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Soil properties and their influence on tree species distribution on and off the floodplain in the Tana River area of Kenya

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ABSTRACT

Variation in soil properties can influence plant composition and distribution in river floodplains of semi-arid regions. Soil data were collected alongside tree species data on and off the Tana River floodplain in South-eastern Kenya from plots that were organized along transects. A t-test was used to compare soil properties and canonical correspondence analysis to relate the soil properties to the tree species distribution. Moisture ($t = 5.92$), pH ($t = 2.03$), P ($t = 5.91$), Mg ($t = 3.25$) and Ca ($t = 2.04$) were significantly higher inside the floodplain ($P < 0.05$), and bulk density outside the floodplain ($t = -8.76$, $P < 0.05$). The influence of soil properties on tree species distribution was higher inside the floodplain with a higher fitted variation of 43% for the first two axes. Bulk density, Ca, Mg, K and CEC significantly influenced the distribution of tree species inside and outside the floodplain. The influence of moisture, P, N and C outside, and pH inside was also significant. The results show that soil properties and flood regime disturbances are important drivers of the vegetation composition. This information is useful in management of tree populations in the light of climate variability and mega dam constructions.

1. Introduction

Plants require mineral nutrients and water for their growth, which they absorb from the soil through their roots. A suitable habitat for plants requires optimal levels of soil nutrients, moisture and other soil properties for sustainable species composition and abundance. Soil properties influence seedling establishment (Loth et al. 2005), growth and survival (Iwara et al. 2011; Adel et al. 2017), community structure, composition and abundance (Bonyongo et al. 2002; Munishi et al. 2007; Mligo, 2017) as well as the distribution (Iwara et al. 2011; Mligo, 2017; Adel et al. 2017) of plant species. Plant habitats may be degraded due to natural or anthropogenic causes (Burgess et al. 2017), which can lead to degradation of soil habitats. This calls for protection of these habitats to enhance conservation of plant biodiversity.

The floodplain in Tana River region is an asset to both crop farmers and livestock keepers because it supports growth of food crops and pasture. Livestock grazing and crop farming have been the main land use practices but their intensity has increased in recent times due to increased human population. Changes in flooding regime and increased drought frequencies have further added pressure on the ecosystem. These changes, coupled with dam construction upstream can reduce water quantity and nutrients downstream, negatively impacting vegetation. The region is also highly invaded by Prosopis juliflora, which was introduced in the 1980's together with other Prosopis species. These biotic and abiotic disturbances can lead to habitat degradation and change vegetation dynamics in the Tana River system.

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A sound understanding of soil properties and their relationships with plant distribution is essential for integrated and sustainable plant management programmes (Udoh et al. 2007). This includes controlling the population of invasive plant species through the identification of site at risk of further colonisation. Several researchers have studied the effect of soils on the composition and distribution of plant species in different regions. However, such a study has not been done in upper Tana River despite the numerous threats facing the ecosystem.

2. Materials and Methods

2.1 Study area

The study was conducted in upper Tana River area of Tana River County, located in south-eastern Kenya.

The main source of water in the region is the Tana River which floods twice annually as a result of the long and short rainy seasons in March–May and October–November respectively (Maingi, 2006). The source of the floods is rain from the river catchment area, the Aberdare Range and Mount Kenya. Climate variability has caused changes in the Tana River flooding regime, and increased drought frequencies, while construction of dams has reduced peak flows and the quantity of water downstream (Maingi & Marsh 2002). Crop farming occurs mainly in the floodplain whereas livestock grazing occurs mainly outside the floodplain except during drought periods. This often leads to a serious conflict between the crop and the livestock owners over damages to crops. The rainfall is lowest in Garissa at 300mm/year and highest in Garsen at 600mm/year, an average of 450mm/year. February is the hottest month and July the coldest month, with a mean annual temperature of 28.0ºC (Maingi, 2006). The key vegetation types include gallery forests, Acacia woodlands, and Acacia-Commiphora scrub forests interspersed with seasonal grasslands (Hughes, 1990). The trees found along the seasonal streams include; Vachellia tortilis, Senegalia senegal, Berchemia discolor, Hyphaene compressa, Salvadora persica and Dobera glabra (Gachathi et al. 1987). Prosopis juliflora, together with other Prosopis species, were introduced in the 1980s (Choge et al. 2002) to mitigate concerns about deforestation, desertification and fuel-wood shortages (Mwangi & Swallow, 2008).

2.2 Data collection

Data were collected from Tana River Primate Reserve, Arawale National Reserve, Bura Irrigation Scheme, Hola Irrigation Scheme, Bura, Hola, Bura East, Makere, Chanani and Wenje (Figure 1).

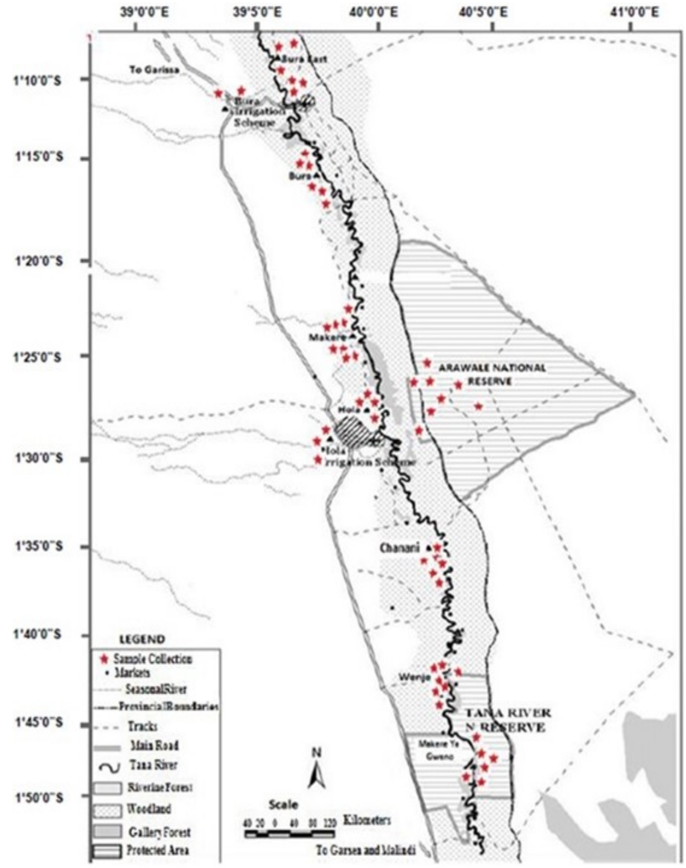

Figure 1: Map showing the location of sampling sites in Tana River (Source: Omari *et al.* 2018)

The Collection and analysis of the tree species data was done by Omari et al. (2019) just before the start of the long rains in March. The soil samples were collected alongside the tree species data from two 10m x10m plots along 100m transects using 0.5m x 0.5m quadrants which were placed randomly within the plots. Three replicate samples were collected per plot and mixed to make composite samples. The soil samples for determination of soil moisture and bulk density were collected using 5cm diameter core rings which were weighed in the field using an electronic balance and put in zip-lock bags. The soil samples for chemical analyses were collected using a soil augur at a depth of 0 - 20cm. These soil samples were stored in labelled plastic bags for determination of pH, organic carbon, total nitrogen, available phosphorus and exchangeable cations (K, Ca and Mg) in parts per million (ppm) at Kenya Agricultural Research Institute, Muguga. Moisture content (%) was determined using the gravimetric method (Black 1986). Bulk density was determined by dividing the weight of each dry soil sample with the volume of the core-ring and multiplying by 100; BD (g.cm-3) = [WDS (g)/ VC (cm3)]*100 where: BD = Bulk density; WDS = weight of dry soil and VC = Volume of core-ring. Soil pH was measured on 2.5:1 ratio of water to soil suspension (Okalebo et al. 2002). Organic carbon (%) was determined using the redox method outlined by Nelson & Sommers (1975). Total soil nitrogen was determined using acid digestion of soil samples followed by colorimetry (Houba et al. 1988), whereas available phosphorus (ppm) was determined using Bray 2 method as described by Okalebo et al. (2002). The amounts of exchangeable cations were measured in mg.kg-1 (ppm) using flame photometry for potassium, and atomic absorption spectrophotometry for calcium and magnesium (Okalebo et al. 2002). Cation exchange capacity (CEC) was estimated by summing K+, Ca2+ and Mg2+ with an estimate of exchangeable hydrogen obtained from the buffer pH in centmoles/kg (Okalebo et al. 2002).

2.3 Data analysis

The soil data from inside and outside the floodplain were compared using a t-test (Zar, 1999). Canonical correspondence analysis (CCA), run in the CANOCO 5.0 Software (Ter Braak & Šmilauer 2012), was used to determine the influence of soil properties on the distribution of tree species. Importance value, determined in a previous study by Omari et al. (2019), constituted the species data while soil properties were the environmental data. A post hoc Monte Carlo permutation test was performed (at the 5% critical level) to identify the soil properties that significantly influenced tree species distribution.

3. Results

3.1 Variation in soil properties

The mean differences of moisture ($t = 5.92$, $P < 0.05$), pH ($t = 2.03$, $P < 0.05$), P ($t = 5.91$, $P < 0.05$), Mg ($t = 3.25$, $P < 0.05$) and Ca ($t = 2.04$, $P < 0.05$) were significantly higher inside the floodplain.

CEC was marginally higher (t = 1.87, $0.05 < P \leq 0.1$) inside the floodplain than outside, whereas bulk density was significantly higher outside the floodplain (t = -8.76, $P < 0.05$). Total soil N (t = 0.797, $P > 0.05$), C (t = 1.21, $P > 0.05$) and K (t = 1.65, $P > 0.05$) were not significantly different inside and outside the floodplain (Table 1).

Table 1: Comparison of soil variables inside and outside the floodplain (Mean±SE)

Soil variable	In floodplain	Outside floodplain	t-value	P-value
Bulk density	1.27±0.03	1.59±0.03	-8.759	0.000***
Moisture	12.38±0.81	6.28±0.64	5.923	0.000***
pH	7.65±0.09	7.19±0.20	2.032	0.047**
Organic	1.04±0.93	0.86±0.09	1.206	0.232
Nitrogen	0.10±0.01	0.09±0.01	0.797	0.429
Phosphorus	174.31±6.84	101.65±10.23	5.905	0.000***
Potassium	927.63±61.00	727.66±105.09	1.646	0.105
Magnesium	715.49±50.65	496.10±44.75	3.246	0.002**
Calcium	2636.49±165.51	1989.35±270.21	2.042	0.046**
CEC	12.79±0.79	10.08±1.22	1.873	0.066*

*** Highly significant
** Significant
* Marginally significant

3.2 Effect of soil properties on tree species distribution inside the floodplain

The total variation and that explained by the soil properties, the eigenvalues and the Monte Carlo permutation test results are shown in Table 2.

Table 2: Summary results of the first four CCA-axes of data from inside the floodplain. Sig. = significant; Total variation = sum of all unconstrained eigenvalues.

Axes	1	2	3	4	Total varia-
CCA-Eigenvalues	0.916	0.831	0.615	0.447	10.960
Explained variation (Cumulative%)	8.4	15.9	21.6	25.6	
Explained fitted variation (Cumulative %)	22.7	43.3	58.5	69.6	
Canonical correlation	0.975	0.978	0.879	0.880	
All unconstrained eigenvalues					10.960
All canonical eigenvalues					4.035
Monte Carlo Permutation test	F-ratio	P-value	Conclusion		
CCA axis 1	1.7	0.002	Significant		
All CCA axes	1.1	0.220	Not Sig.		

CCA axis 1 was the most important in explaining the influence of soil properties on tree species distribution with the highest eigenvalue whereas the fitted variation for the first two axes was 43.3%. The Monte Carlo permutation test showed that soil variables significantly influenced the distribution of tree species along CCA axis 1 (F = 1.7, P = 0.002).

The correlation coefficient of pH was the highest along CCA axis 1, and that of bulk density the highest along CCA axis 2 (Table 4). Magnesium, potassium, pH, calcium and CEC were strongly and negatively correlated with CCA axis 1, and bulk density with CCA axis 2 (Table 4). Bulk density, pH, K, Ca and CEC significantly influenced tree species distribution inside the floodplain ($P < 0.05$), while Mg was marginally significant (P = 0.094).

Table 3: Summary results of the first four CCA-axes of data from outside the floodplain. Sig. = Significant; Total variation = sum of all unconstrained eigenvalues.

Axes	1	2	3	4	Total variation
CCA-Eigenvalues	0.652	0.511	0.438	0.377	7.229
Explained variation (Cumulative %)	9.0	16.1	22.2	27.4	
Explained fitted variation (Cumulative %)	21.0	37.5	51.7	63.8	
Canonical correlation	0.972	0.911	0.924	0.828	
All unconstrained eigenvalues					7.229
All canonical eigenvalues					3.101
Monte Carlo Permutation test	F-ratio	P-value	Conclusion		
CCA Axis 1	1.8	0.082	Marginally Sig.		
All CCA Axes	1.2	0.100	Marginally Sig.		

Table 4: Correlation coefficients of variables with the first two ordination axes showing their influence on the distribution of tree species inside and outside the floodplain. Factors with strong correlation coefficients to each axis are shown in bold.

Variables	Axis 1		Axis 2		Axis 3	
	IN	OUT	IN	OUT	IN	OUT
Bulk density	-0.409	-0.513	-0.640	-0.336	0.031	0.221
Moisture	0.060	0.475	0.082	-0.152	-0.111	-0.420
pH	-0.805	0.558	-0.208	0.230	0.118	-0.195
Organic carbon	-0.046	-0.070	0.417	0.324	0.347	0.516
Nitrogen	0.040	0.154	0.238	0.711	0.301	0.197
Phosphorus	-0.255	-0.020	-0.236	0.758	-0.551	-0.125
Potassium	-0.684	0.848	0.221	0.219	-0.091	0.084
Magnesium	-0.574	0.869	0.160	0.068	-0.098	0.120
Calcium	-0.664	0.824	0.311	0.251	-0.047	0.106
CEC	-0.633	0.839	0.281	0.219	-0.009	0.128

CCA axis 1 indicated gradients of base saturations whose availability was strongly influenced by a pH gradient (Figure 2).

The tree species that ordinated to the left of axis one were *Vachellia elatior, Vachellia nilotica, Vachellia tortilis, Prosopis juliflora, Tamarinda indica, Mangifera indica, Maerua pubescence, Eucalyptus saligna, Salvadora persica, Lecaniodiscus fraxinifolius, Azadirachta indica* and *Dobera loranthifolius* (Figure 2). The latter were abundant in soils with high concentrations of bases, high pH and CEC. The tree species that ordinated to the right of CCA axis 1 were abundant in soils with low concentrations of bases, low pH and CEC. They included *Dobera glabra, Musa paradisiaca, Terminalia parvula, Drypetes natalensis, Kigelia africana, Ziziphus pubescence, Blighia unijugata, Polysphaera multiflora, Hunteria zeylanica, Rinorea elleptica, Celtis philipensis, Alangium salviifolium, Phoenix reclinata* and *Tapura fischeri* (Figure 2). CCA axis 2 was a soil compaction axis in which increasing bulk density resulted to decline in organic carbon. The tree species that ordinated near the bottom of CCA axis 2 were abundant in soils with high bulk density, low organic carbon and low moisture. They included *Polysphaera multiflora, Terminalia parvula, Kigelia africana, Tapura fischeri, Celtis philipensis, Hunteria zeylanica, Alangium salviifolium, Phoenix reclinata, Ziziphus pubescence, Rinorea elleptica, Blighia unijugata, Drypetes natalensis, Excoecaria madagascariensis* and *Musa paradisiaca* (Figure 2). Those that ordinated near the top of CCA axis 2 were abundant in soils with low bulk density, high organic carbon and high moisture. They included *Dobera loranthifolia, Lecaniodiscus fraxinifolius, Azadirachta indica, Salvadora persica, Ficus sycomorus, Diospyros abyssinica, Hyphaene compressa, Sorindeia madagascariensis, Cordia gotzei* and *Pavetta sphaerobotris*. The latter five species grew in very moist or flooded soils (Figure 2). Other species like *Vachellia tortilis, Vachellia robusta, Vachellia elatior, Vachellia zanzibarica, Prosopis juliflora, Tamarindus indica, Eucalyptus saligna, Vachellia nilotica, Mangifera indica, Dobera glabra* and *Maerua pubescence* which ordinated near the center of CCA axis 2 were abundant in soils with moderate bulk density, organic carbon and moisture.

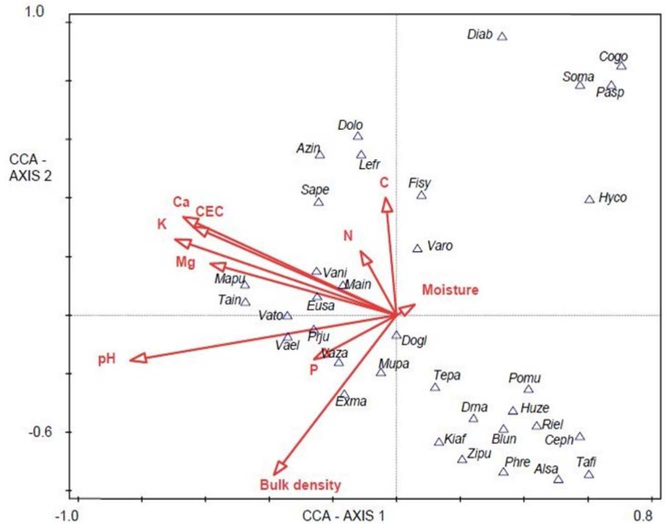

Figure 2: CCA biplot showing the influence of soil variables on tree species distribution patterns inside the floodplain. The arrows represent the soil variables and the triangles the tree species which are denoted by a four code letter where the first two letters represent the generic name and the last two letters the specific name. The species are *Alangium salviifolium, Azadirachta indica, Blighia unijugata, Celtis philipensis, Cordia gotzei, Diospyros abyssinica, Dobera glabra, Dobera loranthifolia, Drypetes natalensis, Eucalyptus saligna, Excoecaria madagascariensis, Ficus sycomorus, Hunteria zeylanica, Hyphaene compressa, Kigelia africana, Lecaniodiscus fraxinifolius, Maerua pubescence, Mangifera indica, Musa paradisiaca, Pavetta sphaerobotris, Phoenix reclinata, Polysphaera multiflora, Prosopis juliflora, Rinorea elleptica, Salvadora persica, Sorindeia madagascariensis, Tamarindus indica, Tapura fischeri, Terminalia parvula, Vachellia elatior, Vachellia nilotica, Vachellia robusta, Vachellia tortilis, Vachellia zanzibarica* and *Ziziphus pubescence*.

3.3 Effect of soil properties on distribution of tree species outside the floodplain

The total variation and that explained by the soil properties, the eigenvalues and the Monte Carlo permutation test results are shown in Table 3. The total variation was less than that inside the floodplain, but the variation explained by the soil variables was more. The eigenvalue of CCA axis 1 was the highest, but less than that inside the floodplain. The fitted variation for the first two axes was 37.5%, while the Monte Carlo permutation test on all the axes and on the first axis indicated that in both cases the soil properties had a marginally significant effect ($0.05 < P \leq 0.1$) on the tree species distribution (Table 3). Magnesium had the highest correlation coefficient along CCA axis 1, and phosphorus along CCA axis 2 (Table 4). Potassium, pH, magnesium, calcium and CEC were strongly and positively correlated to CCA axis 1, bulk density negatively correlated to this axis, while phosphorus and nitrogen were strongly and positively correlated to CCA axis 2 (Table 4). Permutation tests showed that moisture, bulk density, P, K, Ca, Mg and CEC had a significant influence ($P < 0.05$) on the tree species distribution. Nitrogen and organic carbon had a marginally significant effect ($0.05 < P \leq 0.1$) on the tree species distribution. CCA axis 1 was a gradient of available bases that was strongly influenced by pH gradients. The axis was also a soil compaction gradient that negatively affected the soil moisture. The trees correlated with increasing bases, pH, CEC, moisture and low bulk density were *Vachellia zanzibarica, Vachellia robusta, Terminalia brownii, Prosopis julifora, Maerua pubescence, Commiphora campestris* and *Commiphora schimperi* (Figure 3). The latter were abundant in soils with high concentration of cations, high pH, CEC, adequate moisture and low bulk density. The tree species that were abundant in soils low in cations, CEC, pH, moisture and high bulk density included *Vachellia nilotica, Vachellia tortilis, Albizia anthelmintica, Balanites pedicellaris, Boscia coriacea, Commiphora africana, Commiphora baluensis, Commiphora riparia, Dobera glabra, Dobera loranthifolius, Grewia bicolor, Lanea stuhlmannii, Lecaniodiscus fraxinifolius, Salvadora persica, Sterculia africana, Terminalia parvula* and *Terminalia spinosa* (Figure 3).

The tree species that were abundant in soils rich in phosphorus and nitrogen were *Albizia anthelmintica, Vachellia nilotica, Salvadora persica, Sterculia africana, Commiphora baluensis, Lanea stuhlmannii, Vachellia robusta, Commiphora campestris* and *Terminalia brownii* (Figure 3). On the other hand, the tree species that were abundant in soils with low levels of phosphorus and nitrogen included *Vachellia tortilis, Vachellia zanzibarica, Balanites pedicellaris, Boscia coriacea, Commiphora africana, Commiphora riparia, Commiphora schimperi, Dobera glabra, Dobera loranthifolius, Grewia bicolor, Lecaniodiscus fraxinifolius, Maerua pubescence, Prosopis julifora, Terminalia parvula* and *Terminalia spinosa* (Figure 3).

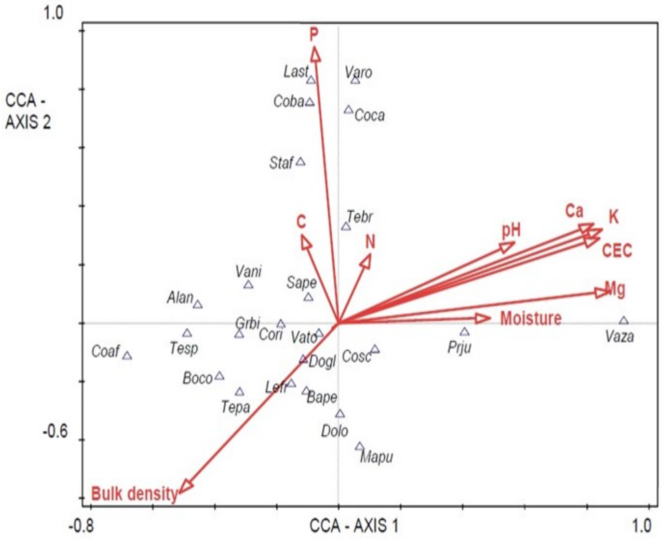

Figure 3: CCA biplot showing the influence of soil variables on tree species distribution patterns outside the floodplain. The arrows represent the soil variables and the triangles the tree species which are denoted by a four code letter where the first two letters represent the generic name and the last two letters the specific name. The tree species are *Albizia anthelmintica, Balanites pedicellaris, Boscia coriacea, Commiphora africana, Commiphora baluensis, Commiphora campestris, Commiphora riparia, Commiphora schimperi, Dobera glabra, Dobera loranthifolius, Grewia bicolor, Lanea stuhlmannii, Lecaniodiscus fraxinifolius, Maerua pubescence, Prosopis julifora, Salvadora persica, Sterculia africana, Terminalia brownii, Terminalia parvula, Terminalia spinosa, Vachellia nilotica, Vachellia robusta, Vachellia tortilis* and *Vachellia zanzibarica.*

Discussion

The findings of this study indicate that there was significantly higher moisture, pH, phosphorus, magnesium and calcium inside the floodplain ($P < 0.05$), while only bulk density was significantly higher outside the floodplain ($P < 0.05$). The increased soil moisture and nutrient content inside the floodplain was due to the floods which deposit mineral rich sediment in the floodplain. This concurs with the findings of other researchers (e.g. Tockner *et al.* 1999; Bonyongo *et al.* 2002; Hein *et al.* 2003). The high bulk density outside the floodplain was attributed to trampling by livestock since grazing occurs mainly outside the floodplain. This finding also concurs with what other researchers have found (e.g. Zhou *et al.* 2010; Pulido *et al*. 2016).

Increasing the amounts of soil nutrients promotes regeneration of plants (Marcia & Anderson 2004) while moisture permits access to dissolved nutrients, which determines the performance of plant species. There were three levels of interaction, soil property-soil property, species-species and soil property-species, which determined the behaviour of canonical ordination axes. For instance, bases and CEC varied in the same direction as pH whereas moisture varied in the opposite direction with bulk density. Tree species distribution followed variation in soil properties as they responded to the existing gradients inside and outside the floodplain. Thus, tree species grew in alkaline or acidic soils, in high or low bulk density soils, in high or low organic carbon soils, in rich or poor nutrient soils and in high or low moisture soils (sections 3.2 and 3.3). The higher eigenvalues inside the floodplain indicated a higher species variation. The influence of soil properties on tree species distribution was also higher inside the floodplain. This was shown by the higher fitted variation for the first two axes inside the floodplain compared to outside, and the highly significant Monte Carlo test for axis one which was only marginally significant outside the floodplain.

The high unexplained variation, both inside and outside the floodplain, means that there were other factors besides the soil properties in this study that influenced tree species distribution. According to Munishi et al. (2007), plant community structure is influenced by a combination of factors. The factors could be other soil properties not considered in this study, flood disturbances, invasion, or anthropogenic disturbances. The unexplained variation was higher inside the floodplain which implies there were more disturbances than outside. Unsustainable crop farming and land clearance in the floodplain can deplete soil nutrients and influence tree species composition and distribution. According to Stevens & Hornung, (1990), land clearance can lead to loss of Mg2+ and Ca2+cations through leaching. However, these minerals were significantly high inside the floodplain, implying that what was lost through leaching or absorbed by plants was replenished by seasonal floods. Changes in flooding regime as a result of climate variability and/or dam developments upstream are likely to change the balance in the species occurring inside the floodplain only and those that occur both inside and outside. This is because the amount of soil nutrients will vary with the quantity of floods, implying fewer nutrients when floods are reduced and more when floods are increased.

Prosopis juliflora, which was found to be significantly higher in the floodplain (Mworia *et al.* 2011; Omari *et al*. 2019), can also alter indigenous plant composition through displacement. In and outside the floodplain, *Prosopis juliflora* was found in locations with diverse soil conditions, implying that it is capable of invading a wide variety of habitats. It was abundant in fertile and non-fertile soils, moist and dry soils as well as low and high bulk density soils.

Similar observations have been reported by Mahmood *et al.* (2016), Saraswathi & Chandrasekaran (2016) and Patnaik *et al*. (2017) on the performance of *Prosopis juliflora* in arid regions and in nutrient-lean wastelands unlike many indigenous tree species.

Iwara *et al.* 2011 found that CEC, phosphorus, nitrogen and silt influenced the distribution of woody species in southern Nigeria. Mligo (2017) reported that Calcium, Magnesium and Phosphorus significantly influenced plant species distribution in Zaraninge forest in Tanzania. In northern Iran, Adel *et al. (*2017) found that nitrogen, phosphorus, organic carbon, pH, potassium, magnesium and calcium were the most important soil factors that influenced the growth and distribution of plant communities. Chemicals play a crucial role in determining plant community composition and distribution, but they vary due to environmental differences between sites. In the Tana River system, Bulk density, Ca, Mg, K and CEC significantly influenced the distribution of tree species inside and outside the floodplain. The influence of moisture, P, N and C outside, and pH inside was also significant.

Conclusion

The results of this study show that moisture, pH, P, Mg, Ca and CEC were significantly higher inside the floodplain, while bulk density was significantly higher outside the floodplain. Bulk density, Ca, K, Mg and CEC influenced tree species distribution both inside and outside the floodplain. Soil properties are among the factors that influence tree species distribution in upper Tana River. The influence was more in the floodplain, probably due to fluctuations in flood quantity, crop farming, charcoal production and invasion. *Prosopis juliflora* is a threat to the indigenous trees and its density should be controlled to enhance socio-economic development in the Tana River system. Dam construction along the Tana River should take into account the impact on plant community structure and the potential for proliferation of *Prosopis juliflora.* The findings of this study are useful in the management of plant populations in the light of climate variability and mega dam constructions.

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