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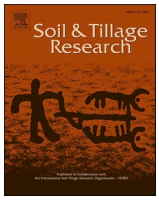

Quantifying root-induced soil strength, measured as soil penetration resistance, from different crop plants and soil types

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ABSTRACT

A common soil mechanical property for assessing soil strength is soil penetration resistance (PR) or soil cone index (CI), which is related to the undrained shear strength of saturated and cohesive soil. Plant roots can increase soil strength, but physical conditions may confound this. Pot experiments were conducted using 70 cm soil columns, three soil types (beach sand, erosion-prone soil, and two typical arable soils), and four crop plants (maize, sorghum, Napier, and vetiver grass). We tested the hypothesis that plant roots impact soil strength, measured as soil PR, and the induced soil strength differs based on plant species. The CI and root system architecture (RSA) traits were measured. Napier grass grown in arable soils recorded higher total biomass. Together with maize, Napier grass had a more significant root length density, particularly at 25–40 cm depth. The CI increased with increasing depth, with a 57–99% increase in CI in the bottom layer compared to the top layer of the soil column. The overall CI of soils grown to Napier grass (2.0 and 2.3 MPa) and maize (1.7 and 2.2 MPa) were similar, but both were higher than the soils cultivated with the other crop plants and unplanted control. The overall CI of the SEA sand of ~2.0 MPa was 36%, higher than that for the arable soils. Soil moisture content did not significantly increase CI, but the interaction of soil bulk density and root system traits could be implicated in increased CI of root-permeated soils. It is concluded that (i) roots growing in arable soils can increase CI and hence soil strength, possibly due to the binding effect of root systems, even when the transpiration effect of plants on soil moisture is low; (ii) crop plants contribute differently to soil strength, and (iii) Napier grass could offer a rapid growth and establishment option when considering plants for soil reinforcement and stability.

1. Introduction

Soil penetration resistance measures the soil's resistance to deformation or compaction. It is the force required to penetrate the soil surface or a specific depth within the soil. It is due to the cohesive forces exerted between individual soil particles and the frictional resistance resulting from the sliding of soil particles during the penetration of growing roots (Marshall et al., 1996). Soil penetration resistance, thus, involves aspects of various components of soil strength. Soil shear strength (τ) describes the resistance to shear stress of a given soil, the maximum stress soil can bear before failure. Typically, τ is a function of three major parameters ($\tau = c + \sigma tan\varphi$), including the normal stress acting on the failure surface (σ; kPa), the cohesion (C; kPa), and the angle of internal friction (φ; °) (Forster et al., 2022). Soil shear strength is influenced by a combination of factors, including cohesion, friction, and effective stress. These factors interact to determine how resistant the

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soil is to penetration. Soil strength is a complex property influenced by numerous factors, including soil composition, structure, moisture content, density, stress history, and vegetation. The interplay of these factors affects the soil's penetration resistance. Plant roots potentially influence soil strength by increasing the soil's shear strength either directly through mechanical resistance and anchorage or indirectly through transpiration-induced soil water loss.

On the other hand, the development of plant roots is significantly affected by the biological and physicochemical properties of the soil (Bengough et al., 2011). Increased mechanical impedance, induced by soil drying or compaction, affects soil porosity, all aspects of root growth, rooting depth, and root system morphology. It also affects plant nutrient and water availability and uptake functions and soil microbial activities, effectively causing a decline in crop growth, productivity, and yield (Mamo and Bubenzer, 2001; Raper and Mac Kirby, 2006; Whalley et al., 2008). There could, therefore, be a reciprocal relationship between soil strength and root system growth and functioning.

A typical soil mechanical property for assessing soil strength is soil penetration resistance or soil cone index (CI) measured by a cone penetrometer. The cone penetrometer is a handy and easy-to-use device for measuring soil strength in cohesive and non-cohesive soils (Ameratunga et al., 2016; Okello, 1991). A data logger records the force per area unit required for the cone to press through the soil profile. The recorded force per area unit is the CI (ASAE standard (S313.3), 2018; Hall and Raper, 2005). Senneset and Janbu (1985) suggested that cone penetration tests may obtain effective shear strength parameters, given that the CI estimates tip resistance related to the undrained shear strength of saturated, cohesive soil. The CI also estimates the sleeve friction associated with the friction of the soil horizon being penetrated by the cone penetrometer. Thus, the CI indicates soil strength and is a compound parameter involving soil shear, compressive and tensile strength, and soil-metal friction (Mulqueen et al., 1977). Factors affecting CI include soil sampling depth, texture, moisture content, soil organic matter, bulk density, electrical conductivity, and cropping (Abbaspour-Gilandeh et al., 2012; ASAE Standard (EP542.1), 2019).

Although many studies have been done to understand how soil strength affects the development of root systems (E.gs., Bengough and Mullins, 1991; Ferreira et al., 2022; Willatt and Sulistyaningsih, 1990), more is needed to know about the feedback effects of root-induced changes on soil strength. Earlier works by Mamo and Bubenzer (2001) found that soils with roots had twice the shear strength as those without roots. Maffra et al. (2019) also confirmed that roots increase soil shear and compressive strengths. However, the authors noted that the kind of contribution of roots to soil strength for clayey soil is different from sandy soils. The question raised but not often considered is whether roots could increase soil strength in different soils, whether plant species could impact soil strength differently, and the interaction between various crop plant species and soil types. Therefore, the objective of the present study was to quantify the effects of roots from different crop genetic materials on CI as a proxy for soil strength of varying soil types. We hypothesized that plant roots impact CI, and root-induced soil strength differs based on crop genotype and soil texture.

2. Materials and methods

2.1. Genetic material

In this study, four crop plants of the grass family, primarily cultivated for food or fodder, namely maize (*Zea mays* L. cv. Obatanpa), sorghum (*Sorghum bicolor* L. cv. Naga red), Napier grass [*Cenchrus purpureus* (Schumach)] and vetiver (*Vetiveria zizanioides*) were used. Maize is a widely grown crop in 75 countries (Shiferaw et al., 2011), and in Ghana, it accounts for 50% of the total cereal production. Sorghum is a staple food for over half a million people, mainly in Africa, and is used in the bioethanol, fuel, brewing, sugar, or syrup industries (Kumar and Dwivedi, 2020). Napier grass is a high-yielding and nutritious grass species for feeding ruminants and also has the potential as a biofuel feedstock for power generation. Vetiver is an evergreen, gramineous, and perennial grass exploited in soil erosion prevention and rehabilitation of metal-polluted soils. Its roots are a valuable source of commercial and medical essential oils (Chou et al., 2016).

2.2. Growth conditions

The experiments were conducted in the greenhouse of the Teaching and Research Farm of the School of Agriculture, the University of Cape Coast (UCC), Ghana. It was conducted under the natural day length of the area, ranging from approximately 11.30 to 12.40 h. During the experimental period, conditions in the greenhouse were: active photosynthetic radiation of 486 ± 135 μmol m^{-2} s^{-1} over the plants for the 11.30–12.40 h per day, air temperature within 33.5 ± 9.1 °C and relative humidity of 62 ± 14% daily. Three soil types with varying textures were used for this study to allow for the assessment of the consistency of plant species' effect on soil penetration resistance or cone index (CI) across soil types. The soils were topsoil (0 −15 cm depth) of two sandy clay loam soils of the Edna-Bronyibima/Benya-Udu series Acrisol (Schad, 2016) (5.1294°N, 1.2857°W; called hereafter UCC soil), and Adawso-Bawjiase/Nta-Ofin series Forest Ochrosol (Schad, 2016) (5.1826°N, 1.2485°W; called hereafter as JUKWA soil), both typical arable soils of Ghana's coastal savannah agroecological zone. The last growth media was beach sand, named hereafter SEA sand, which was also collected at 0 −15 cm depth from the littoral zone of Cape Coast in the Central region of Ghana (5.0985°N, 1.3109°W). Before use, the beach sand was desalinated, and its electrical conductivity (EC) was determined to ensure it met the salinity requirements of the crop plants. The EC, measured with Hanna pH/EC meter H15222 (Hanna Instrument Inc., USA), was 0.075 dS/m. Since the beach sand had become more or less inert, sufficient nutrients were supplied to all its pots through fertigation with a modified Hoagland solution during plant growth.

2.3. Determination of soil physicochemical properties

The soil's field capacity (FC) was determined using the gravimetric method (Cassel and Nielsen, 1986). Briefly, plots measuring 1 m by 1 m from two locations, i.e., Aseibu-Nkrofro (Jukwa) and UCC, were flooded and then covered with a thin plastic sheet to reduce evaporation. The plastic sheet covering was left for 2–3 days to allow for saturation and free drainage of gravitational water. On the third day, core samples were taken at 0–20 cm depth in three replicates from each plot's centre, and the weight of the soil and core sampler were noted. The sample was then oven-dried at 105 °C until constant weight. Gravimetric water content was determined by computing the difference between wet and dry masses divided by the mass of the dry sample. The bulk density of the Aseibu-Nkroful soil, hereafter called JUKWA soil and UCC soil, was estimated as the dry mass weight of the soil core divided by its volume.

The beach sand's FC was determined using a modified hydrogel method (Akhter et al., 2004). This method was adopted because the beach sand was already taken from its source and had significantly been disturbed; its particle sizes were bigger, similar to the hydrogels used in Akhter's study. Briefly, cylindrical metallic containers about 10 cm high and 10 cm wide were perforated at the base and subsequently lined with filter paper and weighed. The metallic container with lined filter paper (hereafter referred to as the set-up) was placed on a weighing scale and tarred before it was filled with SEA sand by gently tapping at a predefined frequency. A 1-cm headspace was left to the brim at the end of each filling to allow for adequate water saturation. The entire set-up was then placed in a bowl with some volume of water, just enough to allow soil saturation and avoid flooding. After saturation, the set-up was removed from the bowl and gently placed on a cloth for free drainage. The surface of the set-up during the free drainage period was covered with a plastic film. Subsequently, the set-up was weighed and oven-dried at 105 °C until constant weight. Water content and soil bulk density

were then computed as was done for the JUKWA and UCC soils. The FC was determined as the difference between the wet and the oven-dried soil divided by the wet soil. The bulk density of the SEA sand was determined as the weight of the set-up and the sample volume.

The soil texture was determined using the pipette method following the procedures of Anderson and Ingram (1994). The pH of the soils was determined in water using soil-to-water ratio suspension of 1: 2.5 (w/w basis) after agitation for 5 min and allowed to stand for additional 2 min. The measurement used a pH meter with a cross-bridge electrode (Hanna Instrument Inc., USA). The organic carbon was determined using the dichromate method of Walkley and Black (Walkley and Black, 1934). Total nitrogen (TN) determination of soils was done using the micro Kjeldahl method after the digestion of soils in sulphuric acid with selenium powder as a catalyst (AOAC, 1990). The modified Molybdenum Blue method determined available phosphorus (AP) in soils (Murphy and Riley, 1962). The buffered ammonium acetate extractant was used in extracting the exchangeable bases (Ca^{2+}, $Mg^{2+,}$ and K^{+}). Measurement of Potassium (K) was done by flame photometry (Jenway PFP 7 model, Fischer Scientific, Goteborg, Sweden), and Ca and Mg were measured using AAS (Buck Scientific model 210 VGP, Norwalk, USA). The measured physicochemical properties of the three soils are shown in Table S1.

2.4. Column experiment set-up

We used plant growth columns made of polyvinyl chloride (PVC) pipes (75 cm high, 20 cm internal diameter) for the experiment. The columns were lined with removable polypropylene woven sacks (pp woven sacks) sewed to fit to facilitate the removal of the soil cylinder and excavation of roots. The bottom of the polypropylene woven bags was sown, and the drawn-out tops were folded over the PVC columns' top end so they could be pulled out with the bulk soil at harvest. The bags were permeable to water. The bags within columns were packed with each soil type up to the height of 70 cm to the bulk density that mimics the field dry bulk density of respective soils. Accordingly, pots of the UCC, JUKWA, and SEA soils were filled to a dry bulk density of 1.3, 1.3, and 1.7 g cm^{-3}, respectively. All columns were filled with air-dried soil and sieved to remove aggregates and vegetative materials. The soil packing into columns was performed in layers with loosening and roughing of the surface between layers to allow for a good connection between packed layers and to avoid displacement of fine soil particles. We covered the top of the columns with a layer of fine gravel to avoid surface effects from irrigation water and to reduce evaporation.

2.5. Experimental design and plant establishment

The experiment was conducted using a factorial arrangement in a completely randomised design. Four replicate pots per crop plant per soil type and four control pots unplanted for each soil were included. Maize and sorghum were sown from two seeds per pot. After germination, the seedlings were thinned to one plant per pot. Napier grass was planted with cuttings, and vetiver grass was planted from slips, each with one propagule per pot. For Napier, 3-node canes were cut and buried in a slanting position in the columns, ensuring that the soil covered at least two nodes. For vetiver, plants were cut 25–30 cm above the ground and dug out, and the culms were divided into slips with 2–3 tillers. We used a dibber to create a 3 cm deep hole in the soil. The slips were pushed into the holes like seedlings, and the soils around the plants were pressed. Except for SEA sand pots which received nutrient solutions as stated earlier, all other pots were watered every second day with tap water to 70% FC, initially determined gravimetrically. Subsequently, a soil moisture sensor (Acclima Digital True TDR-315 H Sensor; Acclima, Inc. Idaho USA) was used to determine how much water to add at every irrigation event.

The duration of the plants' growth was between 60 and 70 days. Maize and sorghum were excavated 60 and 70 days after emergence, respectively. For each crop, these times marked the period of anthesis. Although the target was to excavate each crop at anthesis, this was impossible for Napier and vetiver grass. Napier grass is a perennial grass lasting 3–5 years. While it is ready for harvest 3–4 months after planting, the mean days to flowering can be as high as 240 days after emergence (Sinche et al., 2021). Here, the roots of the Napier grass reached the end of our 70 cm columns by 70 days after planting. Similarly, vetiver is a perennial grass whose flowering time can be extended. Some cultivars recorded flowering 240 days after planting (Suleiman et al., 2018). Accordingly, Napier and Vetiver grasses were excavated 70 days after emergence but had not yet reached anthesis. The experiment was conducted two consecutive times. The first experiment was planted on 7th March 2022, and the second was planted on 11th April 2022.

2.6. Measurements

2.6.1. Cone penetration resistance

Soil moisture was measured with Acclima Digital True TDR-315 H Sensor (Acclima, Inc. Idaho USA) during the experiment for irrigation purposes and before the measurement of cone penetration resistance. We employed a manually operated static penetrometer for penetrometer tests. The penetrometer was an Eijkelkamp penetrologger CBR (model 0615SA) with a 60° circular steel cone and a base area of 100 mm^2 and can measure up to a depth of 80 cm. The shoots of the plants growing in the columns were cut close to the soil surface to enable the depth reference plate to lay flat on the soil within the column. The penetrometer was then operated by placing the cone on the soil surface with the shaft oriented vertically and within the circular hole of the depth reference plate. As much as possible, the depth reference plate was placed so that its circular hole avoids the shoot stump left on the soil surface. An operator exerted a force to push the rod into the soil. Penetration resistance of respective soil columns was measured at depths of 0–25, 25–40, 40–55, and 55–70 cm. The pressure applied to the cone or the force was normalised to the basal area of the cone to form a parameter called the CI. The difference between the CI of rooted and non-rooted pots was computed to estimate roots' contribution to soil strength.

2.6.2. Plant growth and root system

At harvest, root-permeated and control soils were removed from the columns by pulling the soil-containing polypropylene woven bags from the PVC columns. The soil cylinder was divided into four depths by slicing with a saw while still in the polypropylene woven bags. The upper part was 25 cm, and the following three parts were cut in 15 cm increments. We tagged the slices and moved them in a wheelbarrow to a washing station. The polypropylene woven bags were gently severed longitudinally on both sides to remove them from the soil. The soil was then submerged in water for approximately 1 h. The roots were gently removed and washed with tap water from a pressurized hose. The roots were gently shaken before being placed in a bowl of clean water, where they were brushed and washed to remove any last bits of soil and other debris.

The cleaned roots and a scale object were placed on a black matte background to take images with a Canon EOS 70D DSLR camera, suspended with a tripod 0.6 m above the roots. Data were determined from the root images using image analysis software, Rhizo Vision Explorer, version 2.0.3, using the "Broken Root" mode (Seethepalli and York, 2020). The image thresholding level, edge smoothing, and root pruning threshold options were set at 230 pixels intensity, 2, and 1 pixel, respectively. Pixels were converted to SI units (mm). Root features such as total root length, branching frequency, average diameter, and volume were extracted. Finally, shoot and root dry matter was measured after oven-drying at 70 °C until constant weight. The root length density (total length of roots per unit of soil volume; RLD) was estimated for each depth.

2.7. Data analysis

Statistical analyses were performed using the R software program version 3.6.1 (R. Core Team, 2019). The Shapiro-Wilk test was conducted to verify the normality of data assumption. The CI data were logarithmically (ln) transformed as they had log-normal distribution. Analysis of variances (ANOVA) was performed, first for the bulked data and then for individual crop or soil type, to determine whether crop and soil type significantly affected the variables measured in experiments 1 and 2. The factors for the ANOVA were plant species and soil type for root system traits but also included soil depth in the analyses of CI and RLD. When ANOVA detected a significant difference among group means, multiple comparisons were performed using Tukey's HSD to find the significantly different means. Pearson correlation analysis determined the relationship between the CI and measured crop parameters. The significance criterion for all statistical analyses was $p < 0.05$.

3. Results

3.1. Soil penetration resistance

In both experimental periods, crop plants, soil types, and soil depths significantly affected soil CI (Table S2). The CI generally increased with increasing depth (Fig. 1). The overall CI of soils grown to Napier grass (2.0 and 2.3 MPa) and maize (1.7 and 2.2 MPa) were similar, but both were higher than the soils cultivated with the other crop plants and unplanted control. The CI of soils grown to sorghum (1.5 MPa for both experiments) and vetiver grass (1.3 and 1.4 MPa) were similar, but both were higher than the CI of the soil in the unplanted control columns (1.1 and 1.0 MPa). The CI of the SEA sand (~2.0 MPa) was between 20% and 41%, significantly higher than that for the other two soil types (Fig. 1).

When the CI of the control pots is subtracted from that of root-permeated pots, the difference could be ordered as follows: Napier grass>maize>sorghum>vetiver grass (Fig. 2a). The difference for Experiment 2 for each crop plant was higher (Fig. 2a) and varied among the tested soils (Fig. 2b), higher for the SEA sand for the plant species. The difference decreased with increasing soil depth in the first experiment but not in the second (Fig. 2c). Although CI appeared inversely related to soil water content, particularly for the second experiment, it was poorly associated with gravimetric soil water content measured at 0–20 cm in both experiments (Fig. 2d).

3.2. Root system architecture traits of the investigated plants

Total root length showed significant differences ($p < 0.001$) among the crop plants and soil types (Fig. S1). Root length density (RLDs) decreased down the soil profile, generally peaking at 40 cm and declining in the layers below 40 cm (Fig. 3a-f). The densities in the top 25 cm and 40 cm ranged from 0.10 to 2.56 cm cm^{-3} and 0.11–4.00 cm cm^{-3}, respectively, and were variable between crops and soils (Table S2). Vetiver and sorghum had lower overall RLDs than maize and Napier across the profile. In both experiments, RLDs in the SEA sand

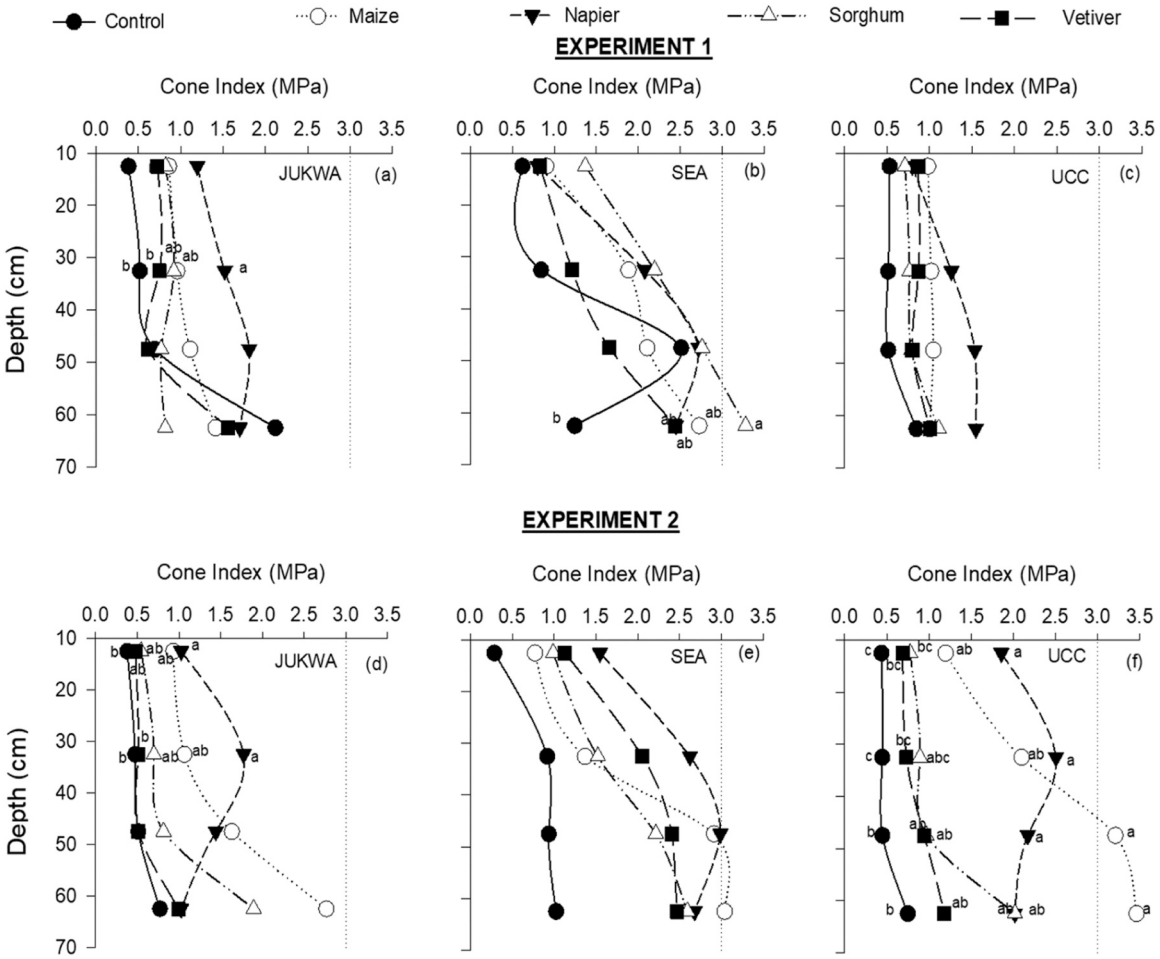

Fig. 1. Cone index measured at 0–70 cm depth for the control, maize, Napier, sorghum, and vetiver cultivated on JUKWA, SEA, and UCC soils in Experiment 1 (a–c) and Experiment 2 (d–e). The dotted line indicates the frequently-stated upper threshold value of soil strength where plant root growth can be impeded. Treatments without letters or the same letters at a given depth are not significant at $p < 0.05$.

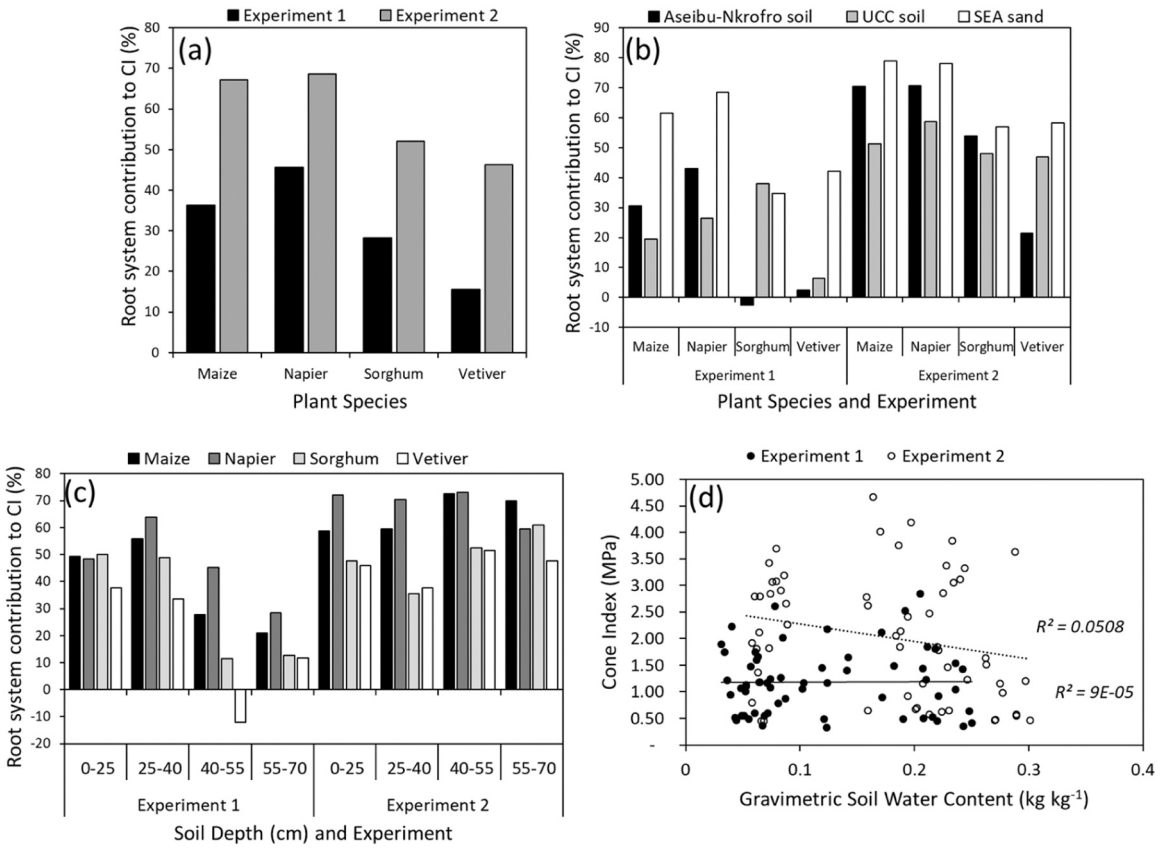

Fig. 2. a-c: Difference in cone index between unplanted control and root-permeated pots a) Difference for the four plant spps.; b) the difference between the three soil types; c) the Difference at various depths; and d) linear regression between cone index and soil moisture content at 0–20 cm depth.

were the lowest (Fig. 3a-f). The distribution of branching frequency per mm, average diameter, and volume of roots for the plant species was highly variable, but some general trends were observed. The branching frequency of roots for the plants generally increased with depth (Table 1). In contrast, the average diameter of the root generally decreased with depth (Table 1). Overall, maize had the largest average root diameter, particularly at 0–25 and 25–40 cm depth. Also, the maize plant tended to have the highest root volume compared to the vetiver, which had the lowest root volume, particularly for the JUKWA (Table 1). SEA.

3.3. Shoot and root biomass of crops

There were significant differences ($p < 0.001$) in shoot dry weight (SDW) between the crop plants and soil types in both experiments (Table S2). The SDW among the crop plants could be ordered as follows: Napier > maize = sorghum > vetiver, and among the soil types was JUKWA soil = UCC soil > SEA sand (Fig. 4a-c). Both experiments had significant ($p = 0.006$ and $p = 0.016$) crop x soil interaction (Table S2). Overall, root biomass significantly ($p < 0.001$) differed between crop plants, soil types, and soil depth in the first experiment (Table S2). The root biomass of Napier grass (4.7 g) was about 2-, 3- and 5-fold higher than that of maize (3.0 g), sorghum (2.0 g), and vetiver (1.0 g), respectively. The root biomass of plants grown in the JUKWA (3.4 g) and UCC (3.3 g) soils were comparable, and these were about 3-fold higher than that of the plants grown in the SEA sand (1.1 g). Root biomass was concentrated in the surface soil (0–25 cm depth) for all crop plants and decreased with increasing soil depth (Fig. 4d-i).

3.4. Plant parameters and cone index relationships

The correlation between mean CI measured at 0–70 and root parameters were highly variable for the different plants and soils investigated. All but one of the significant correlations between RLD and CI occurred in vetiver grown in the SEA sand (Table 2). In the first experiment, the RLD of Napier grass was strongly correlated with CI in the JUKWA (Table 2). In the second experiment, the RLD of vetiver grown in the SEA sand was negatively correlated with CI for maize and Napier. Still, the RLD of sorghum and vetiver was positively correlated with CI (Table 2). The CI generally negatively correlated with average plant root diameter, except for vetiver grass for UCC in Experiment 1 and vetiver for JUKWA in Experiment 2 (Table 2). For example, for both experiments using the SEA soil, it was observed that the CI tends to be negatively correlated with the root diameter of maize and Napier. In the case of the JUKWA soil, the CI correlated negatively with branching frequency for maize in the first experiment but showed a reverse trend for the second experiment. The UCC soil correlated positively with branching frequency for Napier, while a negative correlation was observed for root diameter in both experiments.

3.5. Soil moisture content

Overall, the moisture content at 0–20 cm depth of the three soil types was significantly different ($p < 0.01$) at the time of excavation. There was about a 31% difference in the moisture content of the soils in the first (0.12 kg kg^{-1}) and second (0.17 kg kg^{-1}) experiments (Table S2; Fig. 5).

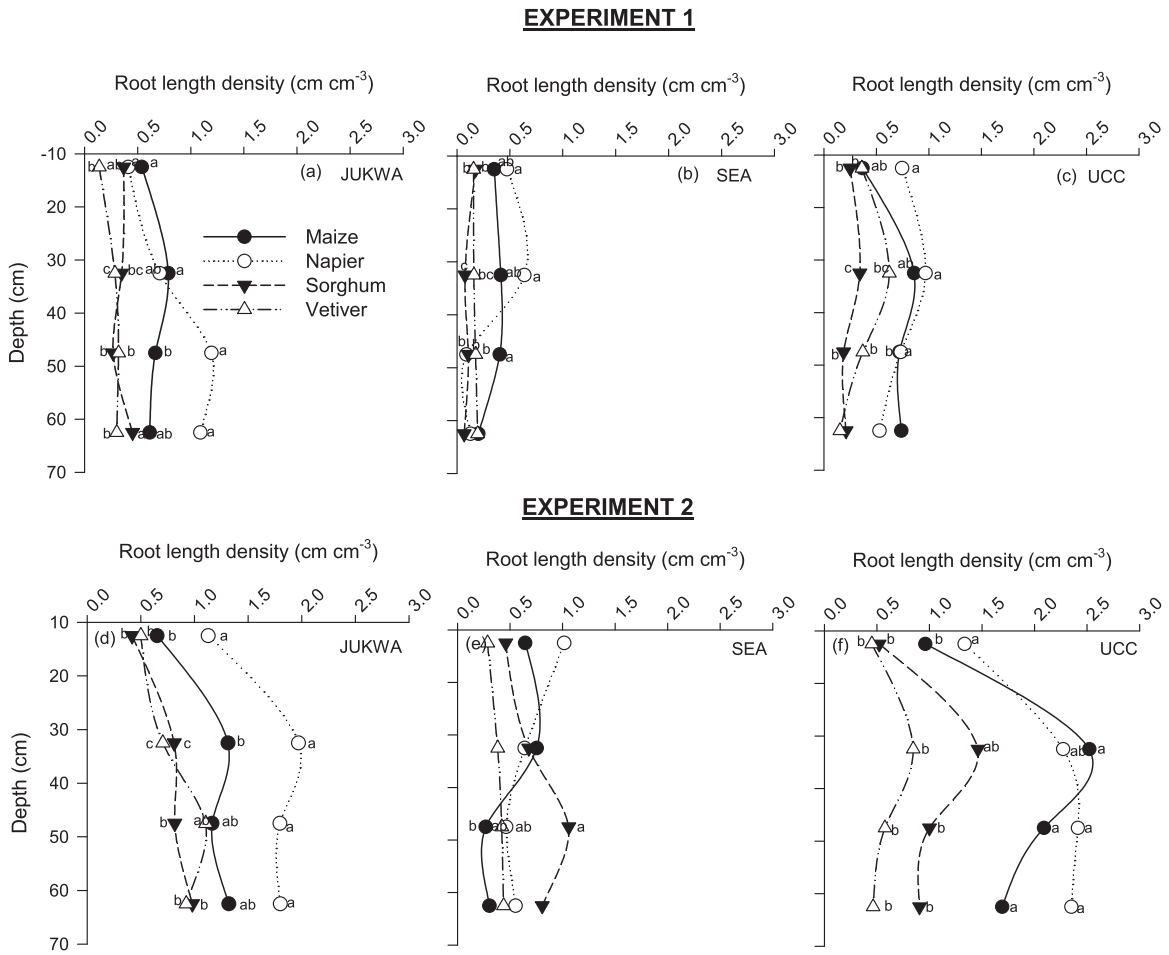

Fig. 3. Root length densities at different depths of maize, Napier, sorghum, and vetiver cultivated in JUKWA, SEA, and UCC soils during Experiment 1 (a-c) and Experiment 2 (d-f). Different letters indicate a significant difference between crops for a given soil depth at $p < 0.05$.

4. Discussion

4.1. Contribution of RSA to cone index

The central hypothesis of the present study was that plant roots provide additional confining pressure to the soil and contribute to the soil's penetration resistance, which is an indicator of soil strength. Still, the foremost question needing answering is whether soil penetration resistance indicates soil strength. Soil penetration resistance is an essential indicator of soil strength (Jiang et al., 2020; Weaich et al., 1992). Soil penetration resistance estimates the cohesive forces between soil particles and frictional resistance met by an inserting object (Cairns et al., 2011). It, therefore, feeds into the significant computational parameters of soil strength. Thus, root penetration resistance, measured as CI in the present study, provides a suitable proxy for soil strength because CI estimates tip resistance which is theoretically related to the undrained shear strength of saturated and cohesive soils. The CI also estimates the sleeve friction, which is theoretically associated with the friction of the soil horizon being penetrated.

In this study, the root-embedded soils presented higher CIs. Internal friction and cohesion are the two main important factors that determine soil shear strength; in sandy soil, roots can increase by 234% (Maffra et al., 2019). Thus, increasing cohesion may be implicated in the high CI of the root-permeated soils. Increased CI of the root-permeated soils could be attributed to reduced soil moisture occasioned by water uptake by roots and reconsolidation due to increased soil bulk density. We computed the difference in CI between control and rooted pots to determine the roots' contribution to CI and soil strength (Fig. 2), but this approach may be overly crude. It fails to determine precisely how much of the difference between pots with roots versus pots without roots is due to the roots' reinforcement and how much is due to differences in water content. Even so, the approach offers a starting point to disaggregate the increased rooted soil strength factors.

Contrary to that observed by Lardy et al. (2022) and Zhang et al. (2006), CI did not vary linearly with gravimetric water content, suggesting that the contribution of soil moisture content to CI in the present study was minimal. Instead, soil bulk density and roots' influence on cohesion and internal friction might govern the increased CIs and soil strength of root-permeated soils in the present study. Assessing the root tensile strength and soil shear strength of root-permeated soils will be critical in quantifying the direct effects of roots on soil strength. Liang et al. (2020) pointed out that the strength provided by roots is a function of their properties, such as tensile strength and root density. The lack of a significant inverse relationship between CI and soil moisture was unexpected and might be because all pots were irrigated similarly in the present study. Although slight differences in soil moisture content might have emerged for the different crops due to their differences in water uptake by the plants, it was insufficient to cause a significant relationship between soil moisture and CI.

It is also important to note that although sandy soils typically have weak cohesion forces among particles, they also tend to have very high values of internal angle friction due to their large particle size. This increases their CIs and explains the high values recorded for the SEA sand in this study. Previous studies examining the relationships between

Table 1
Branching frequency, average diameter, and roots volume at 0–25, 25–40, 40–55, and 55–70 cm depth for maize, Napier, sorghum, and vetiver cultivated on JUKWA, SEA, and UCC soil during Experiments 1 and 2. Different letters indicate a significant difference between crops for a given soil depth at $p < 0.05$.

Soil type	Depth (cm)	Branching frequency per mm				Average diameter (mm)				Volume (mm^{-3})			
		Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver
Experiment 1													
JUKWA Soil	0–25	0.593^{a}	0.632^{a}	0.490^{b}	0.454^{b}	1.914^{a}	1.599^{a}	2.049^{b}	1.616^{b}	295951^{a}	134767^{bc}	176422^{ab}	32558^{c}
	25–40	0.636^{a}	0.665^{a}	0.642^{a}	0.473^{b}	1.682^{a}	1.642^{ab}	1.212^{b}	1.406^{ab}	202221	180111	39303	32176
	40–55	0.643^{a}	0.642^{a}	0.666^{a}	0.489^{b}	1.481^{a}	1.524^{a}	1.146^{b}	1.388^{ab}	141960^{ab}	214794^{a}	25633^{b}	36984^{b}
	55–70	0.674^{a}	0.666^{a}	0.685^{a}	0.469^{b}	1.452	1.465	1.301	1.315	166255	191473	73208	30466
SEA Soil	0–25	0.59	0.81	0.56	0.52	1.91	1.84	1.89	1.65	206248	132880	83691	44225
	25–40	0.66^{a}	0.67^{a}	0.70^{a}	0.48^{b}	1.59	1.38	1.09	1.38	103515	94350	6836	18549
	40–55	0.63^{ab}	0.71^{a}	0.74^{a}	0.52^{b}	1.60^{a}	1.04^{b}	1.07^{b}	1.65^{a}	96461^{a}	8382^{b}	8730^{b}	32019^{ab}
	55–70	0.69^{ab}	0.77^{a}	0.82^{a}	0.55^{b}	1.22^{ab}	0.98^{b}	0.97^{b}	1.45^{a}	23814	12673	7065	27056
UCC Soil	0–25	0.77	0.95	0.49	0.72	2.11	2.51	1.92	2.47	176481	302254	105934	104709
	25–40	0.87	0.82	0.60	0.71	1.59	1.74	1.37	2.50	127249	153982	51203	221351
	40–55	0.91	0.69	0.63	0.77	1.55	1.34	1.09	1.99	90413	97553	25301	38189
	55–70	0.87	0.72	0.72	0.66	1.76	1.20	1.35	2.15	125622	56488	32439	14767
Experiment 2													
JUKWA Soil	0–25	0.380^{b}	0.437^{b}	0.376^{b}	0.495^{a}	2.31^{a}	2.66^{a}	2.28^{a}	1.50^{b}	512502^{b}	1396277^{a}	262256^{b}	118360^{b}
	25–40	0.443	0.460	0.512	0.491	1.67^{b}	2.18^{a}	1.42^{c}	1.49^{bc}	252586^{b}	869805^{a}	115691^{b}	108137^{b}
	40–55	0.444	0.459	0.551	0.547	1.92^{a}	2.02^{a}	1.31^{b}	1.31^{b}	366337^{ab}	647996^{a}	103741^{b}	130597^{b}
	55–70	0.479^{ab}	0.471^{b}	0.549^{a}	0.493^{ab}	1.84^{ab}	2.05^{a}	1.41^{b}	1.45^{b}	374523^{ab}	666496^{a}	154168^{b}	131797^{b}
SEA Soil	0–25	0.406	0.574	0.467	0.409	2.20	2.68	2.11	1.91	422484	813224	305547	121538
	25–40	0.470^{b}	0.473^{b}	0.565^{a}	0.411^{b}	2.06^{a}	1.50^{b}	1.56^{b}	1.53^{b}	268440	150446	149943	54573
	40–55	0.485	0.391	0.610	0.423	1.81	1.05	1.40	1.84	72770	81468	190246	95962
	55–70	0.534	0.392	0.553	0.444	1.47	1.11	1.68	1.64	79099^{a}	115569^{ab}	224267ab	69324^{b}
UCC Soil	0–25	0.456	0.409	0.429	0.430	2.24	2.53	2.27	1.55	1029059	1243016	423952	91378
	25–40	0.531	0.459	0.564	0.425	1.96	2.14	1.66	1.51	912976	925814	433841	124712
	40–55	0.531^{ab}	0.476^{ab}	0.594^{a}	0.437^{b}	1.93^{ab}	2.28^{a}	1.35^{b}	1.43^{ab}	803684	1510859	267607	67400
	55–70	0.531	0.479	0.568	0.476	1.76	2.12	1.63	1.54	510021	1028371	444812	67053

root traits and mechanical soil properties have shown that the RLD influenced soil shear strength. In that context, the plants with high RLD present increased soil strength. In the present study, the RLD of Napier grass was strongly correlated with CI for the JUKWA Soil, and the RLD of sorghum and vetiver was positively correlated with CI (Table 2). Even so, the RLD of the four plant species did not establish a consistent relationship with CI. The lack of consistency could be explained by the fact the CI measures penetration resistance not only due to the presence of roots but also due to other factors. The low RLD of the four investigated plant species (0.003–4.00 cm cm^{-3}) compared to the RLD measured for perennial herbaceous, shrub, and tree species (more than 300 cm cm^{-3}) might explain the absence of significant relationships between RLD and the CI for some of the plant species in the present study.

Several processes through which root systems might influence soil strength have been highlighted in previous reviews (Angers and Caron, 1998; Loades et al., 2013). For example, roots growing in existing pores can create compressive shear stresses reaching 2 MPa (Goss, 1991), akin to the CI measured in this study. Where the size of the root system is small in the ground, the amount of water loss through transpiration might be equally small, probably explaining why the soil moisture content of columns sown to vetiver was similar to the control columns (Fig. 5). The aggregate binding of the soil by root can be through enmeshing with a network of roots or root exudation and mucilage. Plant root hairs of many crop plants form rhizosheaths (Adu et al., 2017; Opoku et al., 2022) and are critical in enmeshing and stabilising soil aggregates. It is instructive to determine how root hairs of the tested crop plants contribute to soil strength and stabilisation.

4.2. Implication for genotypic variation in root system traits to cone index

According to Abdullah et al. (2011), root systems of different crop plants influence soil strength differently, corroborating the observations in this work. Root parameters such as diameter, volume, biomass, numbers, and length have been noted to play essential roles in modifying soil structure and strength (Foresta et al., 2020; Kumi et al., 2016), and therefore, genotypic variation in these traits would be reflected in the root system's contribution to soil strength and stabilisation. Significant genetic variations were observed for the RSA traits evaluated, including biomass, length and RLD, diameter, and the number of roots (Figs. 1 and 2 and Tables S2 and 1). Napier and maize generally had higher root biomass and sizes than sorghum and vetiver for all investigated soils. However, Napier was superior up to 40 cm depth, agreeing with Sekiya et al. (2013) that Napier grass possesses more significant root systems than other grasses. The extensive root systems of the Napier were also reflected in its above-ground biomass, recording the highest shoot biomass across both experiments (Fig. 1). As reported by several others (e.gs., Angima et al., 2002; Dos-Santos et al., 2021), the Napier grew very fast and vigorously, its roots reaching the bottom of the 70 cm column in just about a month. Thus, the present study suggests Napier grass develops fast-growing and extensive root systems with substantially large biomass, lengths, RLD, and numbers. Napier, therefore, represents a possible plant to explore aspects of nature-based soil management, including enhancing soil strength and stabilisation.

In all cases, the vetiver recorded the least values, an occurrence that its slow establishment in the present study may explain. The vetiver's poor performance here is somewhat perplexing. Typically, vetiver is a fast-growing, stress-tolerant plant whose extensive root system can reach a rooting depth of 60 cm in 3 weeks (Yoon, 1991) and 3–4 m in the first year (National Research Council, 1993). Perhaps it is worth repeating that this work was performed in unnatural environments involving soil-filled columns and a greenhouse. Despite its tolerance to stressful conditions, vetiver grows best in the open and has been noted to be highly intolerant to shading, which is said to reduce its growth markedly (Truong and Baker, 1998). Suboptimal photosynthetically active radiation for vetiver and column confinement might have thus adversely impacted the vetiver's establishment in the present study. In the long term, vetiver is a deeply rooted, persistent grass that offers a practical and inexpensive solution for controlling erosion when planted along the contours of sloping lands (National Research Council, 1993). In bioengineering, an integrated system of Napier and vetiver will take advantage of the rapid establishment of Napier until the vetiver is fully established. However, Napier roots' tensile strength, root decay and resultant soil shear strength must be validated.

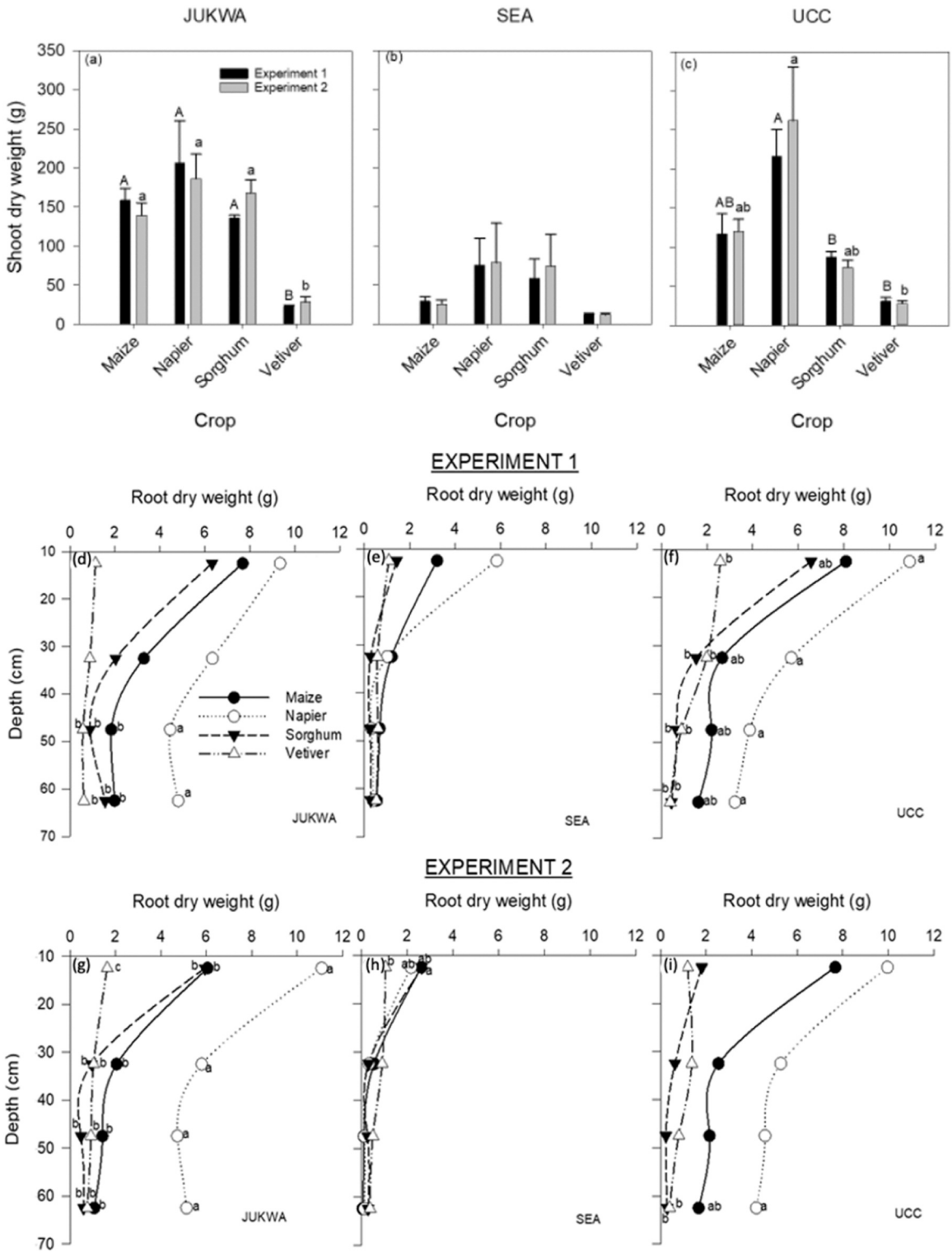

Fig. 4. a-c: Shoot dry weight of maize, Napier, sorghum, and vetiver grown on the (a) JUKWA, (b) SEA, and (c) UCC soils investigated during Experiments 1 and 2. Error bars indicate the standard error of the mean. Treatments with different letters are significantly different for a given soil at $p < 0.05$. Upper and lower case letters denote Experiments 1 and 2, respectively; d-i: Root dry weight measured at 0–70 cm depth for the control, maize, Napier, sorghum, and vetiver cultivated on JUKWA, SEA, and UCC soils in Experiment 1 (d-f) and Experiment 2 (g–i). Different letters indicate a significant difference between crops for a given soil depth at $p < 0.05$.

4.3. Effect of type of soil on RSA and cone index

Plant roots grow unimpeded when soil strength is below 0.7 MPa, but root growth is directly affected between 0.7 MPa and 2.0 MPa. At soil strength of 2 MPa or more, mechanical penetration of roots is seriously hindered (Barnhisel and Hower, 1997), but the threshold varies with plant species (Loades et al., 2013). The average soil strengths across the two experiments for the unplanted SEA sand, JUKWA, and UCC soils were 1.3, 0.8, and 0.6 MPa, respectively, indicating that root growth may have been impeded in the SEA sand. The high soil strength of the SEA sand might be due mainly to the higher sand content, its attendant high bulk density (1.80 g cm^{-3}: Table S1), and its limited capacity to

Table 2
Correlation Between Cone Index and Selected Root Parameters for Experiments 1 and 2.

CI	Experiment 1													
0–70 cm depth		Root length density (cm cm^{-3})				Branching frequency per mm				Average diameter (mm)				Volume (mm^3)			
	Soil type	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver
Pearson Correlation coefficient (r)	JUKWA Soil	0.05 ns	0.99 * **	0.32 ns	0.23 ns	-0.95 * *	0.16 ^{ns}	-0.74 ^{ns}	0.91 *	-0.90 *	-0.60 ^{ns}	-0.03 ns	-0.54 n^{s}	-0.74 ^{ns}	0.99 * ** *	0.05 ^{ns}	-0.78 ^{ns}
	SEA Soil	-0.43 ns	-0.62 ns	-0.83 ns	0.97 * *	-0.92 *	0.12 ^{ns}	-0.93 *	0.40 ^{ns}	-0.90 *	-0.93 *	-0.95 * *	-0.31 ^{ns}	-0.86 *	-0.78 ^{ns}	-0.89 *	-0.36 ^{ns}
	UCC Soil	0.70 ns	-0.33 ns	-0.39 ns	-0.72 ns	0.68 ^{ns}	0.88 *	-0.82^{ns}	0.57 ^{ns}	-0.93 *	-0.98 *	-0.32 ^{ns}	0.11 ^{ns}	-0.95 *	-0.93 *	-0.55 ^{ns}	-0.48 ^{ns}
Experiment 2																	
0–70 cm depth		Root length density (cm cm^{-3})				Branching frequency per mm				Average diameter (mm)				Volume (mm^3)			
	Soil type	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver	Maize	Napier	Sorghum	Vetiver
Pearson Correlation coefficient (r)	JUKWA Soil	0.61 ns	0.65 ns	0.76 ns	0.41 ns	0.85 *	-0.30 ^{ns}	0.82 ^{ns}	0.84 ^{ns}	-0.32 ^{ns}	-0.39 ^{ns}	-0.55 ^{ns}	0.04 ^{ns}	-0.05	-0.28 ^{ns}	-0.23 ^{ns}	0.57 ^{ns}
	SEA Soil	-0.88 *	-0.97 * *	0.89 *	1.00 * **	-0.84 ^{ns}	0.94 * *	0.52 ^{ns}	0.06 ^{ns}	-0.87 *	-0.97 * *	-0.73 ^{ns}	-0.54 ^{ns}	-0.99 * *	-1.00 * *	-0.43 ^{ns}	-0.63 ^{ns}
	UCC Soil	0.66 ns	0.78 ns	0.42 ns	0.52 ns	0.62 ^{ns}	0.85 *	0.42 ^{ns}	-0.91 *	-0.94 * *	-0.68 ^{ns}	-0.34 ^{ns}	-0.19 ^{ns}	-0.80 ^{ns}	-0.42 ^{ns}	0.24^{ns}	-0.79 ^{ns}

ns: $p > 0.05$, * $p \leq 0.05$, * * $p \leq 0.01$, * ** $p \leq 0.001$ and * ** * $p \leq 0.0001$

retain soil moisture for plant uptake (Fig. 5). Again, the high penetration resistance recorded in the SEA sand could be due to an increased angle of internal friction due to the high particle or packing density of this type of soil. Typically, drier soils tend to be more compact, which tends to resist the growth and development of roots (Fan and Su, 2008; Kumi et al., 2016; Raper and Mac Kirby, 2006). Typical sandy soil has very low cohesion but high internal shearing resistance, leading to reduced root growth (biomass, root length, and numbers) and spatial distribution (Figs. 4 and S1).

Cell division and size in mechanically impeded roots can decline by 40% (Bengough and Mullins, 1990). Compared to the arable soils (i.e., the JUKWA and UCC soils), the total root length in the 70 cm soil columns reduced, between 48.3% and 57.3% when plants were grown in the SEA sand. Indeed, the reduced root growth cannot be attributed only to penetration resistance in the SEA sand but also to other factors, such as possible declined soil fertility and moisture in the SEA sand, as stated previously. Even so, the present results suggest that the effect of soil strength on cell division and growth is also evident in other root systems traits, such as the total root length of matured plants, and the effect may vary with plant species. When maize was planted in nine different soils, differences were observed in the root biomass and other RSA traits (Böhm, 1979). Loades et al. (2013) showed that under increased soil penetration resistance, root growth rate might be impeded by the structural degradation of soil pore spaces, with attendant decreases in porosity, hydraulic conductivity, and air permeability.

4.4. Effect of depth on RSA and cone index

The results in the present study corroborate the reports that CI usually varies with penetration depth (Wismer and Luth, 1974). The CI generally increased with increasing depth (Fig. 1), with a 57–99% increase in CI of the bottom layer compared to the top layer of the soil column. The increased CI with depth was, possibly, in response to increasing effective confining stress and increased cohesion of soil particles with depth. Therefore, as Zhao et al. (2018) pointed out, roots' contribution to the overall shear strength decreases with increasing depth. In the present study, root branching frequency generally increased with depth, but the opposite was true for average root diameter (Table 1). Thinner roots could grow through soil pores to deeper layers and produce laterals (Hendry et al., 2014; Putri et al., 2010; Zhao et al., 2018). On the other hand, the growth of larger root axes may be impeded, especially in compacted and drier soils.

Soil strength on root distribution and natural variability in root depth between species appear to influence the variability in root system distribution with depth. For example, Napier, maize, and sorghum partitioned a considerable amount of root biomass in the upper layer (Fig. 3). Still, in both experiments, root biomass and length changed only slightly across layers for vetiver regardless of marked increases in CI with depth (Fig. 3 and 4). Napier, maize, and sorghum performed as typical grasses with fibrous root systems, which proliferate and partition in shallow soil layers, potentially increasing surface soil reinforcement and reducing surface soil erosion (Baets et al., 2007; Gyssels et al., 2005). Indeed, Angima et al. (2002) noted that Napier grass' effectiveness for erosion control could be due to its massive near-surface lateral root system. According to Wang et al. (2020), vetiver root system size decreases with increasing depth. The results demonstrated that if vetiver root systems are characterised by a reasonably constant proliferation and partitioning along the soil profile, it might offer a different or additional role in soil reinforcement compared to the other grasses.

5. Conclusions

The study showed that roots of maize, Napier grass, sorghum, and vetiver contributed to an increase in soil strength quantified as cone index (CI), representing penetration resistance, but in varied ways. Although the CI provide a valuable and quick metric of soil strength, the

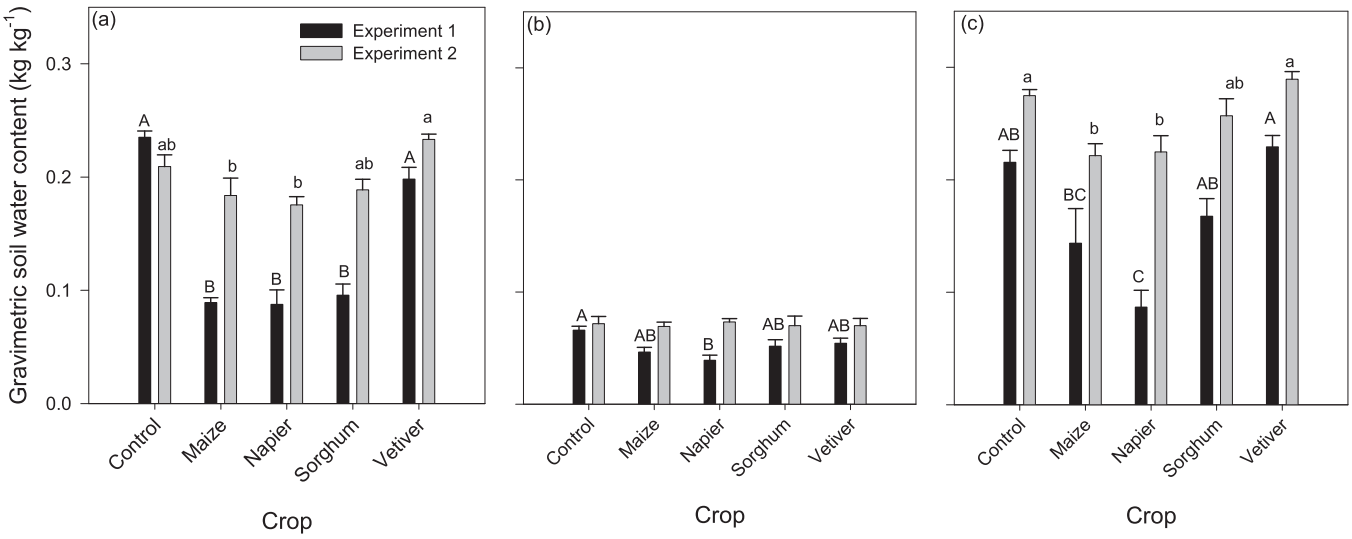

Fig. 5. Soil moisture content at 0–20 cm depth during sampling for the (a) Jukwa, (b) SEA, and (c) UCC soils investigated during Experiments 1 and 2. Error bars indicate the standard error of the mean. Treatments with different letters are significantly different for a given soil at $p < 0.05$. Upper and lower case letters denote Experiments 1 and 2, respectively.

estimates must be indexed with other factors since CI is strongly influenced by soil texture, moisture content, bulk density and soil organic matter content. Here, simple linear regression suggested that soil moisture content did not significantly increase the CI of root-permeated soils. The interaction of soil bulk density, root biomass, and morphological traits contributed substantially to soil strength. Plant roots may have impacted CI or soil strength by transferring soil shear stress into root tensile resistance via the roots' action on friction and interlocking force between soil particles and the root system. As seen in the present study, the transfer of soil shear stress into root tensile resistance might be moderated by natural variability in root system traits between plant species, the interaction between soil texture and root biomass, and root morphological characteristics.

Moreover, root traits and CI varied with increasing depth and for soil types, indicating that the interaction of the physiological parameters of plant roots, soil type, and depth of root profiles influences soil strength. Overall, this short-term study showed that Napier grass, followed by maize, sorghum, and vetiver, presented superior soil penetration resistances. A long-term study would be needed to ascertain how much Napier consistently can contribute to soil stability and strength. Such a study could include modelling the relationship between shear strength and angle of internal friction alongside root tensile strength and decay rate to provide an in-depth understanding of the underlying mechanisms that explain the contribution of the plant root system to soil-root reinforcement.

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CRediT authorship contribution statement

Michael O. Adu: Conceptualization. **Michael O. Adu, Francis Kumi, Emmanuel Arthur, Peter B. Obour, Paul A. Asare, Stephen E. Moore, Joel Asiedu, Donatus B. Angnuureng, Kofi Atiah, Kwadwo K. Amoah**: Methodology. **Michael O. Adu, Samuel Banafo, Kwadwo K. Amoah, Kofi Atiah, Paul A. Asare**: Investigation. **Samuel Banafo, Michael O. Adu**: Data curation. **Michael O. Adu, Peter B. Obour, Emmanuel Arthur, Francis Kumi, Kofi Atiah**: Writing – original draft preparation. **Michael O. Adu, Francis Kumi, Paul A. Asare, Kofi Atiah, Kwadwo K. Amoah**: Supervision. **Michael O. Adu, Francis Kumi, Peter B. Obour, Emmanuel Arthur, Stephen E. Moore, Paul A. Asare, Joel Asiedu, Donatus B. Angnuureng, Kofi Atiah, Kwadwo K. Amoah, Shadrack K. Amponsah, Selorm Y. Dorvlo, Samuel Banafo**: Writing – review & editing. **Shadrack K. Amponsah, Peter B. Obour**: Provision of tools. **Michael O. Adu, Francis Kumi, Peter B. Obour, Emmanuel Arthur, Stephen E. Moore, Paul A. Asare, Joel Asiedu, Donatus B. Angnuureng, Kofi Atiah, Kwadwo K. Amoah, Shadrack K. Amponsah, Selorm Y. Dorvlo, Samuel Banafo**: Validation. **Michael O. Adu, Francis Kumi, Emmanuel Arthur, Paul A. Asare, Stephen E. Moore, Joel Asiedu, Donatus B. Angnuureng**: Funding acquisition.

Declaration of Competing Interest

The authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105811.

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