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Impact of Sediment Load on *Cyperus papyrus* in Lake Tana Buffer Zone

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Impact of Sediment Load on Cyperus papyrus Growth in Lake Tana Buffer Zone, Source of Blue Nile River

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Abstract:
Cyperus papyrus is the cornerstone of Lake Tana's buffer zone, a vital ecosystem supplying the Blue Nile. However, this critical area is under siege from excessive sediment runoff, primarily due to deforestation and unsustainable agricultural practices in the surrounding watershed. The lack of research on papyrus's response to varying sediment levels has hindered restoration efforts. To address this knowledge gap, a study was conducted between May and October 2020 near Lake Tana. Twelve experimental wetlands were constructed, each divided into four sediment treatments: control (0 cm), low (1 cm), medium (5 cm), and high (10 cm). Papyrus growth parameters, including height, diameter, new shoot count, and above and belowground biomass, were monitored every two weeks. Results unequivocally indicate that sediment load significantly impacts papyrus growth. Plants subjected to high sediment levels exhibited stunted growth, with reduced height, diameter, and new shoot production compared to those in lower sediment or control conditions. Biomass measurements also revealed a substantial decline in both above and belowground plant matter under high sediment stress. These findings highlight the urgent need for sediment management strategies to protect and restore the papyrus-dominated wetlands of Lake Tana.

Key words; Restoration, Sediment load, Buffer Zone, Constructed wetland, Growth performance

1. Introduction

Cyperus papyrus wetlands around Lake Tana and along the river banks are increasingly degrading and quickly disappearing and it brings a dramatic reduction of their buffering role in the ecosystem(Mengistu, 2020). High population density within the catchments of the Ethiopian Rift Valley Lakes and in the highlands have been associated with a series of deleterious trends, in particular, those arising from the clearance of vegetation for agriculture and overgrazing (Awulachew et al, 2007;Giweta & Worku, 2019). Human activities heavily influence the nature of river flow and sediment movement, the use of land and water bodies, land cover, and river plan and bedforms; and it may result in affect the growth performance of C. papyrus (Mulatu *et al*., 2024).

High sediment load can fill in and destroy wetlands (Huang et al., 2022). This affects the distribution of the flora and fauna and the overall productivity of the wetlands (Molinos & Donohue, 2009). High sediment deposition has been shown to have a wide range of effects particularly, on *C. papyrus* communities (Molinos & Donohue, 2009). Sediment, in general, can bury seeds, seedlings, and adult plants to varying depths, increasing stress on the plant's survival and growth performance (Aedasong *et al.*, 2019). Excessive accumulation in wetlands causes hypoxia in the root zone and physical stress on aquatic plants. As a result, *C. papyrus* height, new shoot recruitment, stem density, and diameter are impacted (Maithya *et al*., 2021;Geremew *et al*., 2018). High sediment deposition in wetlands affects Eco physiological factors such as photosynthesis rate, number of bundle sheath cells, chlorophyll-a fluorescence, total chlorophyll content, and chlorophyll-a/b ratio (Vickruck & Richards, 2021) .

Wetlands in Lake Tana catchment are now threated from sedimentation (silt load) as a result of upstream intensive agricultural activities and deforestation. Negative effects of sedimentation on plant growth include lower oxygen or light availability in submerged or buried soils. Shoot elongation, high shoot mass ratio, short and thick roots, low specific root length and shallow root systems are examples of morphological adaptations that enable wetland plants to escape sedimentation by acquiring oxygen and light, or by diminishing root oxygen demand (Pan *et al.*, 2014b).Wetlands within agricultural landscapes are increasingly receiving higher sediment inputs (G. Wang *et al*., 2013).

The high productivity of papyrus plays a vital role in ecological functioning and is harnessed for socio-economic purposes. From an ecological perspective, papyrus swamps trap sediments and pollutants entering water bodies (Terer *et al.*, 2012).Conservation work is essential as the papyrus communities in the wetlands around Lake Tana are threatened with extinction (Gebremedhin *et al.*, 2018). Effective management of *C. papyrus* and its ecosystem require the integration of the knowledge of how varied sediment depths impact local wetland ecology. Recent quantitative studies by (Geremew *et al.*, 2018) have shown that catchments with disturbed papyrus swamps resulted in sediment yield three times greater than those with pristine papyrus vegetation. Some of the dominant macrophyte species in the southern and eastern shore of Lake Tana were listed in the studies of (Wondie, 2018). Cyperus Papyrus swamps are highly recognized for their outstanding ecological and economical importance, their historical and current spatial distribution and size in the Lake Tana sub basin have not yet been systematically assessed in detail in the above-mentioned studies.

Lake Tana is a vital resource under stress from mainly anthropogenic activities. A few regional initiatives have been launched, and more are planned, to help narrow its decline and sustain its beneficial services to society and nature. Many knowledge gaps exist for Lake Tana, making it difficult to arrive at the most critical interventions required at different stages of restoration. The impacts of siltation on the Lake Tana community will shed light on how plant populations cope with these environmental stresses and help guide conservation and restoration efforts. Data on sediment depth impacts in one growing season should spur additional research into the impacts of siltation over long periods of time, an important aspect of sustainable wetland management.

Therefore, this project focuses on the impact of varied sediment depths on the growth performance of *C. papyrus* in Lake Tana within managed wetlands on the lake shore.

2. Material and methods

2.1 Experimental design

The experiment was conducted in constructed wetlands at Bahir Dar University Maritime Academy Lake Tana campus near the Lake (11°37.336' N and longitude 37°20.542'). The system consists of three treatment beds and one control with three replications each. The beds were constructed 1 m×2 m with 50 cm depth using a geomembrane liner and filled with composite sediment up to a height of 0.3 m. This composite media was 20-30 mm in diameter, as recommended by the Madania *et al*., (2010), and fed with the same amount of lake water for three consecutive days before planting papyrus. The experimental plants were collected from a Legdiya littoral wetland 10-20 cm deep. Fragments of rhizomes not greater than 40 cm *C. papyrus* plants were selected according to Gikas and Tsihrintzis,(2014) and taken from the natural habitat of Legdiya Wetland and transplanted into their respective constructed beds, each with a surface area of 2 m^2, at a density of 30 rhizomes / 2 m^2.

Following a one-month acclimation period, each bed was fed with water through pipes from Lake Tana with the same average flow rate (measured with a stop watch). The beds were labeled randomly (Fig. 1). All beds were planted with an initial depth of 30 cm of sediment. The control beds received no additional sediment. Treatments beds received 1 cm, 5 cm, and 10 cm of additional sediment, respectively, after one month. During the 10-day acclimation period, water depth was kept at 5 cm to ensure the viability of the specimens. Water was then added every day to maintain a 20-cm water depth. In the natural environment of Lake Tana, high sediment level corresponded to the most shallow section (0.9 m sediment level) and a very low sediment regime represented a relatively deeper section of the lake (< 0.2 m sediment level) (Geremew *et al.*, 2018). The climate conditions of the constructed wetlands were not controlled, such as with a greenhouse, in order to mimic the natural environment. The lake water, tested in the laboratory, produced average concentrations of SO_4^{2-} (0.89 mg/L), Zn (0.28 mg/L), Cr^{+6} (0.08 mg/L), Cu (0.28 mg/L), $NO3^-$ (0.19 mg/L) and NO_2^- (0.82 mg/L).

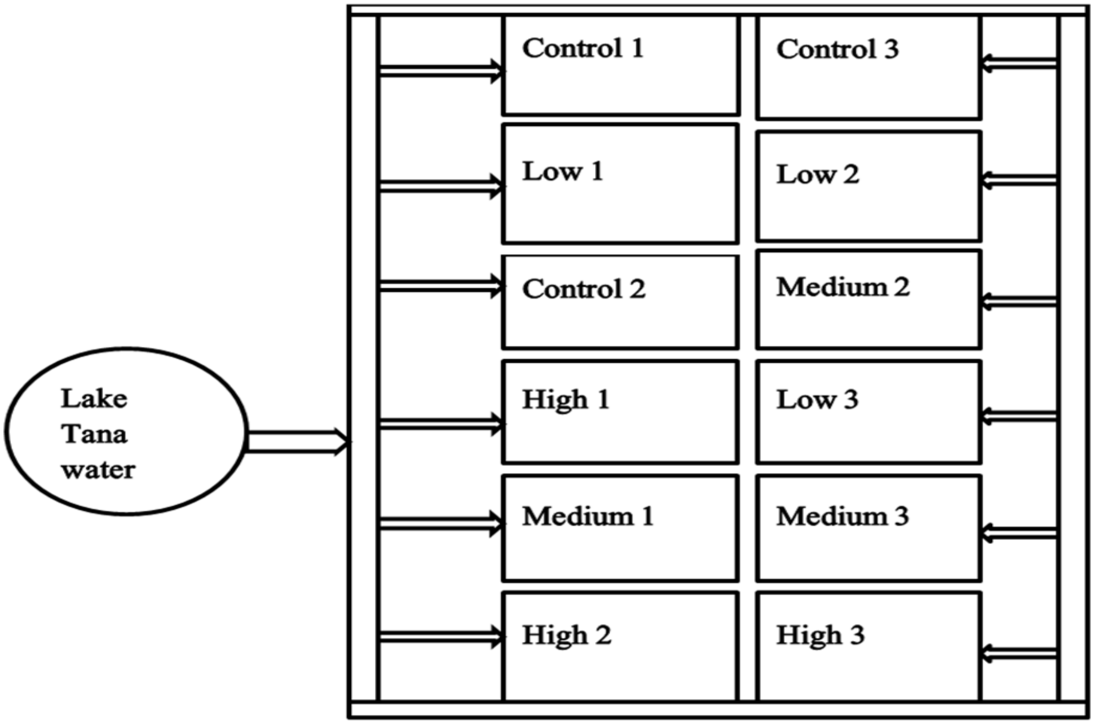


Figure 1. Simple diagram of experimental constructed wetlands, randomly assigned.

The experimental sediment was collected from Gilgel Abay at Chimba, Legdiya, and multiple other wetlands around Lake Tana, up to 10 km from Legdiya. The principal properties, measured once at the laboratory at the beginning of the experiment are listed in Table 1.

Table 1. Properties of sediment used for the experiment.

	Sand (%)	Silt (%)	Clay (%)	Class	pH	K (Cmol+/kg)	TN (%)	TP (ppm)
Values	17	26	57	Clay	5.86	3.59	0.04	9.5

2.2. Data Collection from the Control Beds and Treatment Beds

2.2.1. Measurement of growth parameters

Ten individual culms were marked with a unique number (identification code) using a permanent marker. The length of each culm was measured above the rhizome from the end of the scale leaf to the apex of the umbel while the girth was measured just above the scale leaf according to (Muthuri & Jones, 1997). All plant measurements were taken at two-week intervals from May to October, 2020 (Muthuri and Jones, 1997; Opio *et al.*, 2014). Measures included papyrus culm length and diameter. Papyrus height was measured from the ground to the top-most internodes of the shoot by use of a meter rule. Stem diameter was measured at the base of the stem (10 cm from the soil level) and below the flower using a Vernier caliper.

2.2.2. Recording papyrus culm density and new shoots

In each constructed wetland, individual papyrus culms were counted to get the culm density (i.e., total culms per unit area). New culm shoots were identified, recorded, and marked with a different number in each constructed wetland on every visit.

2.3 Data analysis

Prior to parametric tests, data was checked for conformity to normal distribution using the Shapiro-Wilk test using R and SPSS. The Kolmogorov-Smirnov test and Levene's test were used evaluate normality and homogeneity of variance, respectively. Data that met the assumptions of normality and homogeneity of variance was analyzed using Analysis of Variance (ANOVA) for any significant differences in the measured variables among treatments beds and the control bed. Data that did not meet the assumptions were analyzed using the Kruskal-Wallis test. As most data were not normally distributed, the Kruskal-Wallis One Way non-parametric ANOVA (KW-ANOVA) was used to determine differences between sediment levels and papyrus growth parameters. This was followed by Kruskal-Wallis multiple comparison tests for post-hoc evaluation. Descriptive statistics were also used to analyze the growth parameters of *C. papyrus*. The relationship between population dynamics (culm density and new shoot density) and sediment depth in the constructed wetland was assessed using Spearman's rho rank correlation. To explore variations among treatments, a comparison of mean growth rate of papyrus was done. The relationship between culm height and diameter was determined by a linear regression analysis after data was log-transformed.

3. Results and Discussion

3.1. Results

3.1.1 Growth characteristics of the plants

Papyrus height: Culm height growth was higher in papyrus with medium sediment, but lower in high sediment treatments (Fig. 2). Culm height was significantly smaller in the high sediment as compared to the low sediment treatment beds (KW-ANOVA, $df = 3$, $f = 4.3$, $P < 0.05$). Medium treatment beds also produced significantly greater culm height compared to the high sediment treatment bed (KW-ANOVA f=5.1, df=3, P < 0.05). There was no significant interaction between papyrus growth and sediment levels.

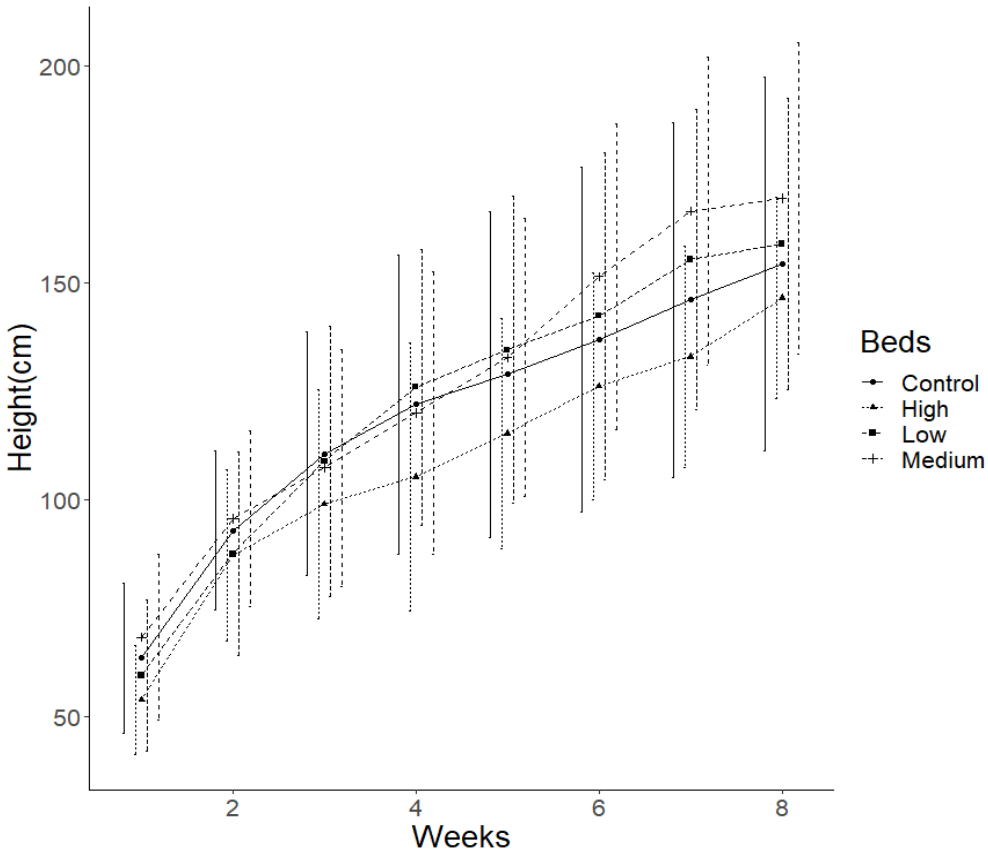
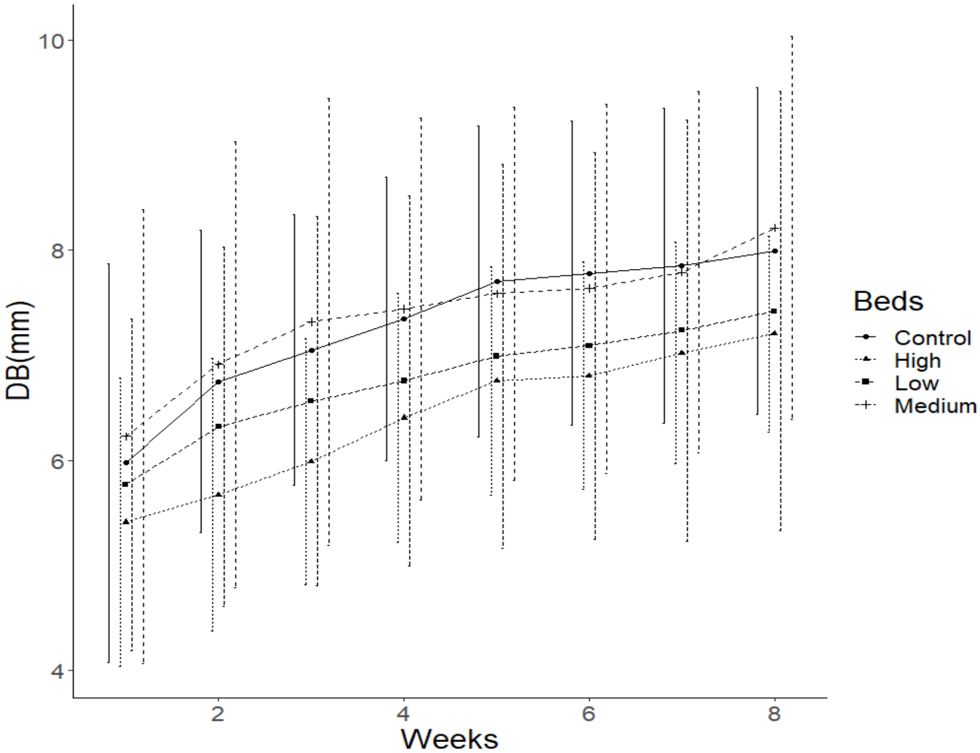


Figure 2. Height of *C. papyrus* (cm) grown at four sediment levels for eight weeks from June 2020 to October 2020 at two-week intervals.

Stem diameter below the flower**:** Stem diameters in medium sediment beds were significantly larger than stems in the high and low sediment beds (KW-ANOVA, f = 8.6, df = 3, P ≤ 0.05; Fig. 3). The mean stem diameter for medium sediment treatments (7.60 mm) was significantly higher

157 than low (6.92 mm) and high treatments (5.04 mm) and the control (6.90 mm).



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159 Figure 3. Stem diameter below the flower (DB) of *C. papyrus* (mm) grown at four sediment levels
160 for eight weeks from June 2020 to October 2020 at two-week intervals.

161 ***Stem diameter above sediment*****:** The stem diameters above the sediment in the medium sediment
162 treatment beds were significantly larger than each of the other treatments and the control beds
163 (KW-ANOVA f=9.6, df=3, $P \leq 0.05$). Stem diameters with medium sediment steadily increased
164 as compared to other treatments and control beds; plants in high sediment beds at the end of the
165 experiment had smaller diameter stems compared to medium sediment beds (Fig. 4). The mean
166 stem diameter for medium sediment beds was high (17.70 mm) compared to the low sediment
167 (15.51 mm), high sediment (12.06 mm), and control beds (16.90 mm).

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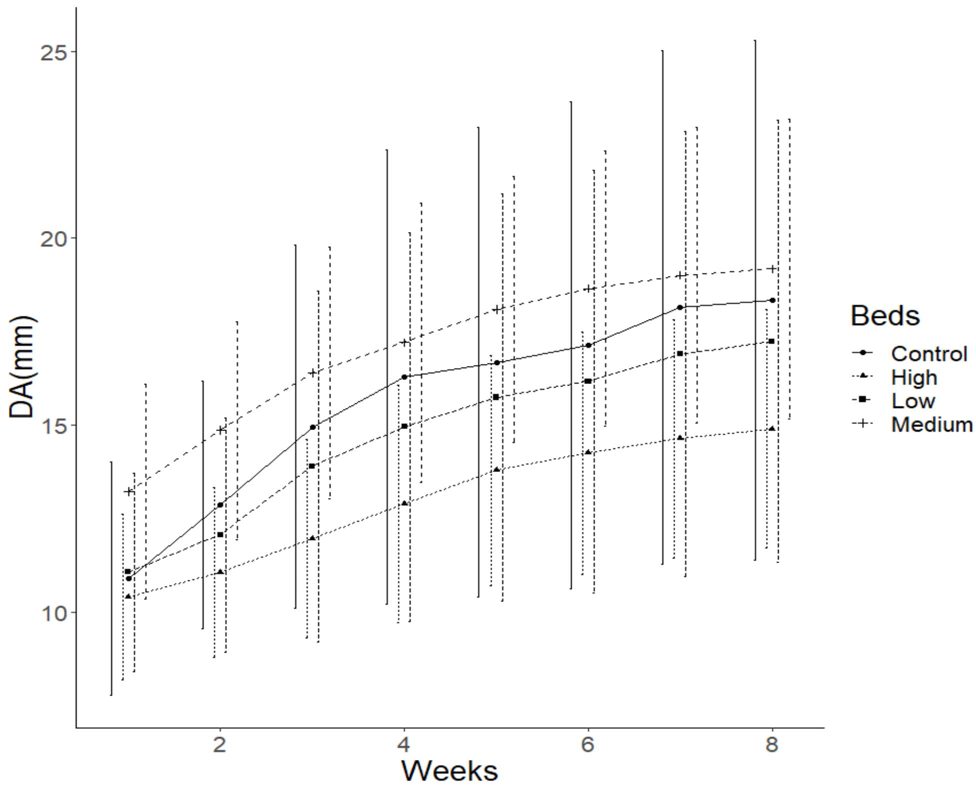

Figure 4. Stem diameter above the sediment growth (DA) of *C. papyrus* (mm) grown at four sediment levels for eight weeks from June 2020 to October 2020 at two-week intervals.

3.1.2 Density and new culm shoot recruitment

Papyrus culm densities differed among treatment beds and plants in control beds had the highest culm density (67 ± 23 culms/2 m^2) as compared to the low (56 ± 21 culms/2 m^2), medium (53 ± 20.5 culms/2 m^2) and high treatment beds (35 ± 8.5 culms/2 m^2). Kruskal-Wallis tests showed that there was a significant difference in papyrus culm density between control and low, medium, and high ($\chi^2 = 19.5$, df = 2, $P < 0.001$). One-way ANOVA and independent samples tests showed that there was significantly higher mean plant density between the control beds and the medium ($P < 0.001$ and high beds ($P \leq 0.002$; Fig. 5).

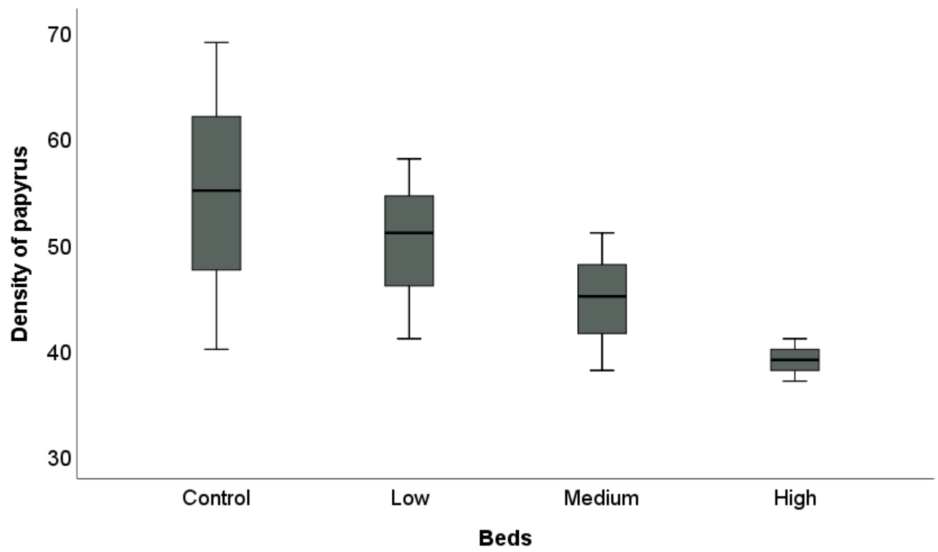

Figure 5. Culm density of *C. papyrus* in the control beds and treatment beds.

The recruitment of new culm shoots was highest in April in all the treatment beds with low treatment beds having the highest number (6.0 ± 2.0 culms/2 m^2), followed by control beds (5.5 ± 1.6 culms/2 m^2), and medium (3.8 ± 1.6 culms/2 m^2) and high treatment beds (1.0 ± 1.5 culms/2 m^2; Fig. 6). Notably, nutrient access is greater in April because of sediment additions at the start of the experiment. Culm density of new shoot recruits was lowest in the month of October in all the treatment beds, with control and low treatment beds having an average of one each while high treatment beds had 2.0 ± 0.3 culms/2 m^2. However, significant variations were not observed among treatment beds in October. The number of new papyruses shoot recruits was significantly affected by sediment depth ($P < 0.05$; Fig. 6). The number of new shoots decreased with 5 cm and 10 cm burial depths, and shallow burial depths (0 cm and 1 cm) usually had more new shoots than medium and high treatments.

Papyrus culm mortality was monitored throughout the study period. Senescing culms were observed to be higher in high sediment in the month of September at an average of 12.5 ± 4.5 culms/2 m^2 (KW-ANOVA, $\chi^2 = 8.24$; df = 2; $P < 0.05$). However, the high sediment treatment had the highest number of dead culms per 2 m^2. Furthermore, no difference in the number of dead culms was observed among and between treatments at the end of the experiment (October). According to Spearman's coefficient of correlation, sediment depth did not have a significant influence on culm density and dying culms in all the treatment beds. However, sediment depth had a positive and significant relationship with the number of new shoot recruits in low (rho = 0.80; P = 0.01) and control beds (rho = 0.80; P = 0.01) but not in high (rho = 0.34; P > 0.05) and medium beds (rho = 0.48; P > 0.05).

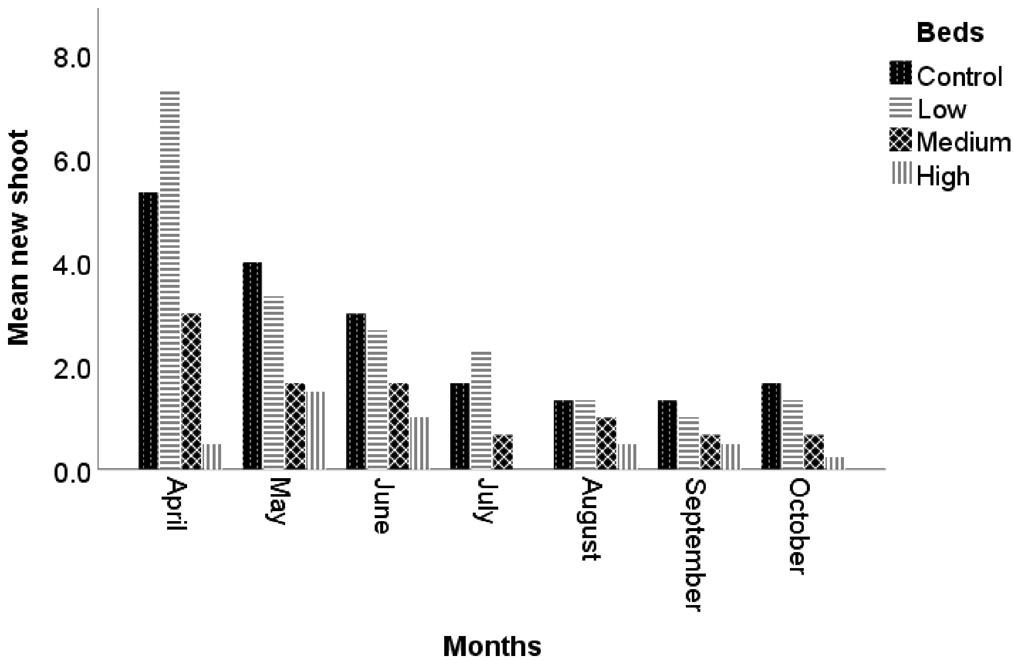

Figure 6. Recruitment of new shoots of *C. papyrus* at four levels of sediment from July to September 2020.

3.1. 3 *Cyperus papyrus* biomass productivity

Wet above-ground biomass: Sediment levels did not significantly affect wet above-ground biomass in control and low sediment treatment beds (df = 3, P ≥ 0.05; Table 2) but it did significantly impact biomass in high and medium treatment beds (df = 3, P ≤ 0.05). Control beds recorded the highest shoot wet weight with a mean of 3.33 kg compared to a low treatment mean of 3.10 kg, a medium mean of 3.00 kg, and a high mean of 1.93 kg.

Table 2. Mean biomass and ranges of production of *Cyperus papyrus*.

	Biomass (kg/2 m^2)			
	Below-ground		Above-ground	
Beds	Wet	Dry	Wet	Dry
Control	21.5 ± 7.1	15.1 ± 5.0	9.0 ± 3.0	13 ± 4.3
Low	18.2 ± 6.0	14.6 ± 3.8	8 ± 2.7	5.0 ± 1.7
Medium	17.8 ± 6.0	11.3 ± 4.9	7.3 ± 2.4	3.9 ± 1.3
High	7.9 ± 3.9	5.8 ± 2.9	3.7 ± 1.9	2.2 ± 1.1

Dry above- ground biomass: Dry above-ground biomass did not increase significantly (df = 3, $P \geq 0.05$) with increasing sediment depth (Table 2). The control beds recorded the highest mean shoot dry weight (2.76 kg/2 m^2) compared with the low treatment beds (2.34 kg/2 m^2), medium beds (2.01 kg/2 m^2), and high beds (1.45 kg/2 m^2).

Wet below-ground biomass: Root wet weights decreased with increasing sediment depth (Table 2). Plants in control beds had significantly higher root wet weight than high sediment treatment beds ($P \leq 0.05$, N = 3 and df = 3). The control beds had the highest mean root wet weight (7.16 kg/2 m^2) compared to low treatment beds (6.26 kg/2 m^2), medium beds (6.06 kg/2 m^2), and high beds (3.80 kg/2 m^2).

Dry below-ground biomass: Dry below-ground biomass decreased with increasing sediment depth among the treatment beds (Table 2). The control beds had the highest mean root dry weight (6.00 kg/2 m^2) compared with the low treatment beds (5.08 kg/2 m^2), medium beds (4.90 kg/2 m^2), and high beds (3.21 kg/2 m^2). There were not significant differences in root dry weights ($P \geq 0.05$) between the treatment beds.

3.2 Discussion

Plant height was significantly decreased by sediment depth (Fig. 2), this agrees well with the findings by (Veeneklaas et al., 2011) working with the clonal structure of *Elytrigia atherica*. The higher densities and a slight increase in papyrus height in the control beds of the present experiment demonstrated that less sedimentation can lead to increased biomass. Previous studies by Chen *et al.*, (2011) indicated a shift of resource allocation to shoots which enhance below-ground growth and productivity with increased sediment. Under deep burial conditions (> 5 cm), our observations were consistent with those of previous studies (Li *et al.*, 2016) which found that papyrus cannot acclimatize to high sediment.

The stem diameter below the flower of plants in the medium sediment treatment (5 cm) steadily increased from 3 mm to 10 mm diameter and then stabilized between 10 mm and 17 mm. This increase may suggest an effect of sediment load. As the sediment load increases, the plants in the high sediment treatment are thinner due to the compaction of the sediment, which reduces the growth of stem diameter. The stem diameter below the flower in medium treatment beds slightly increased with increasing sediment (Fig. 3). A slight decrease in stem diameter may be due to competition for nutrients among the treatment beds.(L. Wang et al., 2005)(Rongoei & Outa, 2016), explain that in a non-self-thinning plant monoculture, many researchers have found that growth prohibition can occur when individuals compete for nutrients.

Stem density in the high treatment beds at the end of the experiment were less than the control beds and the other treatment beds (Fig. 5). This may be a physiological response to increased sediment. The stem density was highest in the control beds, which could lead to increase above-ground biomass. Plant growth may be inhibited as a result of competition (L. Wang et al., 2005); (G. Wang et al., 2013). Many investigators have shown that a biomass distribution consisting of a few large plants and many small plants may develop when individuals compete for resources (G. Wang et al., 2013). In a previous study by Wang *et al*., (2013), dry mass production of *A. prostrates* decreased significantly in the higher density treatments. High density treatments indicated declines in height, and biomass of stems, leaves and roots in *A. prostrates* (L. Wang et al., 2005) (Rongoei & Outa, 2016).

Many changes in papyrus in this experiment were typical of wetland plant responses to sediment loading, including increased biomass production, faster growth in plant height, stem diameter, and the occurrence of new shoots. The observations in this study made over a range of sediment availability in the environment suggest the existence of a compulsory balance between sediment and new shoot recruitment. Sediment depth and ecosystem characteristics influenced papyrus production, including growth rate, shoot recruitment, density, and mortality. Results were consistent with (Webb *et al.,* 2012), who showed that increased sediment depth can diminish shoot recruitment and density and increase shoot mortality.

Both wet and dry weights of each treatment of shoots and roots decreased with increasing sediment depth. The most pronounced effect of sediment depth on both wet and dry shoot and root weights occurred in the control beds in comparison to low, medium and high treatment beds, indicating a greater ability of plants in the control beds to compete for below ground resources. These results indicate that sediment depth could exacerbate the combined effects of climate change, water level fluctuations, and other environmental factors negatively impacting wetland ecosystems and supports sediment load control as a critical factor in managing wetland health.

Our results agree well with the findings by (Deb, 2014), who studied the impacts of varied sediment depth on *Cyperas esculentus* L., *Aframomum angustifolium* (Sonn.) and *Phragmites australis* (Cav.) they demonstrated that sediment depth limitation was effective in increasing final plant weight. Root-shoot ratio decreased with increasing sediment depth in low (31 cm) and medium (35 cm) and high (40 cm) treatment beds. However, wet below-ground biomass in control beds (30 cm sediment) was 7.17 kg/2 m^2 compared to 3.80 kg/2 m^2 in the high treatment beds. Reduction in wet below-ground biomass of the plants with increasing sediment depth signifies greater numbers of new shoots and higher plant density, leading to increased biomass accumulation was similar to other studies where roots were the major biomass component of wetland systems(Hoagland *et al.*, 2011). Papyrus productivity depends on the depth of the sediment and the habitat conditions that enable higher rates of nutrient uptake (Rongoei & Outa, 2016)(Edwards et al., 2003). As papyrus is harvested and flooding with high sedimentation increases, provisioning and regulation services for papyrus diminish. There is a balance in the benefits and costs of sedimentation: although increased sediment depth from runoff can diminish overall productivity in papyrus, flood waters seasonally restore nutrients to the wetland so as to maintain continuous papyrus growth.

As sediment depth increases, the rate of growth decreases in both the below-ground and above-ground parts (Lovelock *et al.*, 2007) An increase in root to shoot ratio as noted in our control beds, may be attributed mainly to a reduction in shoot growth, as has been observed when water is limiting (Osório *et al.*, 1998). During the experiment, some plants dried up and died, a visible indication that deepening sediment reduced root-shoot ratios. Beyond sediment depth, several factors were observed as possible causes of culm mortality in treatment beds, including climate, shade from taller plants, termites, and nutrient availability, however, these were not tested in our experiments. Increases in root-shoot ratio under increasing sediment depth may be attributable to decreased foliage area and intercepted solar radiation. This interpretation would align with Ren *et al.*, (2016), who examined the effects of shading on the photosynthetic characteristics and mesophyll cell ultrastructure of macrophytes. When plants were stressed with high sediment levels and shade simultaneously, their growth was not only influenced by each of these two factors independently, but also by the effects that different sediment level had on the resulting light intensity (Thouvenot *et al.*, 2013). Sediment deposition reduces the range of daily temperature fluctuation and can provide an additional source of nutrients for plant growth Stimulatory effects of shallow burial under waterlogged conditions have been reported in other wetland macrophytes(Pan et al., 2014a). Sediment burial not only promoted the seedling height growth and dry mass accumulation, increased the stem diameter and the number and length of branch, but also altered the dry mass allocation ratio of different parts. These impacts would be favorable for maintaining S. salsa populations and encouraging further growth in barren mudflat. Similar phenomena was also observed in some other species that seedlings emerging from a deeper location had higher seedling height, longer first internode or sub coleoptile internode, longer root system and increased dry mass accumulation (Mou & Sun, 2011).

4. Conclusion

Sediment level significantly influenced the morphological parameters investigated. Height, diameter, new shoots, above and below ground biomass were all impacted by sediment level in the treatments. These results demonstrate the importance of proper sediment management for the benefit of papyrus for maintaining healthy wetland ecosystems. Sediment depth in the constructed wetland significantly affected papyrus growth rates. Good growth performance was achieved in the control beds, while low growth rate, low culm density, and stunted growth of papyrus were observed in the high sediment treatment beds. Similarly, more shoots were developed in low and control treatment beds than medium and high treatment beds, demonstrating that increased sedimentation limits seedling recruitment and clonal dynamics. Control beds had higher rates of biomass accumulation as evidenced by the increase in new shoots and root weights compared to low, medium and high treatment beds. Generally, within this study sediment significantly affected height, diameter below flower, diameter above sediment and new shoot recruitment, but biomass was not significantly impacted by sediment depth. These results suggest that increases in wetland sediment load may lead to negative alterations in the species composition and functions of wetland ecosystems.

The knowledge that sediment loading has a negative impact on papyrus communities must be applied to have real-world value. Research should be conducted to examine various methods of sediment control in buffer zones around Lake Tana and the possible adjacent ecological impacts of sediment load limitation.

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