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ORIGINAL PAPER

Effect of harvesting on temporal papyrus (*Cyperus papyrus*) biomass regeneration potential among swamps in Winam Gulf wetlands of Lake Victoria Basin, Kenya

J. J. L. Osumba · J. B. Okeyo-Owuor ·
P. O. Raburu

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Abstract This study established for the first time the impact of harvesting on post-harvest papyrus (*Cyperus papyrus* L.) biomass regeneration potential, with two harvesting regimes compared. Above-ground papyrus biomass was determined. Biomass varied with site. Site had no effect on regeneration potential, but monthly harvesting reduced papyrus biomass regeneration potential among sites. However, seasonal (6-monthly) harvesting did not appear to affect papyrus biomass regeneration potential. Exponential and polynomial trend analyses revealed a consistent downward trend for monthly harvest biomass, and the polynomial trend was more linear (F = 97.913; $P < 0.001$) than periodic (F = 9.617; $P < 0.05$). The polynomial trend scenario indicated how papyrus biological dynamics are likely to behave as monthly harvests are repeated. This suggests that regeneration potential is significantly reduced with successive monthly harvest, leading to weak spatial connectivity, papyrus stand fragmentation, and increased landscape patchiness. A 6-month harvest regime can be established to regenerate more biomass between harvests than is currently the case, with positive implications for wetland conservation and carbon sequestration. Papyrus harvesters can be kept off the swamps by establishing a riparian buffer zone of agro forestry trees and shrubs which can substitute for the papyrus as it is left to mature. However, while the information presented is useful for papyrus wetland management strategies, it is recognized that the study period was too short to permit a generalized recommendation.

Keywords Biomass · *Cyperus papyrus* · Harvesting · Lake Victoria · Regeneration · Swamps · Wetlands · Winam · Kenya

Introduction

Papyrus (*Cyperus papyrus* L.) biomass (also called standing crop) has been investigated by several authors. Studies that have documented papyrus biomass in East Africa are summarized in Table 1. Its regeneration potential (i.e., the inherent capacity for natural re-growth and replenishment on a site after a disturbance, or “an inherent biomass yield” (Mead 1990)) has been found to be highly variable, ranging from 1,050 to 14,300 g/m^2. One review (Květ et al. 1998) reported a biomass of shoots plus

J. J. L. Osumba (✉) · J. B. Okeyo-Owuor
Department of Environmental Biology and Health,
School of Environmental Studies, Moi University,
P. O. Box 3900, Eldoret 30100, Kenya
e-mail: jlosumba@yahoo.com; osumbajl@yahoo.com

P. O. Raburu
Department of Fisheries and Aquatic Science, School
of Natural Resource Management, Moi University,
P. O. Box 3900, Eldoret 30100, Kenya

Table 1 Above-ground papyrus biomass in Eastern African papyrus swamps

Site	Biomass (g/m^2)	Source
Lake Naivasha, Kenya	3,000	Bacon (1997)
Lake Naivasha, Kenya and Busoro, Rwanda	1,384–3,245	Jones and Muthuri (1985)
Lake Naivasha, Kenya	11,540 ± 3,020	Boar et al. (1999)
Ethiopian wetlands	Up to 14,300	Abebe (2003)
Nakivubo wetland, Kampala, Uganda	883–5,844	Kansiime et al. (2003)
Lake Naivasha, Kenya	6,950 ± 860	Boar (2006)
Yala swamp, Kenya	1,050	Thenya (2006)
Rubondo Island, Lake Victoria—Tanzania	5,789 ± 435	Mnaya et al. (2007)
Winam Gulf, Lake Victoria, Kenya	8,456.5 ± 1,183.89	This study

young rhizomes and roots of 90–5,200 g/m^2 depending on the site. One review (Bacon 1997) established that a papyrus stand produced 3,000 g/m^2 of above-ground papyrus biomass, which was replaced in about 9 months after harvest.

It has also been established that papyrus can be used for several socio-economic purposes by riparian communities, especially along Winam Gulf of Lake Victoria in Kenya (Omollow 2003). However, various authors postulate that papyrus exploitation around Lake Victoria is excessive, uncontrolled, and unsustainable (Twong'o and Sikoyo 2004; Owino 2005; Kipkemboi 2006); that papyrus wetlands in Lake Victoria Basin have undergone considerable decline over the last 30–40 years as a result of, among other anthropogenic factors, over-harvesting of wetland macrophytes (McClanahan and Young 1996; LVEMP 1999; Mallory and Chandler 2001; Vignoli et al. 2004; Owino and Ryan 2007).

The ecology of papyrus swamps around Lake Victoria was first studied during the colonial era (Lind and Visser 1962; Kendall 1969). However, the plant is being accorded renewed interest due to its critical ecological role in wetland ecosystems (Archer 2004) vis-à-vis its importance as a biomass crop for fuel generation (Bacon 1997) and for its role as a handicraft material (Burnmeister 2001). Given its dual role as an ecological and a socioeconomic resource, it is therefore important that innovative ways of utilizing this macrophyte without damaging the ecosystem be developed and promoted. That necessity requires determination of the impact of its extraction and the potential for its biomass replenishment in areas where it is the dominant macrophyte.

Prior to this study information on papyrus biomass harvesting and regeneration potential was lacking in Winam Gulf. No study had compared papyrus harvesting and its biomass regeneration potential to provide reliable information on the sustainability of its extraction in the study area. These factors are essential in determining wise use, and can guide policy formulation and the involvement of riparian communities in wetland conservation. Against this background it was necessary to investigate and compare papyrus harvesting and regeneration among cleared (disturbed) and un-cleared (un-disturbed) plots in order to assess its recovery potential for conservation planning. The findings from this study have provided new information for papyrus wetland management in the face of the increasing need to conserve vulnerable and fragile ecosystems around Lake Victoria Basin.

Materials and methods

Study area sampling sites

This study was undertaken at a 60 km stretch of palustrine swamps in Kano Plains/Nyando River Mouth Wetlands along Winam (also known as Nyanza or Kavirondo) Gulf shores of Lake Victoria in Kenya from Kisumu Bay to Nyakach Bay. Three papyrus swamps were selected for the study, namely Dunga (0°08′01″S, 34°44′37.2″E, 1135 masl), Nduru (0°15′14.9″S, 34°49′17.9″E, 1134 masl), and Ogenya (0°16′27.0″S, 34°51′15.2″E, 1160 masl). All the three swamps were embedded at the littoral zone, and all showed signs of disturbance, but each site was unique in its own way: Dunga is urban and near a river mouth; Nduru is isolated and near a rice scheme; Ogenya is a floodplain near a river mouth.

Methods

Data gathering was carried out from September 2006 through March 2007. In each site three representative papyrus patches, isolated from each other by at least a 5 m open space, were selected for replication. A representative experimental block (30 m × 30 m) was marked out in each patch for sampling. A (2 m × 2 m) quadrat was marked out within each block, at least 20 m from the land edge. Papyrus was cleared from the quadrats by cutting at 5 cm from the base rhizome and removing their sheaths (Fig. 1).

Papyrus fresh weights were taken using a 500 g laboratory spring balance measuring 1 g precision, as recommended by Pearcy et al. (1991). Representative sub-samples were taken and re-weighed fresh, labeled, string-tied, temporarily sun-dried, packed in polythene wrappers and taken to the laboratory for oven-drying. Samples were oven-dried at 100°C for 24 h, which is the recommended upper temperature limit for drying herbaceous plant material (Slingsby and Cook 1986; Sutherland 1996), until they achieved a stable dry weight. The dried sub-samples were then re-weighed to 1 g precision using the same spring balance immediately they were removed (hot) from the oven. This baseline harvest was used to determine the baseline above-ground papyrus biomass. The 2 m × 2 m quadrats used for baseline biomass determination were used to collect monthly above-ground biomass harvests data as recommended by Roberts et al. (1993).


Fig. 1 A (2 m × 2 m) quadrat marked for harvesting in Nduru Swamp

A half (15 m × 30 m plot) of the experimental block was harvested (cleared) and the harvest discarded. Another half was left un-harvested (un-cleared). A nested sampling design was applied to achieve a fair distribution of sampling points. Plant regeneration was monitored fortnightly for 6 months. At the end of the 6 months three quadrats measuring 2 m × 2 m were marked out on each plot and harvested to determine the seasonal (peak) above-ground biomass in cleared and un-cleared patches. Distances between the cleared and the un-cleared were about 3–5 m, depending on within-block accessibility.

Mean papyrus biomass (ß) was determined in g/m^2, using the method of first principles (Chiariello et al. 1991; Underwood 1997) as follows:

No. of plants harvested (#)	No. of plants sampled (#)	Sample fresh weight (g/m^2)	Sub-sample fresh weight (g/m^2)	Sub-sample dry weight (g/m^2)	Quadrat biomass (g/m^2)
N	n	a	b	c	ß

Dry weight (DW$_s$) of sample is given by

$$\mathrm{DW_S} = \left(\frac{a}{b}\right) c\, \mathrm{g/m^2} \tag{1}$$

Dry weight of harvested material (DW$_q$) is therefore given by

$$\mathrm{DW_q} = \left(\frac{N}{n}\right)\left(\frac{a}{b}\right) c = \frac{Nac}{nb}\, \mathrm{g/m^2} \tag{2}$$

Quadrat biomass (ß) is therefore given by

$$ß = \frac{Nac}{nb}\, \mathrm{g/m^2} \tag{3}$$

where

ß	Quadrat biomass (g/m^2)
N	No. of plants harvested
a	Sample fresh weight (g/m^2)
c	Sub-sample dry weight (g/m^2)
n	No. of plants sampled
b	Sub-sample fresh weight (g/m^2)

Since there was an element of flooding at the sites, floodwater depth was also recorded for the duration of the study.

Results

Baseline biomass

Baseline papyrus biomass estimates are provided in Fig. 2. Mean baseline biomass ranged 1,063.1–11,152.8 g/m^2 with an overall mean of 4,942.6 ± 1,187.2 g/m^2. Biomass was lowest in Dunga (1,838.8 ± 415.6 g/m^2) and highest in Nduru (9,295.7 ± 992.2 g/m^2) while Ogenya had 3,693.4 ± 828.1 g/m^2. One-way ANOVA showed significant differences in baseline biomass among sites (F = 24.535; $P < 0.05$). Post hoc (Bonferroni) test revealed no difference between Dunga and Ogenya ($P > 0.05$), but returned significant differences between Nduru and Dunga/Ogenya ($P < 0.05$).

Monthly biomass

Figure 3a presents sequential monthly harvest biomass for the 6-month study period, all measurements taken after the baseline harvest month (month 0). Monthly biomass decreased with successive harvests, although the decline was more for Dunga and Ogenya than for Nduru. The drop between the first and second month was substantial at all sites compared to the subsequent drops. Exponential trend analysis showed a general downward trend for monthly harvest results in all sites (Fig. 3b). General linear model (GLM) repeated measures ANOVA trend analysis showed that the relationship between harvest interval and biomass regeneration potential was more linear (F = 97.913; $P < 0.001$) than polynomial (F = 9.617; $P < 0.05$). Pearson's correlation analysis revealed that frequency of harvesting correlated negatively with biomass regeneration potential ($r = -0.694$; $P < 0.001$). However, no interactive relationship was observed between site (space) and harvest interval (time).

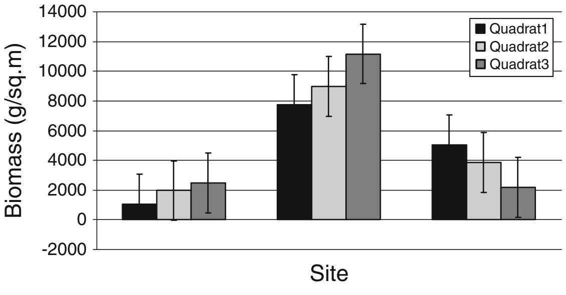

Fig. 2 Baseline papyrus biomass estimates at start of the study

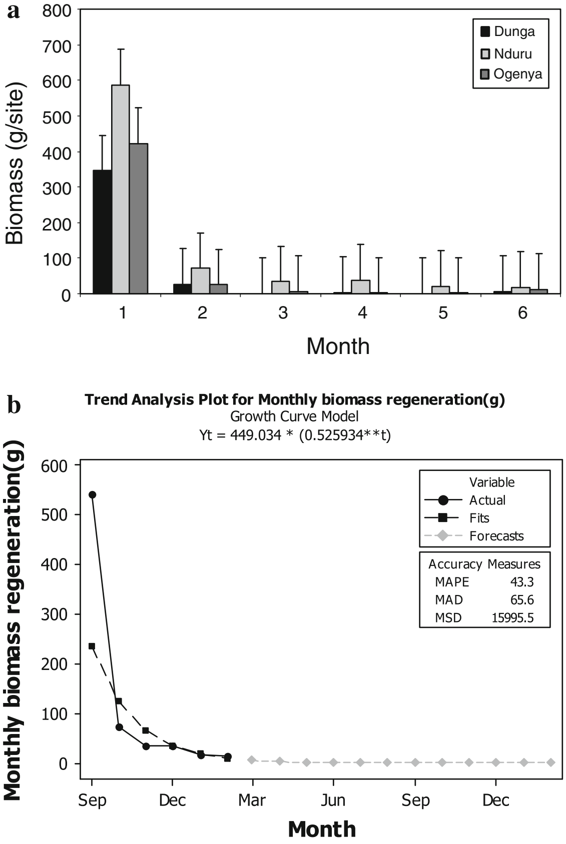

Fig. 3 Sequential monthly papyrus biomass regeneration rates excluding baseline biomass (month 0)

Seasonal biomass

Summary statistics comparing baseline and exit papyrus biomass for the 6-month study period indicated that baseline biomass was 4,942.6 ± 1,187.2 g/m^2, commutative monthly harvest biomass was 540.5 ± 73.4 g/m^2, seasonally cleared plots biomass was 5,883.8 ± 815.2 g/m^2 and un-cleared plots biomass was 14,543.1 ± 1,549.2 g/m^2 (Table 2). It was observed that, at the end of the wetland productive (6 months) season, Nduru still maintained a higher papyrus biomass than Ogenya and Dunga for un-cleared plots (Fig. 4). Inspection of Fig. 4 reveals that biomass at end of the season was generally higher across sites than at start of the season except for Nduru, and that end-of-season biomass was higher in seasonally cleared plots than in the monthly harvested plots cumulated. ANOVA showed significant differences between treatments across sites, namely Dunga (F = 14.791; $P < 0.001$), Nduru (F = 144.896; $P < 0.001$), and Ogenya (F = 62.392; $P < 0.001$). Results for the cleared plots (P_1) were generally closer to those for the baseline plots ($P = 1.000$) than to those for the un-cleared plots ($P = 0.000$), and results for Ogenya were closer to those for Dunga ($P = 1.000$) than to those for Nduru ($P = 0.082$). Post hoc tests revealed no difference in biomass between baseline plots (P_0) and seasonally cleared plots (P_1) among sites (which meant that $P_0 = P_1$; $P > 0.05$). However, there were significant differences between un-cleared plots biomass (P_2) and P_0 and P_1 [which meant that $(P_0 = P_1) < P_2$; $P < 0.05$)], and between cumulative monthly harvest biomass (P_3) and P_0 and P_1 [which meant that $P_3 < (P_0 = P_1)$; $P < 0.05$)]. Cumulative biomass from the monthly harvested plots (P_3) was the lowest overall as illustrated by the relationship [$P_3 < (P_0 = P_1) < P_2$; $P < 0.05$].

Floodwater depth analysis

Results for water depth are given in Fig. 5. Mean floodwater depth (flooding level) for the transect plots were 67.6 ± 3.6 cm for Dunga, 5.9 ± 0.4 cm for Nduru, and 55.1 ± 4.0 cm for Ogenya. Nduru, with the lowest water depth throughout the study period, also consistently had the largest biomass. Dunga, with the highest water depth throughout, also consistently gave the smallest biomass. Statistical analysis for water depth showed no difference within sites (F = 0.016; $P > 0.05$), but returned significant differences among sites (F = 355.734; $P < 0.001$) and through the months (F = 44.243; $P < 0.001$). Bonferroni test showed that floodwater depth was significantly different for all sites.

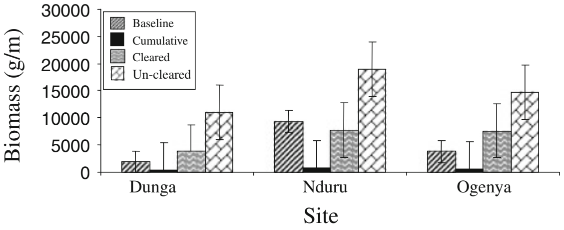

Fig. 4 Papyrus biomass harvests by site

Discussion

Literature reviewed for this study revealed that papyrus has the potential to produce 90–14,300 g/m^2 biomass depending on the site. The range of papyrus biomass measurements observed in this study agrees with the observations in the available literature. The findings of this study have confirmed observations by Jones and Muthuri (1997) that there is no significant seasonal variation in papyrus standing biomass. The mean papyrus biomass obtained in the study was comparable to that reported by Chale (1987) and Kansiime et al. (2003), who studied tropical swamps receiving domestic wastewater. However, the findings were considerably above that observed by Thenya (2006) in Yala Swamp, near Lake Victoria. Although Thenya (2006) did not give the water quality condition under which he worked, it was stated that water nutrients were above ecological limiting levels. Kansiime et al. (2003) observed that on average papyrus vegetation under the influence of wastewater had higher above-ground biomass than those not affected by wastewater. It is possible that water quality in Winam Gulf and Yala

Table 2 Papyrus biomass ((g/m^2) at start and end of season during study period

Biomass	Start of season	End of season (6 months)			Monthly
Plot: Site:	Baseline P_0	Cleared P_1	Un-cleared P_2	Overall $(P_0 + P_1 + P_2)/3$	Cumulative P_3
Dunga	1,838.8 ± 415.6	3,727.7 ± 1,151.3	10,950.0 ± 2,104.9	5,505.5 ± 1,224.0	382.6 ± 119.9
Nduru	9,295.7 ± 992.2	8,663.8 ± 395.1	19,972.2 ± 756.0	12,643.9 ± 714.4	769.9 ± 64.8
Ogenya	3,693.4 ± 828.1	5,260.0 ± 331.6	12,707.2 ± 959.9	7,220.2 ± 706.5	469.1 ± 69.0
Average	4,942.6 ± 1187.2	5,883.8 ± 815.2	14,543.1 ± 1,549.2	8,456.5 ± 1,183.9	540.5 ± 73.4

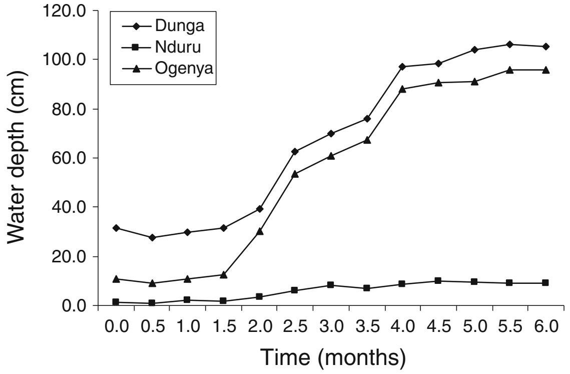

Fig. 5 Depth (cm) of floodwater column at the study sites

Swamp are different, but that factor was not investigated in this study and no inferences can be drawn.

Monthly papyrus biomass

The fact that monthly papyrus biomass showed a consistent downward trend is an indication of how papyrus ecological dynamics is likely to behave temporally as monthly harvesting continues. It suggests that the inherent capacity for natural regeneration of papyrus is significantly reduced with successive monthly harvesting, leading to the possibility of stand fragmentation, weak spatial connectivity, and increased swamp landscape patchiness. This finding concurs with observations that shorter harvest intervals affect the ecology of swamps and hence reduce biomass yields (Kasoma 2003).

Influence of floodwater depth

The effect of monthly harvesting was likely to have been compounded by the influence of flooding (measured as water depth) from the rains, which began in the second month of the experiment. Two of the sites were heavily flooded at the time of collecting the second month's data. As swamp floodwater level rose, monthly papyrus harvests in these sites regenerated less biomass than expected. Cumulative monthly harvest biomass was lowest where water levels were highest, suggesting that the marginality of biomass accumulation was probably due to the effect of flooding. This may partly explain the high variability in monthly harvest biomass between the first two successive harvests after the baseline harvest, which could have been due to floodwater upsurge after the rains began. This trend suggests that apart from harvesting, flooding also appeared to affect on the regeneration potential of papyrus, since the decline was substantial when floods increased, and the potential was slightly regained when the floods began to ebb as the rains subsided at the fifth month, which allowed some papyrus plants to emerge in Dunga and Ogenya.

The increase in biomass in the final (sixth) month was probably due to an increase in the number of shoots occasioned by the reduced floodwater depth, which had submerged papyrus rhizomes and emerging papyrus shoots. Where and when flooding levels were high, the submergence tended to suffocate the young tender plants and affected regeneration, resulting in lower biomass per sample than expected. The findings tend to concur with observations that floods do cause regeneration failure after harvesting, due to submergence, and lead to yield losses (Thenya 2006; Kotera and Nawata 2007). The observation also supports the findings of Boar (2006) that papyrus regeneration rates tend to be higher in shallower waters and when flooding subsides. However, according to Boar (2006), there is no evidence that papyrus biomass can be directly affected by flooding. Although natural papyrus regenerative capacity can be influenced by water depth, papyrus biomass does not appear to be influenced by the same. Any increase in biomass during high flooding is due to increases in the area covered by water rather than increases in water depth. It would therefore suggest that an increase in biomass under such circumstances, however, relates more to the increased area colonized by new papyrus plants than to the increased biomass accumulation by specific papyrus plants. This explains the observation that the biomass of individual papyrus plants which outgrow the water depth are not affected. The flooding influence in this case, therefore, only affected biomass for the monthly offshoots, and not the seasonally cleared culms that had outgrown the flooding level. That leaves harvesting as the most plausible cause of this reduction in harvested biomass.

The effect of harvesting was distinctively depicted by the results for Nduru, where flooding took longer to reach, and where the extent of flooding was not substantial. Although floods might have affected papyrus biomass regeneration, the effect of harvesting on the regeneration potential was still discernible since Nduru, which had very low levels of flooding throughout the study period, also maintained a downward biomass regeneration trend. Therefore, figures for Nduru give a realistic trend of the effect of harvesting without the significant influence of flood-water depth. Furthermore, the within site difference in cleared plots and baseline plots biomass seem to suggest that where flooding was not considerable, as in Nduru, harvesting affected papyrus biomass regeneration potential more than where flooding was substantial, as in Dunga/Ogenya.

Seasonal papyrus biomass

The fact that after 6 months of regeneration papyrus biomass from un-cleared plots had accumulated beyond the baseline levels means that the swamps had not reached a dynamic equilibrium by the time of starting the study. It can be reasoned that the generally high biomass for the un-cleared plots is due to old growth accounting for part of the harvest. However, even if old growth accounted for part of the difference, it is still substantial. Květ et al. (1998) observed that a mature papyrus stand in the tropics is at equilibrium with itself, balancing biomass through interplay of mortality and regeneration, and can fluctuate by only up to 25% margin of error. The difference between baseline and exit (un-cleared plot) biomass in this case was 194.2%, while that between baseline and seasonal (cleared plot) biomass was 19.0%.

It is possible that even the un-cleared plots were still increasing their biomass and had not attained their threshold by the time the study began, which led to a substantial net increase by the end of the study period, old growth notwithstanding. This could only mean that even the un-cleared plots were still increasing their biomass (having not yet attained their dynamic equilibrium) by the time the study began, which led to a significant net increase by the end of the study period. The findings suggest that either the baseline harvest was less than a season old when the study began, or the patches were previously subjected to shorter harvesting regimes which then reduced their potential to regenerate a significant quantity of biomass in 6 months. Either way, the results suggest that the frequency of harvesting in this area does not allow the swamps enough time to regain their ecological balance.

Other studies have shown that a cleared papyrus stand is able to regain its original biomass state in 9 months to 1 year after complete harvesting (Hails 1997; van Dam et al. 2007). Informal interviews with papyrus harvesters during the study revealed that, for various purposes, papyrus is mostly harvested between 3 and 6 months of age. Thenya (2006) observed that after 14 weeks (3.5 months) incremental gain in regeneration became minimal and recommended wetland macrophyte harvesting at 14 week intervals if the natural ecological setup is maintained.

Conclusions and recommendations

This study has confirmed that above-ground papyrus biomass varies with site, and established that papyrus has the potential to replace cleared biomass within one 6-month growing season in Winam Gulf. The results agree with the findings of Gaudet (1977), Květ et al. (1998) and Thenya (2006). Monthly harvesting has been found to significantly reduce papyrus biomass regeneration potential. However, seasonal (semi-annual) harvesting does not significantly affect papyrus biomass regeneration potential. The potential for regeneration tends to be high where flooding is low. The big challenge in this case is to weigh between its biomass extraction by harvesters and its biomass replenishment by natural means, thereby increasing sustainable ecosystem utilization while maintaining the benefit flow to the local communities. A balance has to be struck between the environmental functioning of wetlands and their use for livelihood purposes. Since monthly harvesting has been found unsustainable and seasonal harvesting does not significantly affect regeneration, a sustainable harvesting programme can be established around the seasonal cycle by employing a staggered harvesting regime.

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