

PLATFORM

The potential use of papyrus (*Cyperus papyrus* L.) wetlands as a source of biomass energy for sub-Saharan Africa

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Abstract

Four of five people in sub-Saharan Africa rely on the traditional use of solid biomass, mainly fuelwood, for cooking. In some areas, the current rate of fuelwood consumption will exhaust biomass reserves within the next decade or two. A largely unrecognized source of biomass are tropical wetland ecosystems which have been shown to be some of the most productive ecosystems globally, exhibiting rates of net primary productivity comparable with high-input, intensively managed agricultural systems. Papyrus (*Cyperus papyrus* L.) is an emergent sedge with C₄ photosynthesis which is native to the wetlands, river valleys and lakes of central, eastern and southern Africa. The mean standing dry matter of culms and umbels measured at a number of locations throughout East Africa is 38.3 ± 21.6 tDM ha⁻¹, and the aerial net primary productivity ranges between 25.9 and 136.4 tDM ha⁻¹ yr⁻¹. Papyrus vegetation can be harvested by hand and stacked on the rhizome mat for partial air-drying, and it has been demonstrated that an annual harvesting regime has no negative impacts on long-term productivity. The use of papyrus as a biofuel for cooking and heating depends on converting it to a suitably combustible form, such as compressed or carbonized briquettes with a calorific value approximately one-third less than wood charcoal. While papyrus has significant potential as a biofuel, we argue that an integrated management and decision-making framework for the sustainable utilization of papyrus wetlands is required, in which all ecosystem services including the provision of biomass energy need to be assessed. Sustainability of papyrus wetlands requires management which combines the strength of traditional communal governance and modern legislation to promote its utilization. In this way, local communities can benefit from the inherent advantages of tropical wetlands as very productive ecosystems.

Keywords: bioenergy, briquettes, *Cyperus papyrus*, densification, ecosystem services, papyrus, sustainability

Received 6 April 2016; accepted 30 May 2016

Introduction

The primary source of energy for over 80% of the households of sub-Saharan tropical Africa is biomass (International Energy Agency, 2010), predominantly in the form of charcoal or wood (Cerutti *et al.*, 2015), which is used mainly for cooking and heating (Murphy, 2001). Fuelwood remains the main source of domestic energy for the rural poor but charcoal is the major source of energy for the urban poor and even though the share of the energy source provided by biomass is declining, the numbers dependent on it continue to grow. An estimated 40% rise in the demand for bioenergy by 2040 will increase the pressure on the forest biomass stocks, with efforts to promote more sustainable wood production

hindered by the operation of much of the fuelwood and charcoal supply chain outside the formal economy (International Energy Agency, 2014). The supply of fuelwood to produce charcoal or for burning directly is obtained from a wide range of sources ranging from scrubland and savannah to forest ecosystems. In many areas, the supply of this wood is not sustainable and its continued use has led to the depletion of natural ecosystems, contributing to the net global increase in atmospheric CO₂ concentrations and the loss of biodiversity (Wessels *et al.*, 2013; Cerutti *et al.*, 2015). This situation has long been recognized as the 'other energy crisis' (Eckholm, 1975), and it has recently been shown in some areas that at current levels of biomass use, reserves of fuelwood could be exhausted within the next decade or two (Wessels *et al.*, 2013). It is therefore essential to identify new forms of biofuel that can be produced and supplied sustainably and would reduce the current

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dependence on unsustainable forms of energy. An obvious source is productive, nonwoody natural vegetation which could be harvested on an annual basis which then regenerates, but without the need for expensive inputs (Somerville *et al.*, 2010). In North America, for example, Tilman *et al.* (2006) have highlighted the potential of low-input high-diversity grasslands as a sustainable biofuel option as they represent a carbon neutral or carbon-negative solution, where carbon dioxide assimilation and sequestration during the growth cycle exceeds release during combustion, and can be targeted at marginal agricultural land, reducing competition for land for food production (Valentine *et al.*, 2012) and biodiversity loss through habitat degradation. Samson *et al.* (2005) have reviewed the potential of C₄ perennial grasses to supply a bioenergy industry based on densified plant material for stoves and boilers which has a 14 : 1 energy output : input ratio. This is dependent on the use of high-yielding grasses with minimal fossil fuel use during production and energy conversion. We demonstrate here that a largely unrecognized yet significant source of biomass supply are tropical wetland ecosystems which have been shown to be some of the most productive ecosystems globally, exhibiting rates of net primary productivity comparable with high-input, intensively managed agricultural systems (Piedade *et al.*, 1991; Jones & Muthuri, 1997; Morison *et al.*, 2000; Saunders *et al.*, 2007).

Wetlands cover approximately 7% of Africa (Junk *et al.*, 2013), and many of the permanently inundated wetlands are dominated by the emergent sedge papyrus (*Cyperus papyrus* L.) (Fig. 1a). These wetlands directly support the livelihoods of millions of rural people in sub-Saharan Africa through the provision of key ecosystem functions and services, such as the supply of water, food and building materials, a buffer function to regulate river discharge, carbon storage and maintenance of biodiversity. They also serve as the basis for a rich cultural tradition (Maclean *et al.*, 2011; Gaudet, 2014). Moreover, they perform important ecosystem services on a larger spatial scale through biogeochemical cycling and their impact on the local and regional hydrological cycle and climate (Junk *et al.*, 2013). However, they tend to be largely unused as a source of biofuel. The exact geographical extent of papyrus wetlands is not known, but in the East African region alone, papyrus wetlands are estimated to cover approximately 40 000 km² (Hughes & Hughes, 1992), although the area is almost certainly decreasing as a result of agricultural encroachment and economic development (Kansiime & Nalubega, 1999; Saunders *et al.*, 2012). Currently, papyrus wetlands are under significant human pressure as large areas close to urban areas have been cleared for the cultivation of crops such as *Colocasia esculenta* (cocoyam), which has

had a significant, negative impact on the ecology and ecosystem service provision of these wetlands (Saunders *et al.*, 2012). As a result of this encroachment, it has been estimated that in some areas, such as the shores of Lake Victoria, the papyrus swamps could disappear by 2020 (Owino & Ryan, 2007).

As there is a significant risk that the valuable ecosystem services provided by papyrus wetlands will be degraded or even lost, it is important to draw attention to the importance of papyrus wetlands, to review the existing knowledge base and to present the most recent research findings. To enhance the use of such information in land management decisions and policy-making, this must be undertaken in an interdisciplinary context where the results from the natural sciences are linked to social science research (Peh *et al.*, 2013). In this platform article, we suggest that in the search for new sources of biomass for biofuel production, wetlands, such as those dominated by papyrus, have been largely overlooked in recent times, possibly because of the highly variable estimates of documented productivity and regeneration potential (Osumba *et al.*, 2010) but also because of concerns about the unsustainable utilization of these ecosystems that provide other valuable ecosystem services (Terer *et al.*, 2012). The key question addressed here is whether papyrus vegetation can be used as a source of biofuel and can this be achieved without incurring negative impacts on the ecosystem. In other words, is it sustainable? We argue that while papyrus plant material has been shown to have significant potential as both a domestic fuel in the form of biomass briquettes (Jones, 1983; Morrison *et al.*, 2013) and as a biofuel substrate (Charuchinda *et al.*, 2011), sustainable harvesting regimes are required to maintain the biofuel supply chain while at the same time continuing to support the provision of multiple ecosystem services from these wetlands (Morrison *et al.*, 2014).

Ecology, distribution and use of papyrus vegetation

Papyrus (*Cyperus papyrus* L.) is an emergent C₄ photosynthetic sedge which is native to the wetlands, river valleys and lakes of central, eastern and southern Africa and has been successfully introduced to Italy, United States and India (Haines & Lye, 1983; Hughes & Hughes, 1992; Terer *et al.*, 2012). Papyrus tends to form floating monotypic stands consisting of plant culms, the main aboveground vegetative structure, which are topped by an umbel consisting numerous cylindrical rays and flattened, leaf-like, bracteoles which represent the main photosynthetic surface of the plant as true leaves are absent in mature plants (Fig. 1b). Culms emerge sympodially on a continual basis from the leading growth edge of the plant rhizome and extend up

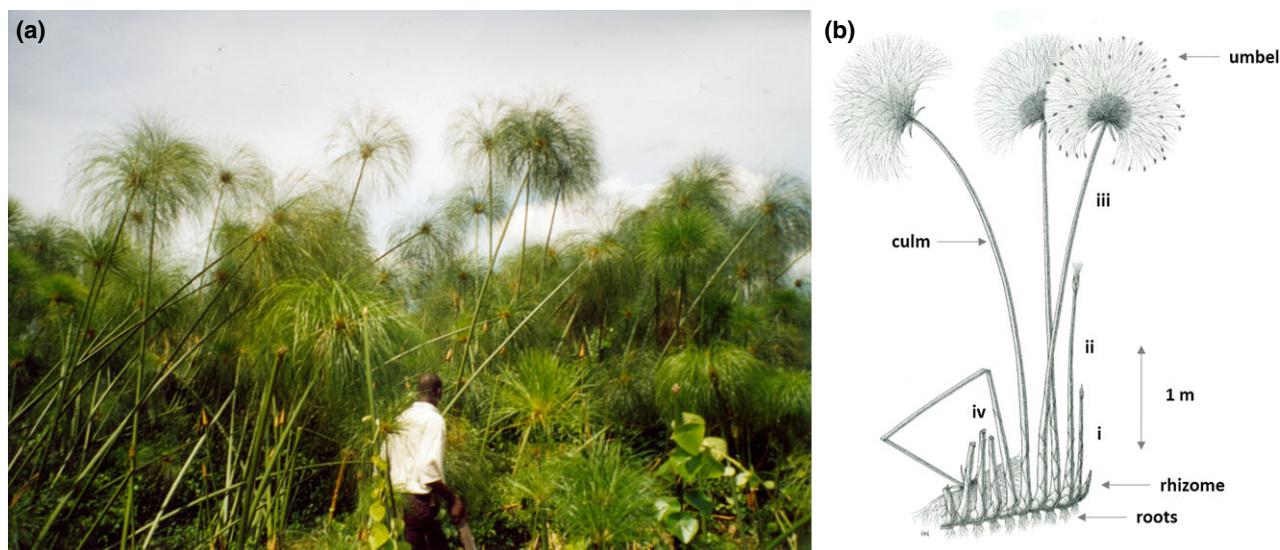


Fig. 1 (a) A view of vegetation on a papyrus swamp located at the Kirinya wetland, Jinja, Uganda, and (b) drawing of papyrus (*Cyperus papyrus*) showing the main components of the vegetation structure (root, rhizome, culm and umbel) and four age classes of the culms as they develop [(i) emergent, (ii) young, (iii) mature, (iv) senescent].

through the canopy reaching heights of up to 5 m where the umbel fully expands once the culm is completely extended. The height of the papyrus canopy ranges from 2.48 to 5.0 m at sites from Botswana to Sudan, and the number of culms per square metre ranges from 9.2 to 133 (Saunders *et al.*, 2013). The life cycle of a culm and umbel ranges between 5 and 12 months depending on site (Jones, 1982; Osumba *et al.*, 2010) after which the structure senesces and dies, resulting in the recycling of nutrients to the rhizomes and the formation of significant organic detrital deposits on the rhizome surface. Historically, papyrus was cultivated and used by the ancient Egyptians, Greeks and Romans in the production of papyri, a kind of paper made from strips of the culm pith laid and pressed together (Laws, 2011; Gaudet, 2014). However, papyrus is currently used only on a largely subsistence basis for making fences, roofing and matting (Kansiime & Nalubega, 1999; Terer *et al.*, 2012).

Yield potential of papyrus

The optimization of biofuel production is dependent on utilizing the high primary productivity of vegetation while minimizing the energy inputs required during the production life cycle and maintaining the environmental and social acceptability of bioenergy products (Tilman *et al.*, 2006; Elghali *et al.*, 2007; Zhang *et al.*, 2010). The highest rates of dry-matter production and the greatest efficiencies of nitrogen and water use tend to be found in species which possess the C_4 photosynthetic pathway (Beadle & Long, 1985). Some of the highest records of

primary productivity in either managed or natural ecosystems have been recorded in tropical wetlands where the predominant species utilize the C_4 photosynthetic pathway (Jones, 1988). For example, in South America, the C_4 grass *Echinochloa polystachya* has an annual net primary production (NPP) of up to $3.97 \text{ kg C m}^{-2} \text{ yr}^{-1}$ (Piedade *et al.*, 1991; Morison *et al.*, 2000), and in Africa, the aerial NPP of *C. papyrus* ranges between $2.51 \text{ kg C m}^{-2} \text{ yr}^{-1}$ (Muthuri *et al.*, 1989) and $3.09 \text{ kg C m}^{-2} \text{ yr}^{-1}$ (Saunders *et al.*, 2007). Carbon dioxide and water vapour flux measurements made over stands of both *E. polystachya* and papyrus have confirmed their very high net ecosystem production and have shown that these systems are potentially very large sinks for carbon. There is, however, a major difference between the growing cycle of *E. polystachya* and papyrus in that the former shows a very marked annual cycle of growth linked to seasonal fluctuations in water levels where the vegetation decomposes very rapidly and carbon is lost as the water levels fall. However, in the river valleys and lake fringing papyrus wetlands of East Africa, the hydrological status of the wetlands is less variable on a seasonal basis, and as a result, the canopy is maintained continuously and individual culms are present in multiple age classes and emerge continually from the plant rhizome (Jones & Muthuri, 1997).

The yield potential of papyrus wetlands is high because it has C_4 photosynthesis and it forms a continuously closed canopy which grows throughout the year (Jones, 2011). The standing dry matter of culms and umbels has been measured at a number of locations

throughout East Africa, where estimates of harvestable biomass ranged between 11.6 and 86.9 t DM ha⁻¹ across sites in the Democratic Republic of the Congo (DRC), Kenya, Rwanda, Tanzania and Uganda (Table 1). The values of standing biomass are relatively stable throughout the year as demonstrated by Jones & Muthuri (1997) and Osumba *et al.* (2010) who found no significant seasonal variation in monthly estimates of standing aerial biomass. In undisturbed papyrus wetlands, estimates of aboveground NPP show significant variability, ranging from 25.9 to 136.4 t DM ha⁻¹ yr⁻¹ across sites in the DRC, Kenya and Uganda (Table 2). At these rates of productivity, the canopy turnover time ranges from 705 days at its longest to 158 days at its shortest. The high rates of aboveground productivity in papyrus wetlands highlights the potential of this plant as a bioenergy source, as they represent some of the highest

Table 1 Estimates of harvestable aboveground biomass from papyrus wetlands in east and central Africa

Site	Country	Aerial biomass (t DM ha ⁻¹)	Reference
Upemba Island	DRC	31.44	Thompson <i>et al.</i> (1979)
Mulenda Island	DRC	11.63	Thompson <i>et al.</i> (1979)
Kahawa	Kenya	49.55	Chale (1987)
Lake Naivasha	Kenya	32.45	Jones & Muthuri (1985)
Lake Naivasha	Kenya	32.72	Jones & Muthuri (1997)
Lake Naivasha	Kenya	36.02	Muthuri <i>et al.</i> (1989)
Lake Naivasha	Kenya	46.52	Terer <i>et al.</i> (2012)
Lake Naivasha	Kenya	36.05	Boar (2006)
Winam Gulf	Kenya	84.57	Osumba <i>et al.</i> (2010)
Busoro	Rwanda	13.84	Jones & Muthuri (1985)
Rubondo Island	Tanzania	86.91	Mnaya <i>et al.</i> (2007)
Mpigi	Uganda	20.62	Jones & Muthuri (1997)
Kirinya Wetland	Uganda	22.6	Saunders <i>et al.</i> (2007)
Akika Island*	Uganda	50	Thompson <i>et al.</i> (1979)
Akika Island†	Uganda	29.5	Thompson <i>et al.</i> (1979)
Kampala	Uganda	29	Thompson <i>et al.</i> (1979)

DRC denotes the Democratic Republic of the Congo.

*Estimate from swamp fringe.

†Estimate from swamp interior.

Table 2 Measured rates of aerial net primary productivity of papyrus wetlands in tropical Africa

Site	Country	Net primary productivity (t DM ha ⁻¹ yr ⁻¹)	Reference
Upemba Island	DRC	72.3	Thompson <i>et al.</i> (1979)
Mulenda Island	DRC	72.3	Thompson <i>et al.</i> (1979)
Mulenda Floodplain	DRC	25.9	Thompson <i>et al.</i> (1979)
Lake Naivasha	Kenya	51.5	Muthuri <i>et al.</i> (1989)
Lake George	Uganda	115.2	Thompson <i>et al.</i> (1979)
Kampala	Uganda	90.2	Thompson <i>et al.</i> (1979)
Kirinya Wetland	Uganda	80.9	Saunders <i>et al.</i> (2007)
Lubigi Wetland	Uganda	61.1	Opio <i>et al.</i> (2014)
Lubigi Wetland	Uganda	136.4	Opio <i>et al.</i> (2014)

recorded rates of primary productivity in any natural ecosystem. In comparison, Piedade *et al.* (1991) found that *E. polystachya* had an NPP of 99 t DM ha⁻¹ yr⁻¹ and the highest annual dry-matter yield for the forage crop *Pennisetum purpureum* (elephant grass or Napier grass) was 85 t DM ha⁻¹ yr⁻¹ (Beadle *et al.*, 1985). In temperate climates, the average dry-matter yields from a large number of trials in N. America and Europe of the two perennial rhizomatous grasses with greatest potential for use as bioenergy crops are 22 t ha⁻¹ yr⁻¹ for *Miscanthus × giganteus* and 10 t ha⁻¹ yr⁻¹ for *Panicum virgatum* (Heaton *et al.*, 2004).

The effect of harvesting frequency on the sustainable yield of papyrus has been investigated in a small number of trials. Osumba *et al.* (2010) studied the effects of repeatedly harvesting papyrus over a six-month period on Lake Victoria and found that a monthly harvesting regime reduced biomass to nil after three consecutive months of harvesting. This dramatic effect of frequent harvests on growth was anticipated by Muthuri & Jones (1997) who pointed out that the removal of large quantities of nutrients as a result of papyrus harvesting may lead to reduced rates of production in subsequent regrowth periods. Terer *et al.* (2012) investigated the effects of repeatedly harvesting papyrus at 6 and 12 monthly intervals compared with unharvested controls over a period of 3 years in an undisturbed site at Lake Naivasha, Kenya. They showed that the six monthly harvesting regime for papyrus significantly reduced

aerial biomass production, culm density, canopy height and young shoot regeneration compared to the 12 monthly harvesting regime. These results illustrated the importance of allowing enough time between harvests for a full cycle of growth from young stems to senescence. However, there have not been any studies which have continued this process for several years, so that long-term sustainability is not assured at present.

Utilization of papyrus as a biofuel

Papyrus vegetation can be harvested by hand and stacked on the rhizome mat for partial air-drying before it is utilized (Jones, 1983, 1984; Morrison *et al.*, 2013). Currently marketable goods derived from harvested papyrus include furniture, mats, baskets but no market for biofuel has been developed. The use of papyrus as a biofuel for cooking and heating depends on converting it to a suitably combustible form. Papyrus culms are not dense enough to be burned directly in stoves so they need to be densified or converted into charcoal. Jones (1983) described trials to compress the papyrus into briquettes which have a moisture content of 9–15%, a density of 1.2 g cm^{-3} , ash content of 5% and energy content of 20.5 kJ g^{-1} . The briquettes were manufactured in a single piston press as a long cylinder with a diameter of 6 cm. A pilot factory was established near Kigali, Rwanda, in the early 1980s but it did not proceed to commercial operation. More recent innovations in the small-scale production of charcoal briquettes for papyrus, developed by the 'Fuel from the Fields' project at Massachusetts Institute of Technology have been described by Morrison *et al.* (2013). Bundles of dried culms were carbonized using a methodology developed by MIT's D-Lab (2012), which utilizes a converted 200-l oil drum as a carbonizing kiln. A large hole in the top of the drum and a number of smaller holes in the base allow for airflow during the initial combustion of the biomass. The majority of the volatile organic compounds in the papyrus burn off during the initial stages of the combustion. Once the papyrus has reached carbonization temperature ($\sim 450 \text{ }^\circ\text{C}$), the kiln was sealed to create an anaerobic environment to produce charcoal. The cooled carbonized papyrus was crushed by hand and mixed with a 5–10% by weight binder of cassava (*Manihot esculenta*) flour in heated water to a porridge-like consistency and made into cuboid briquettes using a simple press made locally from scrap metal (Morrison *et al.*, 2013). These briquettes have a calorific value of 20.25 kJ g^{-1} , which is around one-third less than locally available wood charcoal at 32.43 kJ g^{-1} (Morrison *et al.*, 2013). One distinct advantage of the combustion of carbonized over the noncarbonized briquettes was lower emissions of concern to human health (Morrison *et al.*,

2013). Combustion of biomass in the form of wood and charcoal is estimated to lead to the annual premature death of 400 000 individuals in sub-Saharan Africa, and it is suggested that a move from firewood to 100% charcoal would reduce air pollution by 90% (Bailis *et al.*, 2005). The mean volatile matter of the papyrus briquettes (28.85%) was considerably less than that of firewood (79.87%) but more than wood charcoal at 10.96%.

At a more industrialized scale, it has become increasingly clear in attempts to derive maximum benefits from the utilization of biomass that there are potentially a wide range of opportunities to utilize new methods to generate bioenergy while also producing new products of high value through the process of biorefining (Parajuli *et al.*, 2015). Biorefining is fundamentally the sustainable processing of biomass to produce a spectrum of marketable products as well as energy. A form of biorefinery referred to as 'green' biorefining is probably the most suitable for the type of small-scale processing of biomass that is appropriate for sub-Saharan Africa (Bruins & Sanders, 2012). In this process, the green biomass is separated into fibre-rich press cake for combustion while the green juice can be processed to produce high-quality protein for animal fodder or human consumption. As yet, papyrus has not been trialled as a feedstock for a biorefinery.

Economic assessment, environmental risk assessments and ecosystem service provision of papyrus wetlands

There have been a small number of investigations into how the natural capital of papyrus wetlands can be harnessed for the benefits of local communities (Morrison *et al.*, 2012; Johnston *et al.*, 2013). Morrison *et al.* (2013) identified 27 subsets of human welfare benefits derived from papyrus wetlands associated with Lake Naivasha, Kenya, and Lake Victoria, which they organized into four groups, corresponding to the major categories of ecosystem services (provisioning, regulating, cultural and supporting) as defined by the Millennium Ecosystem Assessment (2005), with between six and eight subsets in each category. The most significant of the ecosystem services provided by papyrus wetlands are as a carbon sink (Mitsch *et al.*, 2010; Saunders *et al.*, 2012), in wastewater treatment (Kansiime *et al.*, 2007), in flood control (Kansiime *et al.*, 2007; Ryken *et al.*, 2015) and as a biodiversity reserve (Owino & Ryan, 2007). Principles of sustainable utilization of papyrus wetlands should mean that while benefits can be derived by utilizing papyrus for bioenergy, there would be maintenance of the large number of other human welfare benefits. At the same time, the external benefits of conservation of forest ecosystems, which currently provide the primary source

of fuel wood in sub-Saharan Africa, need to be recognized.

Management and decision-making for wetlands needs an integrated approach in which all ecosystem services are identified, their importance assessed and objectives for their desired outputs are formulated (Rebelo *et al.*, 2010; Morrison *et al.*, 2012). Assessment of ecosystem services that inform local decision-making needs to be performed at a site scale which often involves technically demanding and expensive fieldwork (Fisher *et al.*, 2011). Because the resources to achieve this are unlikely to be universally available, Peh *et al.* (2013) have recently described a Toolkit for Ecosystem Service Site-based Assessment that guides local, nonspecialists through a selection of relatively accessible methods for identifying which ecosystem services may be important at a site and evaluating the benefits from them. However, this may be difficult to achieve in practice because of divergent perceptions among stakeholders regarding the priority issues in the management of papyrus wetlands that are subject to agricultural conversion. For example, Namaalwa *et al.* (2013) found that in an area in Eastern Uganda, resource users worry about water and land use conflicts, while local and national governments are more concerned about agricultural encroachment and biodiversity loss.

The sustainability of biofuels should be assessed based upon the net energy they contribute to society and the amount of greenhouse gases they emit compared to their energy equivalent in fossil fuel use. More importantly in the case of utilizing papyrus wetlands, the judgement should be based on the efficient use of resources such as land and water as these are competed for in the production of food, fibre and wood for ecosystem services. It is widely accepted that the metrics of this sustainability should be assessed by analytical tools developed to model impacts and assist with decision-making such as life cycle assessment (LCA). A key concern in constructing LCAs for biomass production in Africa is the realistic delineation of boundaries around the various inputs, outputs and processes that make up the theoretical life cycle of biofuel production and use. This is compounded by the fact that almost all LCAs so far have been undertaken in a European or North American context and not in lesser developed countries (Smith, 2010).

Conclusions

There is still a dearth of information concerning our understanding of the physiological, environmental, socio-economic and cultural functions of papyrus wetlands, which makes the development of strategic, interdisciplinary management and conservation measures difficult in the face of increasing human pressure for

food, fuel and water. The potential utility of papyrus as an energy source will, however, depend on assurances that these ecosystems can produce a reliable supply of biomass which does not lead to the ultimate demise of these wetlands and that exploitation of this type does not compromise the other important ecosystem services provided by these wetlands. We therefore place strong emphasis on assessing the impact of repeated harvesting of biomass from the papyrus swamps on the range of ecosystem services provided by these wetlands and demonstrating how the use of papyrus biomass can provide a replacement for the current sources of wood-based biomass used by both the rural and urban populations of Central and East Africa.

Although we are advocating the sustainable utilization of papyrus vegetation, it is ironic that there is no consensus on what the term 'sustainable' actually means, particularly in lesser developed countries (Bosch *et al.*, 2015). Currently, biomass assessments are a patchwork of voluntary standards and regulations and Bosch *et al.* (2015) argue that this leads to mistrust and protectionism, slow investment and slower growth. Consequently, a metric for evaluating biomass sustainability needs to be designed which includes social as well as environmental and economic factors. Management and decision-making for wetlands needs an integrated approach in which all ecosystem services are identified, their importance assessed and objectives for their desired outputs are formulated. This requires a decision support framework (DSF) to arrive at an optimum solution (Zsuffa *et al.*, 2014). Components of the DSF should include calculation of biomass production and optimum harvesting strategies, estimates of nutrient removal and quantification of downstream water quality. There should also be a critical analysis of the social and economic factors that underpin the use of wetland resources (Rebelo *et al.*, 2010). Life cycle assessments do not look at social impacts, so Bosch *et al.* (2015) have suggested a starting point could be the total factor productivity metric used to measure agricultural productivity.

Sustainability of papyrus wetlands requires management which combines the strength of traditional communal governance and modern legislation to promote its utilization (van Dam *et al.*, 2014). In this way, local communities can benefit from the inherent advantages of tropical wetlands as very productive ecosystems. This will become increasingly important where growing populations and improving standards of living demand increased use of available resources.

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