harvesting. In Amazonian Ecuador the understory palm *Geonoma macrostachys* Mart. is often the preferred species for thatching. Here we explore the limits to sustainable harvesting of this species combining ethnobotanical data on the use of this species by the Huaorani indigenous group with ecological data and transition matrix modeling. We find that due to severe light limitation there seems to be little scope for sustainable harvesting of this species from old-growth forest. Instead high rates of sustainable harvesting could probably be achieved in semi-open anthropogenic habitats, e.g. agroforestry systems or young secondary forests. We also find that harvesting scheme has a strong impact on sustainable harvesting rates; if only adults (leaf length 100–223 cm) are harvested, while subadults (leaf length 35–99 cm) are left unharvested, two to three times as much leaf material can be harvested per area (at a fixed density) as when subadults are also harvested. © 2002 Elsevier Science B.V. All rights reserved.

**Keywords:** Extractivism; Non-timber forest products; Palm leaves; Sustainable management; Transition matrix analysis; Tropical rain forest

## 1. Introduction

Palms constitute one of the most important plant families for rural people of many parts of the humid tropics (e.g. Balick, 1988; Kahn and de Granville, 1992; Pedersen and Balslev, 1992). Palms supply food, beverages, fibers, thatch, house construction materials, medicine, domestic artifacts and handicrafts as well as numerous other minor products

(e.g. Balslev and Barfod, 1987; Balick, 1988; Kahn and de Granville, 1992; Pedersen and Balslev, 1992; Pedersen, 1996; Macía, 1999). Palm leaves are used for roof thatch throughout the tropics (e.g. Balick, 1988; Kahn and de Granville, 1992; Ratsirarson et al., 1996). In Amazonia the leaves of abundant understory palms, notably *Geonoma* spp., *Hyospathe elegans*, and *Lepidocaryum tenue* are often used for thatching (Boom, 1988; Mejia, 1988; Parodi, 1988; Kahn and de Granville, 1992; Rioja, 1992; Flores and Ashton, 2000; Zuidema, 2000). Thus, in Amazonia and other parts of the humid tropics native palms provide materials for non-commercial or low-cost, good quality rural housing (e.g. Parodi, 1988; Gomez et al., 1996; Flores and Ashton, 2000). While such

\* Corresponding author. Present address: Unit 0948, Smithsonian Tropical Research Institute, APO AA 34002-0948, USA.

Tel.: +1-507-276-6252; fax: +1-507-276-6823.

E-mail addresses: svenning@biology.au.dk (J.-C. Svenning), mmacia@ma-rjb.csic.es (M.J. Macía).

extractivism may promote local commitment to forest conservation, harvesting of non-timber forest products may not always be ecologically sustainable (e.g. Hall and Bawa, 1993; Phillips, 1997). Specifically, it has been reported that certain Amazonian palm populations are being depleted by over-harvesting of various plant parts (Davis and Yost, 1983; Kahn and de Granville, 1992; Pedersen and Balslev, 1992; Rioja, 1992; Flores and Ashton, 2000; Zuidema, 2000). While this over-harvesting is often associated with modern commercial exploitation (Pedersen and Balslev, 1992; Rioja, 1992; Flores and Ashton, 2000; Zuidema, 2000), indigenous over-harvesting of local populations of preferred palm species also occurred before the advent of Western civilization (Davis and Yost, 1983). Large amounts of leaf material are needed for thatching; e.g. 39,000 *L. tenue* leaves for a 6 m × 9 m house in the Peruvian Amazon (Parodi, 1988), 1250–1500 kg of *Geonoma supracostata* (as *G. aff. macrostachys*) leaves for a 10 m × 10 m house in the Ecuadorian Amazon (Gomez et al., 1996), and 1000 *G. deversa* leaves per square meter of roof in Bolivia (Zuidema, 2000). It is easy to imagine that such leaf harvesting might well not always be sustainable, as has indeed been reported for *G. supracostata* (as *G. aff. macrostachys*) and *G. deversa*. Both species have reported to be locally disappearing due to over-exploitation (Rioja, 1992; Gomez et al., 1996). Given the generally increasing rural population sizes and decreasing or static forest area available to many rural populations in the tropics, assessing the limits to ecologically sustainable harvesting of palms and other native plants and developing harvesting schemes with minimum ecological impact are clearly relevant (cf. Zuidema, 2000).

Here, we will explore the limits to ecologically sustainable harvesting of *G. macrostachys* var. *macrostachys* leaves for thatch in the Ecuadorian Amazon. Geonomoid palms, especially *Geonoma* spp., but also *Pholidostachys synanthera*, are used for thatch throughout Amazonia (Wessels Boer, 1968; Balslev and Barfod, 1987; Mejia, 1988; Parodi, 1988; Henderson, 1995). In the Ecuadorian Amazon *G. macrostachys* or the closely related *G. supracostata* are used for thatch by most indigenous groups, often being the preferred species: Huaorani (Cerón and Montalvo, 1998; Macía, 1999), Achuar (Borchsenius et al., 1998), Cofán (Cerón et al., 1994; Cerón, 1995),

Quichua (Cerón, 1993; Gomez et al., 1996; Balslev et al., 1997), Shuar (Gomez et al., 1996), and Siona-Secoya (Borchsenius et al., 1998). The leaves are even commercialized on markets where they are sold for US\$ 5–6.5 (1996) per 25–30 kg, thereby also being a source of cash income (Gomez et al., 1996). The species also have several minor uses: the leaves are used as umbrellas and for packaging, (Cerón, 1993, 1995; Cerón et al., 1994; Borchsenius et al., 1998; Cerón and Montalvo, 1998; Macía, 1999), and the palm heart is used in local folklore (Borchsenius et al., 1998). Here, we combine ethnobotanical data on the amount of leaves needed for thatching with ecological data on the density and demography of this species to estimate the maximum ecologically sustainable harvesting intensity. As a further, but necessary sophistication, we also investigate how human modification of forest structure might affect the sustainability limits.

## 2. Study area and methods

### 2.1. Study area

We conducted fieldwork in Amazonian Ecuador (Fig. 1). Ecological and demographical data were collected at the Yasuní Scientific Station (0°40'S; 76°23'W) in the Yasuní National Park. The climate is equatorial wet and the vegetation is mainly old-growth lowland tropical rain forest (Svenning, 1999), although some parts of the forest have been disturbed by past or present human use (Macía and Svenning, personal observation; Netherly, 1997). Further information can be found in Romoleroux et al. (1997) and Svenning (1999, in press). The Huaorani is the indigenous ethnic group traditionally living in the study area (Davis and Yost, 1983; Basaglia, 1991; Yost, 1991; Rival, 1996; Smith, 1996; Macía, 1999). Ethnobotanical information was gathered in the Huaorani communities Dicaro (0°56'S; 76°12'W) and Tiputini (0°36'S; 76°27'W) in the Huaorani Ethnic Reserve and Yasuní National Park, respectively, as well as in the Omaere Ethnobotanical Park (Puyo, Pastaza province 1°30'S; 77°59'W).

### 2.2. Description of the species

The study species was the understory palm *G. macrostachys* Mart., which is widespread and

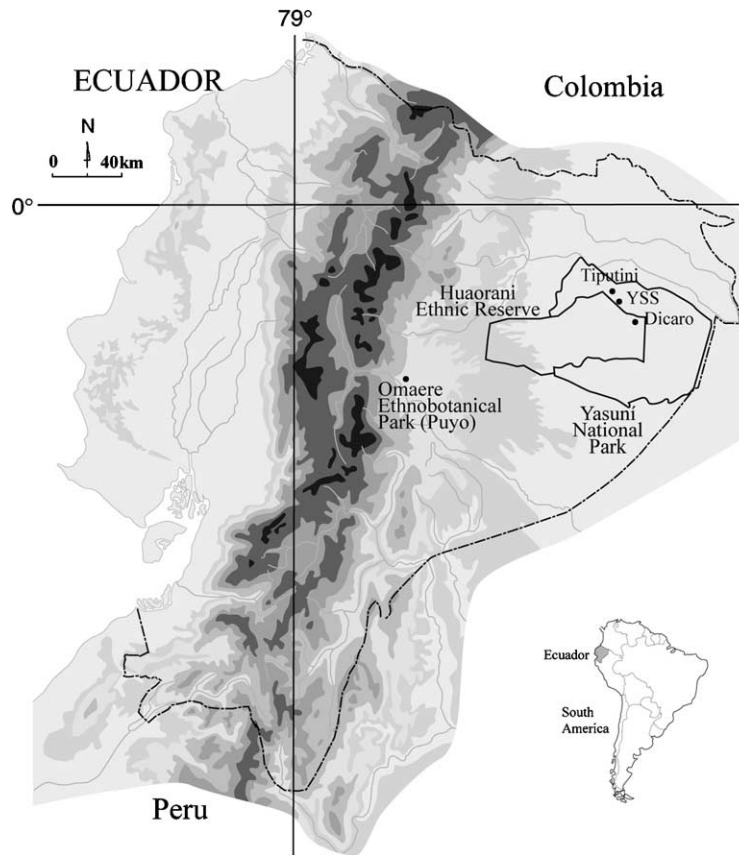


Fig. 1. Map of Ecuador showing the location of the Yasuní National Park, the Huaorani Ethnic Reserve, and our study areas: the Yasuní Scientific Station (YSS), the Huaorani communities Tiputini and Dicaro, and the Omaere Ethnobotanical Park. The shading indicates 500 m altitudinal limits.

abundant in Amazonian Ecuador as well as throughout the rest of Amazonia (Henderson, 1995; Borchsenius et al., 1998). This species includes several sympatric morphological varieties (Henderson, 1995; Borchsenius et al., 1998), some of which appear to be distinct biological species (Svenning, personal observation). Consequently, we restricted the study to *G. macrostachys* var. *macrostachys* (hereafter *G. macrostachys*). Even this variety is quite morphologically variable (Macía and Svenning, personal observation). The variety for which we collected demographic data had a short underground stem and usually a single rosette of up to 22 bifid leaves, each being up to ca. 2.5 m in length (Svenning, in press). Longevity is >65 years (Svenning, unpublished data). Flowering and fruiting occur throughout the year, and the fruits are eaten by gray-winged Trumpeters (*Psophia crepitans*)

and probably also smaller birds (Svenning and Macía, unpublished data; Borchsenius et al., 1998). *G. macrostachys* is abundant with 190–220 adults/ha in the upland forests of the Yasuní National Park (Svenning, in press; Hall and Balslev, personal communication). A demographic study based on 866 seedlings and 1726 larger individuals have quantified the population-level effect of microenvironmental heterogeneity on the demography of *G. macrostachys* in old-growth forest at the study site (Svenning, in press). This study found that although *G. macrostachys* is shade tolerant, its growth and fecundity are light limited and this light limitation is strong enough to control its population performance.

The traditional Huaorani houses are typically 10–20 m long, 6–10 m wide, and 4–7 m high, each housing 15–25 people, and palm leaves are always

used for thatching (Basaglia, 1991; Macía, personal observation). The roof is thatched with an outer layer of large palm leaves (mainly *Attalea butyracea*, *Oenocarpus bataua*, or *Phytelephas tenuicaulis*) and an inner layer of smaller palm leaves. *G. macrostachys* is the species most used for this inner thatch, but other *Geonoma* spp. are used when there is shortage of *G. macrostachys* leaves (Macía, personal observation). The Huaorani ethnic group harvest *G. macrostachys* leaves in two ways (Macía, personal observation): for thatching, they cut all the leaves of a plant, killing the plant in the process, while for packaging and other domestic uses some leaves are always left on the plant. Leaves are cut with a machete and transported to the community for immediate use. Leaves are harvested from both subadults and adults (Table 1). At present, zinc plates are sometimes replacing palm leaves as roofing.

### 2.3. Quantification of indigenous use of *G. macrostachys* thatch

Traditionally a Huaorani community was constituted of two or three houses and ca. 30–40 people (Rival, 1996; Yost, 1991), but today communities are generally larger with an average of 50–70 people (Smith, 1996) and thus at least four houses. Three traditional Huaorani houses, one at each ethnobotanical site, were measured and the total number of *G. macrostachys* leaves used for thatch estimated. In the community of Tiputini, we also participated in the

construction of a new Huaorani house, following all steps in the construction process from the initial harvesting of the construction materials onwards. From these observations and information on the durability of the Huaorani houses (1–3 years; Macía, personal observation), we were able to calculate the amount of leaf material that a typical Huaorani community would need each year.

### 2.4. Demographic limits to sustainable harvesting

Demographic field data were collected in old-growth upland forest (for a detailed description, see Svenning (in press)). The demographic behavior of a total of 866 seedlings and 1726 larger individuals, all permanently marked and mapped, was recorded by a first census in January–May 1997 and a second census in September–October 1998. The size of each individual was described by its maximum leaf length (rachis length), which is highly correlated with whole-plant leaf area ( $r = 0.99$ ) and apical stem diameter ( $r = 0.97$ ) (Svenning, in press). Size classes are defined in Table 1. Apart from the demographic data, data on the canopy environment of each individual was also recorded: (1) the forest phase of the 20 m × 20 m subplot in which the individual was located and (2) the crown illumination index of each individual (Svenning, in press). Forest phase could be mature, having no major gap and an average canopy height >20 m in both years, or immature. Individuals with low crown illumination were at most exposed to a single, small lateral gap in the canopy, while individuals with medium/high illumination were exposed to more and/or larger gaps (Svenning, in press). From these demographic and environmental data several transition matrices were constructed (see Svenning (in press) for details), three of which are used as the basis of the demographic analyses in this paper: a matrix based on all individuals ( $n = 2497$ ), a matrix based on only those individuals that were located in immature forest-phase plots in at least one of the years ( $n = 1181$ ), and a matrix based on individuals with medium/high illumination in at least one of the years ( $n = 688$ ). Transition matrix models have frequently been used to evaluate the ecological sustainability of harvesting of non-timber forest products (e.g. Pinard and Putz, 1992; Ratsirarson et al., 1996; Bernal, 1998; Zuidema, 2000).

Table 1  
Stage class criteria for *G. macrostachys* for the 10 stages in the demographic transition matrices that were used to estimate population growth rate (Yasuní, Ecuador)

Stage	Substage	Maximum leaf length (cm)	Fertile
Seedling	Small	1–6	Never
	Large	7–9	Never
Juvenile	–	10–34	Never
Subadult (sa)	sa1	35–66	Very rarely
	sa2	67–99	Rarely
Adult (ad)	ad1	100–124	Often
	ad2	125–149	Often
	ad3	150–174	Often
	ad4	175–199	Often
	ad5	200–223	Often

To explore the possibilities for sustainable harvesting of *G. macrostachys* we performed simulations of a range of harvesting intensities under two different harvesting schemes in three habitat types. The two harvesting schemes were (1) only adults were harvested or (2) both subadults and adults were harvested. Different harvesting intensities were simulated by multiplying the stasis, regression, and progression rates of the harvested stages with a constant  $1 - i$  ranging from 0.00, 0.01 to 1.00. Thus,  $i$  is the proportional decrease in the overall survival rate due to harvesting, i.e. the harvesting intensity. Since the population growth rate of *G. macrostachys* depends on forest phase and crown illumination (Svenning, in press), we explored the effect of harvesting in three habitat types—(1) old-growth: the matrix based on all individuals; (2) disturbed forest: the matrix based on only those individuals that were located in immature forest-phase plots in at least 1 year; (3) semi-open: the matrix based on individuals with medium/high illumination in at least 1 year. The disturbed forest habitat is meant to approximate an environment similar to the disturbed old-growth forest around the Huaorani villages, while the semi-open habitat should simulate the more closed part of the Huaorani home gardens or similar agroforestry conditions.

In this paper we consider harvesting to be ecologically sustainable if it does not lead to a population decline, i.e. if it allows the population growth rate ( $\lambda$ ) to be at least 1.0 (for a further discussion, cf. Hall and Bawa, 1993; Zuidema, 2000). As  $\lambda$  for the complete observed population was 0.999 and the associated 95% bootstrap percentile confidence interval was (0.983; 1.014) (Svenning, in press), we judge harvesting to be sustainable when  $\lambda \geq 0.983$  and strictly sustainable when  $\lambda \geq 1.000$ . The maximum sustainable harvesting intensity ( $i_s$ ) is the maximum value of  $i$  that allows  $\lambda \geq 0.983$ , while the maximum strictly sustainable harvesting intensity ( $i_{ss}$ ) is the maximum value of  $i$  that allows  $\lambda \geq 1.000$ . The proportion of the individuals in a stage that are harvested for a given  $i$ ,  $H(i)$ , is calculated as the sum of the stasis, growth, and retrogression rates of the stage multiplied by  $i$ .

### 2.5. Sustainability requirements for harvesting of *G. macrostachys* thatch

We measured the size and recorded the condition of all leaves on 16 individuals ranging in maximum leaf

length from 67 to 198 cm and in number of leaves from 10 to 20. From these data we were able to calculate the linear fits of the number of usable leaves (living, fully expanded leaves with a fairly intact lamina) as a function of the total number of living leaves and of the mean leaf length of the usable leaves as a function of maximum leaf length. Based on all the individuals included in the matrix analyses we also calculated the mean maximum leaf length and mean number of leaves of individuals in each of the subadult and adult stages, and from the linear fits we could then estimate the mean number of usable leaves and the mean length of these leaves for each stage. Combining these data with the sustainable harvesting rates and the natural densities of *G. macrostachys*, we were able to estimate the amount of rachis length that can be sustainably harvested in each of the three habitats under the two harvesting regimes. From these data on the maximum sustainable harvest per area and the annual amount of leaf material that a Huaorani community needs (see Section 2.3), we could then estimate the area of a given type of forest that such a community would require for the leaf harvesting to be ecologically sustainable.

## 3. Results

### 3.1. Quantification of indigenous use of *G. macrostachys* thatch

The Huaorani house in Dicaro was 12.5 m long, 10.2 m wide, and 6.2 m high, and 4250 *G. macrostachys* leaves were used to thatch the inside of its roof. The Tiputini house was 6.4 m long, 5.2 m wide, and 4.5 m high, and 2220 *G. macrostachys* leaves were used. The house at the Omaere Ethnobotanical Park was 7.3 m long, 4.7 wide, 4.9 m high, and 2340 leaves were used. As the house in Dicaro was most representative of a typical Huaorani house, the others being made to be used as a kitchen only (Tiputini) or for exhibition (Omaere), we use the data from Dicaro in all further calculations. Given an average durability of 2 years per house, a community of four traditional houses (with 50–70 people) would therefore need 8500 *G. macrostachys* leaves per year for thatch. The average rachis length of the leaves used for thatch was 0.90 m. Thus, a community of four houses will need an annual harvest of 7650 m rachis length.

Table 2  
Leaf data for the harvested stages of *G. macrostachys* (Yasuní, Ecuador)

Stage	$n^a$	Max LL <sup>b</sup> (cm)	No. of leaves <sup>c</sup>	Mean LL <sup>d</sup> (cm)	No. of usable leaves <sup>e</sup>
sa1	283	48.7	7.6	39.1	7.3
sa2	193	82.2	8.5	70.0	8.0
ad1	189	111.4	10.4	96.9	9.6
ad2	235	134.1	12.0	117.9	10.9
ad3	130	155.3	12.8	137.5	11.6
ad4	33	182.7	14.1	162.7	12.8
ad5	5	206.1	15.6	184.3	14.0

<sup>a</sup> The number of individuals in the 68 400 m<sup>2</sup> quadrats (2.72 ha) average of 1997 and 1998.

<sup>b</sup> Max LL is the mean maximum leaf length, averaged over the two censuses, of individuals belonging to a given stage in 1997.

<sup>c</sup> No. of leaves is the mean number of living leaves, averaged over the two censuses, of individuals belonging to a given stage in 1997.

<sup>d</sup> Mean LL is the estimated mean leaf length (usable leaves only). Linear fit: Mean LL =  $-5.92 + 0.92 \times \text{Max LL}$ ,  $r^2 = 0.94$ ,  $n = 16$  subadults and adults.

<sup>e</sup> No. of usable leaves is the estimated number of usable leaves. Linear fit: No. of usable leaves =  $0.79 + 0.85 \times \text{No. of leaves}$ ,  $r^2 = 0.91$ ,  $n = 16$  subadults and adults.

### 3.2. Demographic limits to sustainable harvesting

At the demographic study site the average number of harvestable individuals is  $392.1 \text{ ha}^{-1}$ , divided between 174.6 subadults/ha and 217.5 adults/ha (cf. Table 2). These densities are the densities used in all

the calculations in this paper. The average number and length of usable leaves both increase strongly within increasing size (Table 2).

Harvest scheme and forest structure both have a strong influence on the maximum sustainable harvesting intensities (Fig. 2). Harvesting only adults allows

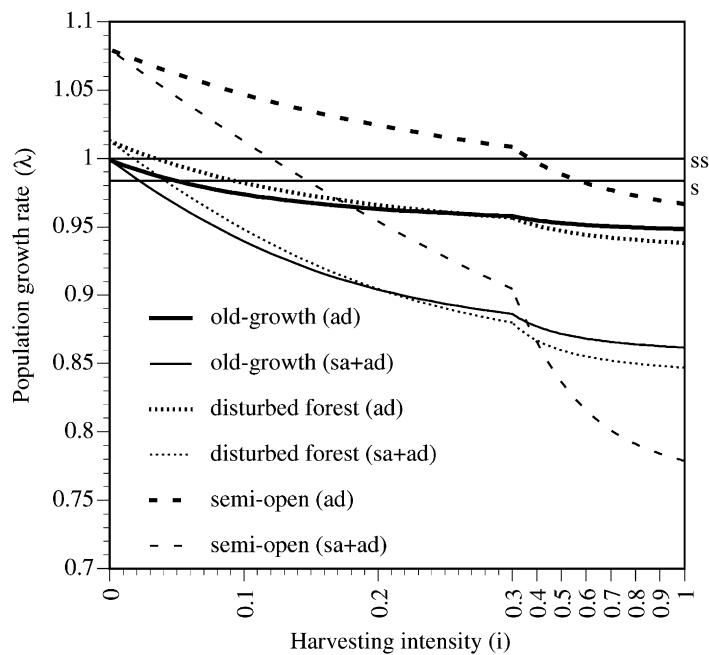


Fig. 2. Population growth rate ( $\lambda$ ) of *G. macrostachys* (Yasuní, Ecuador) as a function of simulated harvesting intensity ( $i$ ), simulated harvesting scheme, and habitat. Harvesting scheme is ad (only adults harvested) or sa + ad (both subadults and adults harvested). The two horizontal lines indicate the limits to simple sustainability (s,  $\lambda \geq 0.983$ ) and strict sustainability (ss,  $\lambda \geq 1.000$ ). Note the scale change on the x-axis.

2–4 times the harvesting intensities of the harvested stages ( $i_s$ ,  $i_{ss}$ ) when subadults are also harvested (Table 3). Under old-growth conditions only very low harvesting intensities are sustainable, and under the condition of strict sustainability no harvesting is possible (which follows from the natural  $\lambda = 0.999$ , i.e.  $<1.000$ ). Under disturbed forest conditions about twice as high harvesting intensities ( $i_s$ ) are possible, and some harvesting can even be done under the condition of strict sustainability. Semi-open conditions offer dramatic increases in the maximum sustainable harvesting intensities (Fig. 2 and Table 3).

Table 4 gives the stage-specific natural mortality rates and the stage-specific harvesting rates (anthropogenic mortality rates) under the different harvesting schemes and habitat conditions. Harvesting rates are below 10% per 1.5 years except under semi-open conditions, where harvesting rates are between 12 and 58% depending on the sustainability requirements and harvesting scheme (Table 4).

When the data on harvesting rates (Table 4) and the stage-specific densities at the study site (Table 2) are combined, so that the annualized sustainable leaf harvest (summed rachis length) can be calculated, it

Table 3

Sustainable harvesting intensities ( $i$ : the proportional decrease in the overall survival rate due to harvesting) for *G. macrostachys* (Yasuní, Ecuador)<sup>a</sup>

Habitat	Harvest scheme <sup>b</sup>	$i_s$	$i_{ss}$
Old-growth	ad	5	– <sup>c</sup>
Old-growth	sa + ad	2	– <sup>c</sup>
Disturbed forest	ad	9	3
Disturbed forest	sa + ad	4	1
Semi-open	ad	58	37
Semi-open	sa + ad	14	12

<sup>a</sup> The sustainable harvesting intensity ( $i_s$ ) and the strictly sustainable harvesting intensity ( $i_{ss}$ ) are the maximum  $i$  that allows a population growth ( $\lambda$ )  $\geq 0.983$  or  $\geq 1.000$ , respectively.

<sup>b</sup> ad: only adults harvested; sa + ad: subadults also harvested.

<sup>c</sup>  $\lambda$  without harvesting is 0.999.

becomes clear that both harvesting scheme and forest structure has a strong effect on the amount of leaf material that can be sustainably harvested (Table 5). Refraining from harvesting the subadults allows increasing the total sustainable harvest by as much as 100–200%. Forest structure has an even stronger effect on the potential sustainable harvest (Table 5).

Table 4

Sustainable harvesting rates ( $H(i)$ : the proportion of individuals in a stage that are harvested for a given harvesting intensity, over 1.5 years) of *G. macrostachys* (Yasuní, Ecuador)<sup>a</sup>

Variable	Habitat	Harvest scheme <sup>b</sup>	Stage						
			sa1	sa2	ad1	ad2	ad3	ad4	ad5
$M$	Old-growth and semi-open <sup>b</sup>	–	0.0255	0.0255	0.00538	0.00877	0.00690	0	0
	Disturbed forest <sup>b</sup>	–	0.0379	0.0213	0.0135	0	0	0	0
$H(i_s)$	Old-growth	ad	0.000	0.000	0.050	0.050	0.050	0.050	0.050
	Old-growth	sa + ad	0.019	0.019	0.020	0.020	0.020	0.020	0.020
	Disturbed forest	ad	0.000	0.000	0.089	0.090	0.090	0.090	0.090
	Disturbed forest	sa + ad	0.038	0.039	0.039	0.040	0.040	0.040	0.040
	Semi-open	ad	0.000	0.000	0.577	0.575	0.576	0.580	0.580
	Semi-open	sa + ad	0.136	0.136	0.139	0.139	0.139	0.140	0.140
$H(i_{ss})$	Old-growth	ad	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Old-growth	sa + ad	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Disturbed forest	ad	0.000	0.000	0.030	0.030	0.030	0.030	0.030
	Disturbed forest	sa + ad	0.010	0.010	0.010	0.010	0.010	0.010	0.010
	Semi-open	ad	0.000	0.000	0.368	0.367	0.367	0.370	0.370
	Semi-open	sa + ad	0.117	0.117	0.119	0.119	0.119	0.120	0.120

<sup>a</sup> Harvesting intensities  $i_s$  and  $i_{ss}$  are defined in Table 3.  $M$  is the natural observed mortality rate (proportion of individuals in a stage that died over 1.5 years).

<sup>b</sup> Mortality is related to forest phase, but not to crown illumination (Svenning, in press).

Table 5

Annualized sustainable harvest,  $L$  (amount of *G. macrostachys* rachis length that can be sustainably harvested per year) and the corresponding area ( $A$ ) that a Huaorani community with four houses will need, given that they use 7650 m *G. macrostachys* rachis per year<sup>a</sup>

Habitat	Harvest scheme	$L_s$ (m/ha per year)	$L_s/T$ (% per year)	$A_s$ (ha)	$L_{ss}$ (m/ha per year)	$L_{ss}/T$ (% per year)	$A_{ss}$ (ha)
Old-growth	ad	93.34	2.66	82	0.00	0.00	–
Old-growth	sa + ad	46.30	1.32	165	0.00	0.00	–
Disturbed forest	ad	168.59	4.81	45	56.20	1.60	136
Disturbed forest	sa + ad	92.80	2.65	82	23.20	0.66	330
Semi-open	ad	1082.73	30.86	7	690.71	19.69	11
Semi-open	sa + ad	324.08	9.24	24	277.79	7.92	28

<sup>a</sup> The subscript refers to whether the simple (s) or the strict (ss) sustainability requirement was used (see Table 3 for definitions). Total harvestable rachis length,  $T = 3508.42$  m/ha, available in our natural demographics study area in Yasuní, Ecuador (based on data in Table 2).

Under old-growth conditions only 0–3% of the total leaf material can be harvested each year, while an approximately doubled, but still low harvest is possible under disturbed forest conditions. Semi-open conditions allow a much greater harvest, especially if only adults are harvested, in which case a staggering 31% of the total leaf material can be harvested each year (Table 5).

### 3.3. Sustainability requirements for indigenous use of *G. macrostachys* thatch

The area required for the harvest of a Huaorani community of four houses to be sustainable is also given in Table 5. Both under old-growth and disturbed forest conditions relatively large areas would be required for achieving even simple sustainability (82 and 45 ha, respectively).

## 4. Discussion

### 4.1. Importance of forest structure

The results suggest that harvesting of *G. macrostachys* leaves for thatch may not be sustainable under old-growth forest conditions even at very low intensities. Only low levels of harvesting per area are possible in old-growth forest even under the more liberal definition of sustainability ( $\lambda \geq 0.983$ ). Thus, the potential for sustainable extractivism of *G. macrostachys* from areas with forest that have been little disturbed by humans, e.g. forest reserves where

only non-timber forest products can be harvested, is probably small. The sensitivity of *G. macrostachys* to harvesting contrasts the results found for *G. deversa*, a species often used for thatch in Peru and Bolivia (Flores and Ashton, 2000; Zuidema, 2000). This contrast probably reflects that *G. deversa* is a clonal species and that clonal survival is not affected by harvesting (Flores and Ashton, 2000; Zuidema, 2000), while each individual of the non-clonal *G. macrostachys* is killed by the harvesting process. Sustainable extractivism can probably more easily be achieved for clonal than non-clonal understory species. Our modeling shows that the sensitivity of *G. macrostachys* to harvesting, apart from its non-clonal habit, also results from the severe light limitation under which it exists in old-growth forest (also cf. Svenning, in press). As *G. macrostachys* is clearly a relatively shade-tolerant species (Svenning, in press), it is quite likely that many other non-clonal, understory species are similarly sensitive to harvesting under old-growth conditions. Given these findings, Gomez et al. (1996) report that *G. supracostata* (as *G. aff. macrostachys*) has become rare around the Amazonian town of Puyo is hardly surprising.

Contrary to old-growth conditions, sustainable harvesting of *G. macrostachys* seems more possible in disturbed forest, albeit still at rather low intensities per area. The demographic data for the matrix model for *G. macrostachys* in disturbed forest comes from individuals growing in 400 m<sup>2</sup> quadrats with an average canopy height <20 m and/or containing a major treefall gap. While these quadrats were located in old-growth forest we believe that the



conditions they reflect are similar to the disturbed conditions found in forests close to indigenous communities and mestizo villages in the Ecuadorian Amazon.

Semi-open conditions provide even better conditions for sustainable harvesting than disturbed forest. The modeling suggests that as much as 20% of the total usable leaf material can be harvested annually under the condition of strict sustainability, and a typical Huaorani community would need to use only 7–11 ha of semi-open habitat to achieve ecologically sustainable harvesting. The demographic data for the model of semi-open conditions are based on individuals with medium/high crown illumination in at least one of two census years. While these individuals were also located in old-growth forest, we think that the environmental conditions they represent are comparable to the conditions found in young secondary forests (cf. Nicotra et al., 1999) or in the denser part of indigenous home gardens.

Our findings for the simulated disturbed forest and semi-open habitats reflect the greater light availability in these anthropogenic habitats (cf. Nicotra et al., 1999), and the consequent release from the severe light limitation under closed canopy old-growth conditions (cf. Svenning, in press). Thus, sustainable extractivism of *G. macrostachys* leaves for thatch will be easier to achieve in forests where the canopy has been opened by the felling of timber or is kept open under managed conditions. Pedersen (1996) likewise found that fiber production by *Aphandra natalia* strongly increased with increasing exposure to light, thereby probably allowing for higher sustainable rates of harvesting. This result needs careful interpretation, though. Seedlings of *G. macrostachys* are damaged by solarization under even moderate light availability, e.g. in the center of a 1–200 m<sup>2</sup> gap (Svenning, in press), and other *Geonoma* species are also damaged by moderate light intensities (Chazdon, 1986). Likewise, many Old World rain forest understory palms are damaged by the increased light availability associated with logging (Dransfield, 1969; Kiew, 1972) and have been reported to disappear even from selectively logged forests (Dransfield, 1969). Thus, a strong opening up of the forest is not likely to be favorable to sustainable harvesting of *G. macrostachys* leaves. This is contrary to *A. natalia*, in which fiber production is maximized under full or nearly full exposure to

sunlight (Pedersen, 1996). *A. natalia* is a large subcanopy palm, not an understory palm, and the differing response to high light levels probably reflects the greater shade-adaptation and lesser drought resistance of most understory palms relative to larger palms (cf. de Granville, 1992). Overall, young secondary forests with their high representation of 1–5% full sunlight microsites and low representation of very dark and high light microsites (Nicotra et al., 1999) would seem to be a perfect habitat for the extractivism of *G. macrostachys* thatch.

The observation that *G. macrostachys* and most other understory palms are often absent or rare in young secondary forests in the Ecuadorian Amazon (Macía and Svenning, personal observation) would seem to be in conflict with this conclusion, and many palaeotropical understory palms have likewise been noted to be absent from this habitat (Dransfield, 1969; Kiew, 1972). As these understory palms appear to do well under light conditions similar to those found in young secondary forests (Kiew, 1972; Svenning, in press), their absence probably merely reflect dispersal limitation (Kiew, 1972). Providing evidence for this scenario, Vandermeer (1993) found that 10 species of understory palms, including three *Geonoma* species, were recolonizing a small abandoned cacao plantation abutting an old-growth tropical rain forest in Costa Rica, but that the distribution patterns of many species suggested that their occurrence in the plantation, abandoned 20 years earlier, was still dispersal limited. It is notable that the seeds of *G. macrostachys* are dispersed by large trumpeter birds (although perhaps also by other birds), a preferred game bird that will often be locally extinct, or at least rare, close to human communities due to over-hunting (Redford, 1992).

#### 4.2. Importance of harvesting scheme

Our modeling shows that harvesting scheme has a strong influence on sustainability. When only adults are harvested, two to three times as much leaf material can be harvested (varying according to the habitat and definition of sustainability) as when subadults are also harvested. We note the one exception that no harvesting can be done under strict sustainability in old-growth forest no matter the harvesting scheme. Leaving subadults, i.e. individuals with leaf rachis

shorter than 1.00 m, unharvested seems to be a simple, easily communicable suggestion for improving sustainability of the harvesting.

We have modeled harvesting as destructive extractivism, i.e. where an individual is killed when it is harvested, because this is the way the Huaorani generally harvest *G. macrostachys* for thatch (Macía, personal observation). More gentle harvesting methods, where the harvested individuals are not killed, would probably allow higher rates of sustainable harvesting (cf. Flores and Ashton, 2000). In the Pastaza province of the Ecuadorian Amazon Quichua Indians are reported to leave at least three leaves and the trunk itself untouched on each harvested individual of *G. supracostata* (as *G. aff. macrostachys*) (Gomez et al., 1996). In Amazonian Peru some rural communities harvest the leaves of *G. deversa* without damaging the stems (Flores and Ashton, 2000). Similarly, when *A. natalia* leaves are harvested for their fibers in the Morona-Santiago province of the Ecuadorian Amazon, nearly half the leaves are left on each individual palm to secure its continued fiber production (Pedersen, 1996). Further, when leaves of *Chamaedorea* spp. are harvested in the Guatemalan Petén to be commercialized for use in floral arrangements just one or two leaves are harvested from each plant, allowing the harvester to repeatedly harvest the same plant (Reining and Heinzman, 1992). While such practices may reduce immediate mortality, it is possible that mortality may simply be delayed, not avoided. Under natural conditions, individuals of *G. macrostachys* damaged in 1 year suffer increased mortality risk in the subsequent year (Svenning, in press). Conversely, experimental defoliation simulating harvesting for thatch, taking care not to damage the stem or the developing leaf, had little impact on population growth rate in *G. deversa* (Zuidema, 2000). Nevertheless, another study of this species found that leaf harvesting had a negative effect on reproduction and ramet production even when stems were not damaged (Flores and Ashton, 2000). While more gentle harvesting methods probably would improve sustainability in the case of *G. macrostachys*, they implicate a more time-consuming harvesting process (cf. Flores and Ashton, 2000) and may consequently be difficult to get implemented in practice given the huge quantities of leaves that need to be harvested for even a single house.

## 5. Conclusion

The use of *G. macrostachys* for thatch is of great importance and further potential to Amazonian communities with low economic resources. When the exploitation of this source is made by a small group of people, such as the Huaorani in the past, ecologically sustainable harvesting was probably fairly readily achieved. Today, however, harvesting can easily cause local depletion, as indicated by the modeling reported here and reported from field studies of congeneric species (Rioja, 1992; Gomez et al., 1996). Our results suggest that harvesting scheme has a strong effect on sustainability, and in particular, that harvesting subadults should be avoided. Our modeling further indicates that ecological sustainable harvesting might not be possible from old-growth forests no matter the harvesting scheme, and that sustainable harvesting of *G. macrostachys* in sufficient quantities can best be achieved in forests or plantations where the canopy is maintained somewhat more open than under old-growth conditions. *G. macrostachys* would probably be most easily and most productively managed as part of the understory layer of rather closed-canopy agroforestry systems, in young secondary forests, or in 'managed' forests (sensu Salick, 1992), i.e. forests from which timber and non-timber forest products are selectively harvested and which are purposely enriched with useful species. Thus, *G. macrostachys* seems more promising as part of diverse semi-cultivated systems than as a non-timber forest product to be harvested from reserves. Further studies on potential for cultivation of *G. macrostachys* are needed, e.g. development of reproduction methods for local nurseries and experimental studies of the leaf production rates and potential harvesting rates in different anthropogenic habitats such home gardens and young secondary forests and under different harvesting schemes.

## Acknowledgements

We thank the Dicaro and Tiputini communities for sharing their ethnobotanical and ecological knowledge with us and for their hospitality. We also thank INEFAN for research permits, Pontificia Universidad Católica del Ecuador for providing research facilities

in Ecuador, and Yasuní Forest Dynamics Project/CTFS for allowing us to work in their 50 ha plot. The authors received economic support from the European Commission (INCO-DC, IC18-CT960038; to MJM), Centre for Tropical Biodiversity (Danish Natural Science Research Council, Grant no. 11-0390; to JCS), Svend G. Fiedler og hustrus legat til fremme af botanisk og arkæologisk forskning (to JCS), European Science Foundation's Programme on Tropical Canopy Research (to JCS), and the Faculty of Natural Sciences at the University of Aarhus (to JCS). Finally, we acknowledge support from the Smithsonian Tropical Research Institute and the Carlsberg Foundation (Grant no. 990086/20) (to JCS) during the final part of this work.

## References

- Balick, M.J. (Ed.), 1988. The palm—tree of life: biology, utilization and conservation. In: *Advanced Economic Botany*, Vol. 6. The New York Botanical Garden, New York.
- Balslev, H., Barfod, A., 1987. Ecuadorian palms—an overview. *Oper. Bot.* 92, 17–35.
- Balslev, H., Rios, M., Quezada, G., Nantipa, B., 1997. Palmas útiles en la Cordillera de los Huácamayos. *Etnobotánica de palmas de la comunidad Quichua de Santa Rita, provincia del Napo, Ecuador*. Colección Manuales de Aprovechamiento Sostenible del Bosque 1, 1–56.
- Basaglia, P., 1991. Tipología habitativa y embarcaciones del Ecuador. Acosta Solís, M. (Ed.), *Ecuador en la sombra de los volcanes*. Ediciones Libri Mundi & Enrique Grosse-Luemern, Quito, Ecuador, pp. 151–160.
- Bernal, R., 1998. Demography of the vegetable ivory palm *Phytelephas seemannii* in Colombia, and the impact of seed harvesting. *J. Appl. Ecol.* 35, 64–74.
- Boom, B.M., 1988. The Chácobo Indians and their palms. *Adv. Econ. Bot.* 6, 91–97.
- Borchsenius, F., Pedersen, H.B., Balslev, H., 1998. Manual to the palms of Ecuador. AAU Reports, Department of Systematic Botany, University of Aarhus, Aarhus.
- Cerón M.C.E., 1993. *Etnobotánica del Ecuador—estudios regionales*. Hombre y Ambiente, Ediciones Abya-Yala, Quito, Ecuador.
- Cerón, M.C.E., 1995. *Etnobiología de los Cofanes de Dureno: Provincia de Sucumbíos, Ecuador*. Pueblos del Ecuador, Ediciones Abya-Yala, Quito, Ecuador.
- Cerón, M.C.E., Montalvo, A.C.G., 1998. *Etnobotánica de los huaorani de Quehueiri-ono, Napo-Ecuador*. Ediciones Abya-Yala, Quito, Ecuador.
- Cerón, M.C.E., Montalvo, A.C.G., Umenda, J., Umenda, E.C., 1994. *Etnobotánica y notas sobre la diversidad vegetal en la comunidad Cofán de Sinangüe, Sucumbíos, Ecuador*. Investigación y Monitoreo, EcoCiencia, Quito, Ecuador.
- Chazdon, R.L., 1986. Light variation and carbon gain in rain forest understorey palms. *J. Ecol.* 74, 995–1012.
- Davis, E.W., Yost, J.A., 1983. The ethnobotany of the Waorani of eastern Ecuador. *Bot. Museum Leaflets* 29, 159–217.
- de Granville, J.-J., 1992. Life forms and growth strategies of Guianan palms as related to their ecology. *Bulletin de l'Institut français d'études andines* 21, 533–548.
- Dransfield, J., 1969. Palms in the Malayan forest. *Malayan Nat. J.* 22, 144–151.
- Flores, C.F., Ashton, P.M.S., 2000. Harvesting impact and economic value of *Geonoma deversa*, Arecaceae, an understorey palm used for roof thatching in the Peruvian Amazon. *Econ. Bot.* 54, 267–277.
- Gomez, D., Lebrun, L., Paymal, N., Soldi, A., 1996. Palmas útiles en la provincia de Pastaza, Amazonia ecuatoriana. *Manual práctico*. Manuales de plantas útiles amazónicas, Fundación Omaere, Quito, Ecuador.
- Hall, P., Bawa, K., 1993. Methods to assess the impact of extraction of non-timber tropical forest products on plant populations. *Econ. Bot.* 47, 234–247.
- Henderson, A., 1995. *The palms of the Amazon*. Oxford University Press, New York.
- Kahn, F., de Granville, J.-J., 1992. Palms in forest ecosystems of Amazonia. In: *Ecological Studies*. Springer, Berlin.
- Kiew, R., 1972. The natural history of *Iguanura geonomaeformis* Martius: a Malayan undergrowth palmlet. *Principes* 16, 3–10.
- Macía, M.J., 1999. *Investigaciones de botánica económica y manejo de recursos vegetales promisorios en Ecuador y México*. Ph.D. dissertation, Facultad de Ciencias (Biológicas), Universidad Autónoma de Madrid, Madrid, Spain.
- Mejía, C.K., 1988. Utilization of palms in eleven mestizo villages of the Peruvian Amazon (Ucayali River, Department of Loreto). *Adv. Econ. Bot.* 6, 130–136.
- Netherly, P., 1997. Loma y ribera: Patrones de asentamiento prehistóricos en la Amazonía ecuatoriana. *Fronteras de Investigación* 1, 33–54.
- Nicotra, A.B., Chazdon, R.L., Iriarte, S.V.B., 1999. Spatial heterogeneity of light and woody seedling regeneration in tropical wet forests. *Ecology* 80, 1908–1926.
- Parodi, J.L., 1988. The uses of palms and other native plants in non-conventional, low-cost rural housing in the Peruvian Amazon. *Adv. Econ. Bot.* 6, 119–129.
- Pedersen, H.B., 1996. Production and harvest of fibers from *Aphandra natalia* (Palmae) in Ecuador. *For. Ecol. Manage.* 80, 155–161.
- Pedersen, H.B., Balslev, B., 1992. The economic botany of Ecuadorian palms. In: Plotkin, M.J., Famolare, L.M. (Eds.), *Sustainable Harvest and Marketing of Rain Forest Products*. Island Press, Washington, DC, pp. 173–191.
- Phillips, O.L., 1997. The changing ecology of tropical forests. *Biodiversity Conserv.* 6, 291–311.
- Pinard, M.A., Putz, F.E., 1992. Population matrix models and palm resource management. *Bulletin de l'Institut français d'études andines* 21, 637–649.
- Ratsirarson, J., Silander Jr., J.A., Richard, A.F., 1996. Conservation and management of a threatened Madagascar palm species, *Neodypsis decaryi*, Jumelle. *Conserv. Biol.* 10, 40–52.

- Redford, K.H., 1992. The empty forest. *BioScience* 42, 412–422.
- Reining, C., Heinzman, R., 1992. Nontimber forest products in the Petén, Guatemala: why extractive reserves are critical for both conservation and development. In: Plotkin, M.J., Famolare, L.M. (Eds.), *Sustainable Harvest and Marketing of Rain Forest Products*. Island Press, Washington, DC, pp. 110–117.
- Rioja, G., 1992. The Jatata Project: the pilot experience of Chimane empowerment. In: Plotkin, M.J., Famolare, L.M. (Eds.), *Sustainable Harvest and Marketing of Rain Forest Products*. Island Press, Washington, DC, pp. 192–196.
- Rival, L., 1996. Hijos del sol, padres del jaguar. Los Huaorani de ayer y hoy. Abya-Yala, Quito, Ecuador.
- Romoleroux, K., Foster, R., Valencia, R., Condit, R., Balslev, H., Losos, E., 1997. Árboles y arbustos (dap  $\geq$  1 cm) encontrados en dos hectáreas de un bosque de la Amazonía ecuatoriana. In: Valencia, R., Balslev, H. (Eds.), *Estudios sobre diversidad y ecología de plantas: memorias del II Congreso Ecuatoriana de Botánica realizado en la Pontificia Universidad Católica del Ecuador*. PUCE, University of Aarhus & DIVA, Quito, Ecuador, pp. 189–215.
- Salick, J., 1992. The sustainable management of nontimber rain forest products in the Si-a-Paz Peace Park, Nicaragua. In: Plotkin, M.J., Famolare, L.M. (Eds.), *Sustainable Harvest and Marketing of Rain Forest Products*. Island Press, Washington, DC, pp. 118–124.
- Smith, R., 1996. Crisis under the canopy. In: *Tourism and Other Problems Facing the Present Day Huaorani*. Abya-Yala, Quito, Ecuador.
- Svenning, J.-C., 1999. Microhabitat specialization in a species-rich palm community in Amazonian Ecuador. *J. Ecol.* 87, 55–65.
- Svenning, J.-C., in press. Crown illumination limits the population growth rate of a neotropical understorey palm (*Geonoma macrostachys*, Arecaaceae). *Plant Ecol.*
- Vandermeer, J., 1993. Successional patterns of understorey palms in an old cacao plantation on the Caribbean coast of Costa Rica. *Principes* 37, 73–79.
- Wessels Boer, J., 1968. The geonomoid palms. *Verhandelingenn der Koninklijke Nederlandse Akademie van Wetenschappen, Afd. Natuurkunde. Tweede Reeks* 58, 1–202.
- Yost, J.A., 1991. Los Waorani: un pueblo de la selva. Acosta Solís, M. (Ed.), *Ecuador en la sombra de los volcanes*. Ediciones Libri Mundi & Enrique Grosse-Luemern, Quito, Ecuador, pp. 95–115.
- Zuidema, P.A., 2000. Demography of exploited tree species in the Bolivian Amazon. *PROMAB Scientific Series* 2, PROMAB, Riberalta, Bolivia.