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Review Article

Papyrus as an ecohydrological tool for restoring ecosystem services in Afro-tropical wetlands

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1. Introduction

The concept of Ecohydrology, stressing the inter-relationship that exists between macrophytes and aquatic ecosystem health (Harper et al., 2016), originates from the scientific recognition of the dominant impact that vegetation can have on the physico-chemical conditions of lakes and streams. Riparian macrophytes play a key role in the control of wetland ecosystem processes by acting as chemical filters as well as hydrological and climatic buffers. Wetland managers can strengthen environmental health and progress towards conservation targets by maintaining or re-establishing submerged and/or riparian macrophyte beds/stands. The effective functioning of stands of macrophytes, particularly emergent macrophytes at the land-water interface, thus becomes an important tool for ecohydrological management.

The most widespread emergent macrophyte in Africa is the giant sedge *Cyperus papyrus* L. (Cyperaceae), the largest of the 400 tropical sedge species within the genus, which represents perhaps the best-known example of long standing human use of a riparian resource. Since the early Holocene, human populations living along the lower Nile have harvested papyrus and used it for multiple needs, including building materials, baskets, as well as canoes and sailing boats used for transporting light cargo and during religious events (Gaudet, 2014). It is estimated that by 3000 B.C., Egyptians had invented paper using papyrus; thus it became widely known across the Mediterranean. The original name of the plant derived from an ancient Egyptian term meaning "royal". Papyrus then gave origin to the word "paper", as well as to "Bible" – which derives from the ancient Greek "*biblon*" (book), a term which originally referred to the bundle of fine papyrus strips that were assembled together to compose a single paper sheet. Phoenicians, Greeks and later Arabs traded papyrus and attempted to grow it abroad. In ancient times, papyrus swamps used to be grown in Mesopotamia and in Syria. Papyrus still grows today along the river banks of the Ciane, a small stream in southeastern Sicily (Gaudet, 2014).

Papyrus is a key species dominating Afrotropical swamps across a wide latitudinal range (17 N–29 S; Jones and Muthuri, 1985) stretching well beyond the inter-tropical belt. It also grows across a high altitudinal range extending from sea-level up to a maximum of 2300 m a.s.l.

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(Ol Bolossat swamp in Kenya grows right across the Equator at 2340 m a.s.l.; pers. obs.). The original distribution of papyrus ranged from the southern African region up to the southern shores of the Mediterranean, leaving out much of West Africa (Van Dam et al., 2014). The portion of the 2,072,775 km^2 of wetlands in the African continent (Mitchell, 2013) that is covered by papyrus swamps is not well known, despite technological advances that should enable tracing papyrus by means of satellite imagery (Adam and Mutanga, 2009; Adam et al., 2012). The main centres of papyrus distribution include the swamps in the Sudd of South Sudan, the Okavango inland delta in Botswana, the Upemba region in Congo including Lakes Tumba, Mai Ndombe and the complex of wetlands bordering the lower Ubangi and the mid Congo Rivers, the Bangweulu and Kafue Flats along the Zambesi. Papyrus also grows along the shores of most freshwater lakes in East Africa. It used to be common all along the lower Nile and in its delta, but because of intense exploitation by humans, riparian degradation by cattle and farming within the riparian zone, it became progressively rare. Papyrus had virtually disappeared from Egypt by the early twentieth century (Täckholm and Drar, 1950); it has recently been re-recorded in the Nile delta, but with low occurrence (El-Ghani et al., 2011).

In East Africa, papyrus swamps probably do not exceed 40,000 km^2, an average figure estimated in the early 1990s (Hughes and Hughes, 1992); this surface is believed to undergo frequent inter-annual variations because of the water level changes that are common in Afrotropical swamps. Throughout East Africa now, papyrus wetlands are polluted by wastes from industry, agriculture and households (Owino and Ryan, 2007; Kansiime et al., 2007; Munabi et al., 2009). More than 70% of the Upper Nile and Congo wetlands have been lost during the last two decades of the twentieth century (Maclean, 2004). Papyrus swamps on Lake Victoria have been extensively destroyed by overharvesting (Osumba et al., 2010 and references therein) and often replaced by subsistence crops such as cocoyam *Colocasia esculenta* (Kansiime et al., 2005a), sugarcane and/or rice, or even common vegetables (tomatoes, cabbages, carrots, potatoes; Maclean et al., 2011). When swamps have been drained for large-scale agricultural exploitation, papyrus has specifically been targeted (Maclean et al., 2014); papyrus swamps are drained 4 times more often than wetland ecosystems in general and this is leading to a severe restriction of available habitat for papyrus endemic birds (Mafabi, 2000; Maclean et al., 2014). Deliberate swamp drainage as well as natural water level fluctuations can turn papyrus swamps into significant carbon sources through peat decomposition (Jones and Humphries, 2002). Their conversion to agricultural land reduces valuable ecosystem services (Kansiime et al., 2007) with a severe economic loss for local communities (Maclean et al., 2011; Van Dam et al., 2014). Damming and channelisation also increase malaria incidence by raising water temperature and by increasing the occurrence of biotopes that shelter mosquitoes; conversely, papyrus establishment shades out mosquito breeding sites and reduces their suitability to develop dense mosquito colonies (Mekonnen et al., 2005; Lindblade et al., 2000; Goma, 1960).

The value of papyrus in providing ecosystem services to the human populations surrounding swamps has been highlighted by several authors in attempts to prevent them from destruction, and we review these studies concisely here. This sets the scene for addressing regulating services of prime ecohydrological relevance that, we argue, are the most important, yet poorly studied and poorly understood. We summarise and discuss the existing evidence for processes indicating that papyrus can be vital in moderating local climate and in preventing desiccation through its contribution to the water cycle. This evidence also includes limited measurements, carried out by us, of temperature gradients within papyrus swamps. We thus argue that papyrus protection and enhancement should be pursued as an important management tool in Afro-tropical wetlands, particularly in the face of the recent and greater hydrological uncertainties brought about by climate change.

2. Ecosystem services

2.1. Provisioning services

Several authors reviewed the ecosystem services provided by papyrus swamps; most of them have highlighted direct human uses and the high value of provisioning services (Maclean et al., 2011; Terer et al., 2012a, 2012b; Morrison et al., 2012), including: water, food, materials for building, crafts and fuel, medicinal herbs, among others (Bacon, 1997; Van Dam et al., 2011; Maclean et al., 2011). Riparian sedges and grasses are used for weaving baskets, thatching roofs, assembling fish traps and building canoes, as in ancient Egypt for more than 5000 years until 2000 years ago; these activities still occur on Lake Tana, in Ethiopia (Gaudet, 2014). Riparian macrophytes are important forage resources, especially at times of drought; papyrus wetlands have been regularly used to feed cattle (Muthuri and Kinyamario, 1989). Because of its rapid growth, the wise use of papyrus fibre can be a source of valuable sustainable resources for direct use balanced by natural regrowth; this explains the high value attributed to its provisioning services.

It has been estimated that average aerial dry weight biomass regeneration can reach 6.28 $kg\,m^{-2}\,y^{-1}$, similar to a sugarcane crop (Muthuri et al., 1989). More recently, estimated production rates derived from different swamps ranged widely between 0.09 and 14.3 $kg\,m^{-2}\,year^{-1}$ (Osumba et al., 2010). This suggests that, with responsible husbandry in some swamps, papyrus could be more widely exploited in a multipurpose wise-use fashion that would take advantage of its water treatment capacity as well as its sustainably renewable standing biomass as a source of fuel and fibre (Perbangkhem and Polprasert, 2010). A sustainable annual harvest of up to 15 $t\,ha^{-1}\,yr^{-1}$ was suggested by Jones (1982, 1983). It takes only 6 months for germinating papyrus to reach maturity (Van Dam et al., 2011), and a harvesting rate between 9 and 12 months was recommended to maintain high standing biomass (Van Dam et al., 2007). No further increment in biomass was