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Spatial and temporal variation of papyrus root mat thickness and water storage in a tropical wetland system

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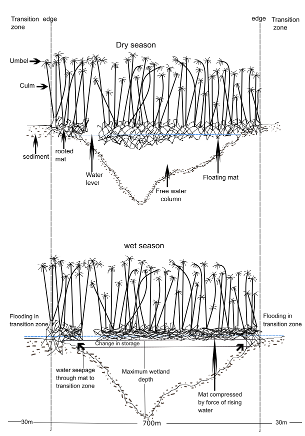
HIGHLIGHTS

- We quantified water storage and the response of papyrus root mat to changing water levels in a tropical wetland
- We measured root mat thickness and depth of the free water column along transects in the dry and wet season
- Free water column increased across all transects in the wet season. This facilitates storage of extra water in the wetland
- There was a negative correlation between changes in free water column and papyrus mat thickness between the two seasons
- The wetland's storage function can contribute to agriculture through sustainable use of the water for irrigation

GRAPHICAL ABSTRACT



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ABSTRACT

Papyrus wetlands are predominant in permanently inundated areas of tropical Sub Saharan Africa (SSA) and offer both provisioning and regulatory services. Although a wealth of literature exists on wetland functions, the seasonal behaviour of the papyrus mat and function in water storage has received less attention. The objective of this study was to assess the response of the papyrus root mat to changing water levels in a tropical wetland system in Eastern Uganda. We delineated seven transects through a section of a wetland system and mapped wetland bathymetry along these transects. We used three transects to measure spatial and temporal changes in mat thickness and free water column, and to monitor variations in total depth during two seasons. The free water column increased across all transects in the wet season. However, changes in the mat thickness varied spatially and were influenced by the rate of increase of the free water column as well as wetland bathymetry. The proportion of mat compression was higher at the shallow end of the wetland (83%) compared to the deep end (67%). There was a significant negative correlation between changes in free water column and papyrus mat thickness ($r = -0.85$, $p = 000$). Therefore, the mat compresses in response to increase in free water column, which increases the ratio of the free water column to root mat thickness. Hence, the wetland accommodates excess water during rainy seasons. Water depth varied from 1.5 m to 2.1 m during the monitoring period, corresponding to a water storage of 61,597 m^3 and 123,355 m^3 respectively. This means a 50% change in water volume for the studied wetland

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section. This water regulatory function mitigates severity of floods downstream, but the stored water is also useful to the surrounding communities for wetland-edge farm irrigation during dry seasons.

1. Introduction

Papyrus wetlands are predominant in permanently inundated areas of Sub Saharan Africa (Mburu et al., 2015; Morrison et al., 2013). They are dominated by monocultures of *Cyperus papyrus* L., which is a large herbaceous sedge whose culm grows up to five metres (Terer et al., 2012). Sometimes they grow in combination with other species like *Miscanthidium violaceum*, *Phragmites mauritianus and Typha domingensis* (van Dam et al., 2007). The wetlands are a source of fuel, medicinal herbs, fishing grounds, raw materials for crafts, building materials, and inundated wetland edges are utilised for agricultural activities (Donaldson et al., 2016; Terer et al., 2014).

Papyrus wetlands also provide services of water purification, flood mitigation, water storage, and are important carbon sinks (Mburu et al., 2015; Saunders et al., 2007; Saunders et al., 2013; van Dam et al., 2007). For example, papyrus wetlands can store up to 1.6 kg C m^{-2} y^{-1} (Jones and Humphries, 2002) and contribute to improved water quality through uptake of faecal coliforms, phosphorus, as well as nitrogen uptake varying between 17.2 g N m^{-2} y^{-1} and 76.7 g N m^{-2} y^{-1} (Kansiime and Nalubega, 1999; Okurut, 2000; van Dam et al., 2007).

Although the water purification function of papyrus wetlands has been widely studied, their provisioning and regulatory functions especially water storage and flood mitigation have received less attention (van Dam et al., 2014). A few studies highlight the importance of the papyrus mat system in water storage (Kansiime et al., 2007; Kipkemboi et al., 2002); but to the best of our knowledge, there is no literature describing the spatial and temporal variation of the papyrus mat structure in different seasons and how this phenomenon affects water storage.

Papyrus plants exist either in rooted or floating form, rooted papyrus are anchored in the sediment at shallow ends of the wetlands. Some stands can be detached during inundation by fast flowing water, forming floating mats. The mats are made up of loosely intertwined roots and rhizomes, and can spread by rhizome propagation over open water to form a continuous root-rhizome-mat system (Boar, 2006; Saunders et al., 2012; van Dam et al., 2007). The mat system can support the weight of an adult male of approximately 80 kg. The loose structure of the floating mat allows exchanges of water between the free water column beneath the plant and its root system (Azza et al., 2000), which enables the plants to access nutrients in the water.

The configuration or morphology of the rhizome-root-mat complex is believed to influence the functioning of papyrus wetlands. For example, Kipkemboi et al. (2002) observed that the floating papyrus mat in Namiiro and Lubigi wetlands moved upwards with rising water levels during periods of flooding. In addition, the mat system reduces water velocity which increases water retention time (Kansiime and Nalubega, 1999). Indeed, Ryken et al. (2015) demonstrated the buffering capacity of papyrus wetlands when they showed that the timing and amount of peak discharge was delayed and lowered for catchments with intact wetlands compared to those with degraded wetlands.

We illustrate a typical papyrus wetland cross-section in Fig. 1. The wetland has a peat-sediment layer overlaying a solid bottom of varying topography. The dominant vegetation is papyrus, which is rooted at the edges but floats over the water in the wetland centre. We define the wetland edge as the dry season water boundary, while the transition zone is the area that is seasonally flooded in the wet season. The term 'free water column' is used to define the column of water beneath the floating vegetation and we use this term from here on. The wetland has open water areas at inlets and outlets, although small patches of open water occur in the central parts too. The density of plants in the figure is simplified but actual culm density varies between 16 and 36 culms m^{-2} (Opio et al., 2014).

Fig. 1 also illustrates the response of the papyrus mat to seasonal changes in the hydro period. The friction of the floating mat as well as return flow within the free water column reduce water velocity. These processes are described by Liu et al. (2017) and Zhang and Nepf (2011) who demonstrated using tank experiments, that velocity is reduced both within the root layer as well as in the free water column. This increases the retention time, which in turn mitigates impact of floods downstream and enhances aquifer recharge and bank storage through infiltration.

In wet seasons, water levels increase because of higher flows. The papyrus plant rises with the water because it is buoyant. In this way, the water storage of the wetland increases. When the water level exceeds the maximum wetland depth, water seeps through the rooted papyrus mat and floods the transition zone (Fig. 1). The wetland releases stored water slowly in the dry season, which makes it available for domestic and irrigation use.

Despite the services of papyrus wetlands, increasing pressure for agricultural expansion has led many wetlands to be converted for agriculture especially rice growing (Kipkemboi and van Dam, 2016). As a result, agricultural crops replace natural vegetation in the wetlands (Kansiime et al., 2005). The conversion starts at the wetland edges during periods of low flow when farmers slash the above ground biomass (culms) of rooted papyrus. They then dig out the roots and rhizomes from the ground and burn them to prevent regeneration of the plant in the wet season.

Gradually this procedure extends into the wetland. In the deeper parts of the wetlands, farmers create artificial channels to drain water from slightly raised rice plots established in the wetland. As a result, draining reduces the water level in these parts of the wetland to a level near the ground surface. There are two ways of wetland conversion, the first involves creating artificial drainage channels and the second involves filling the wetland with soil especially for very deep channels. Small-scale farmers rarely attempt the latter process because it is costly, but it is easier to undertake for commercial rice expansion.

Due to the mounting pressure on wetlands, it is crucial to understand the regulatory (flood control) and provisioning (water provision) services of papyrus wetlands. Improved understanding of the dynamics of this system could enhance sustainable management and utilisation of wetlands to increase agricultural productivity under a changing climate. For example, rather than draining wetlands to grow crops (van Dam et al., 2014), local communities could utilize stored wetland water to irrigate crops grown at wetland edges especially during the dry season.

This study was carried out to assess the response of the papyrus root mat to changing water levels. The wetland of interest has rooted papyrus at the edges and floating papyrus in the centre of the wetland. The changes in the root mat are important to know, since they influence flow paths as well as the amount of interaction between water and the root-rhizome mat complex. We measured detailed wetland bathymetry, and the spatial distribution of mat thickness at different water depths.

The hypothesis is that during periods of high water flow, the depth of the free water column beneath the papyrus mat increases. This increase exerts a force on the papyrus mat, which causes it to rise. However, as the water level increases further, the papyrus mat begins to compress. In this way, the wetland accommodates more water, which increases its storage in the wet season.