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SOIL STRUCTURAL DEGRADATION AND NUTRIENT LIMITATIONS ACROSS LAND USE CATEGORIES AND CLIMATIC ZONES IN SOUTHERN AFRICA

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SOIL STRUCTURAL DEGRADATION AND NUTRIENT LIMITATIONS ACROSS LAND USE CATEGORIES AND CLIMATIC ZONES IN SOUTHERN AFRICA

Short title: SOIL STRUCTURAL DEGRADATION IN SOUTHERN AFRICA

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ABSTRACT

While soil degradation is a major threat to food security and carbon sequestration, our knowledge of the spatial extent of the problem and its drivers is very limited in southern Africa. Using data on soil clay, silt, organic carbon (SOC), total nitrogen (N), available phosphorus (P) and sulphur (S) concentrations collected from 4468 plots on 29 sites across Angola, Botswana, Malawi, Mozambique, Zambia and Zimbabwe, this study presents novel insights into the variations in soil structural degradation and nutrient limitations with land use categories (LUCs) and climatic zones. The analysis revealed strikingly consistent stoichiometric coupling of total N, P and S concentrations with SOC across LUCs. The only exception was on crop land where available P was decoupled from SOC. Across sample plots, the probability (φ) of severe soil structural degradation was 0.52. The probability of SOC concentrations falling below the critical value of 1.5% was 0.49. The probabilities of soil total N, available P and S concentrations falling below their critical values were 0.95, 0.70 and 0.83, respectively. N limitation occurred with greater probability in woodland (φ = 0.99) and forestland (φ = 0.97) than in cropland (φ = 0.92) and grassland (φ = 0.90) soils. It is concluded that soil structural degradation, low SOC concentrations and N and S limitations are widespread across southern Africa. Therefore, significant changes in policies and practices in land management are needed to reverse the rate of soil structural degradation and increase soil carbon storage.

Key words: isometric coupling; miombo; woodland; soil carbon; stoichiometry

INTRODUCTION

Land degradation is expanding at an alarming rate in sub-Saharan Africa (SSA), and it is now posing unprecedented environmental, social and economic problems (FAO & ITPS, 2015). Among the major manifestations of the degradation are loss of soil organic matter (SOM), decline in fertility, elemental imbalances, deterioration of soil structure, acidification and salinization (Lal, 2015).

According to the Intergovernmental Technical Panel on Soils (FAO & ITPS, 2015) the loss of vegetative cover and subsequent loss of soil organic carbon (SOC) are the root causes of most soil degradation in SSA.

Land use changes including deforestation and forest degradation have been linked to the loss of 20-50% of the original SOC in the top soil in SSA (Henry *et al.*, 2009). In southern Africa, deforestation often results from agricultural expansion, settlement, extraction of timber, firewood and charcoal burning and uncontrolled bushfires (Geist & Lambin, 2002). ~~For example, in the Miombo ecosystem (the world's largest contiguous tropical dry forests), tobacco-related deforestation alone represents up to 50% of the total annual forest loss (WHO, 2017).~~ Land use changes prompt immediate soil disturbance that can fundamentally alter both carbon inputs and decomposition rates, triggering greenhouse gas (GHG) emissions (Henry *et al.*, 2009).

In order to compensate for global CO_2 emissions from anthropogenic sources, the "4 per mille" initiative was launched at the COP21 conference in Paris (van Groenigen *et al.*, 2017; Minasny *et al.*, 2017). According to Minasny *et al.* (2017), with good land management, this target can be achieved especially for soils with low initial SOC stocks (topsoil less than 30 Mg/ha C). Recently van Groenigen *et al.* (2017) questioned the feasibility of this goal based on stoichiometric arguments. The formation and turnover of SOM depends largely on the stoichiometric relationships between carbon (C), nitrogen (N), phosphorus (P) and sulphur (S) in the soil (Frossard *et al.*, 2016; Lal, 2015; Tipping *et al.*, 2016; Yang *et al.*, 2010). The C:N:P:S stoichiometry determine key biogeochemical processes including nutrient inputs and outputs, SOM mineralization patterns and nutrient imbalances associated with changes in land use (Frossard *et al.*, 2016; Tipping *et al.*, 2016; Xu *et al.*, 2018). Stoichiometric relationships in the soil also influence SOC sequestration and GHG emissions (van Groenigen *et al.*, 2017; Yang *et al.*, 2010), and the loss of soil nutrients from intensive agricultural systems (Zhang *et al.*, 2018).

A number of studies especially from China have reported significant influence of land use and climate on soil C, N, P and S concentrations and their stoichiometric ratios (Wang *et al.*, 2014; Xu et al., 2018). On the other hand, lack of quantitative information on soil structural degradation and nutrient limiting conditions has been one of the main obstacles for designing sustainable land management practices in southern Africa. Therefore, the objectives of this study were to (1) quantify the risk of soil structural degradation and (2) determine the variation in soil stoichiometry and nutrient limitations with LUCs and climatic zones. The main hypotheses being tested were that: (1) the risk of soil structural degradation is greater on crop land than on other LUCs; (2) soil stoichiometric ratios do not significantly vary with LUCs and climatic zones; and (3) soil N, available P and S concentrations are coupled with SOC content.

MATERIALS AND METHODS

The study sites

This study was carried out in 29 sites distributed across Angola, Botswana, Malawi, Mozambique, Zambia and Zimbabwe (Figure 1a). According to the Koppen-Geiger climatic zoning, 17 sites were classified as humid or subhumid while the remaining sites were either semiarid or arid (Supplementary Table S1). The classification of vegetation types and LUCs in this study strictly follows the Land Degradation Surveillance Framework (LDSF) field guide (Vågen *et al*., 2015). The LUCs included forestland, woodland, bush land, shrub land, grassland and cropland (Table S1). The definition of each LUC and vegetation type is presented in the supporting information (Methods S1). ~~The terrain, geology and soil types also differ markedly between sites (Tamene *et al*., 2016).~~ The dominant soils ranged from Arenosols and Cambisols on arid sites to Ferralsols, Lixisols and Luvisols on humid sites (Table S1). A large proportion of the sites experience soil erosion, bush fires and livestock grazing (Tamene *et al*., 2016).

Soil sampling and analysis

Soil samples were collected using the Africa Soil Information Service (AfSIS) and LDSF protocol (Vågen *et al*. (2015) from 4468 plots across the 29 sites. A hierarchical random sampling approach (Figure 1b) was ~~employed~~ used where a sentinel site of 100 km^2 area was selected, and within each sentinel site 16 clusters of 2.5 km x 2.5 km were created. Within each cluster ten plots measuring 1000 m^2 each were randomly laid. Each plot had four subplots had an area of 100 m^2. A Global Positioning System was used to navigate to sampling plots, once a plot was located, the central position of the plot (referred as the central subplot, c) was marked (Figure 1c). From the center-point of the plot, a distance of 12.2 meters was measured to the upper slope position using measuring tape and the center of the subplot was marked as subplot 3. Subplots 1 and 2 were offset at 120 degrees from subplot 3 (Tamene *et al*., 2016). The radius of each subplot was 5.64 m, which gives approximately 0.01 ha area.

Soil samples were collected from the 0–20 cm and 20–50 cm soil depths from the center of each subplot. A composite sample of 500 g (from the four subplots) was taken from the 0–20 cm and 20–50 cm depths separately, which amounted to a total of 320 samples per site. Each soil sample was air dried to constant weight and sieved using a 2 mm sieve (Vågen *et al*., 2015). Near infrared (NIR) and mid infrared (MIR) spectroscopy analyses of all the soil samples were done in the ICRAF laboratory in Nairobi. ~~This method was chosen due to the large number of samples and the time and resources constraint.~~ Reference analysis was carried out using wet chemistry for samples from plot 1 of each cluster, which constituted about 10% of the samples. The wet chemistry results were used for calibration of NIR and MIR models.

Soil bulk density was calculated as the dry weight of soil divided by its volume (Arshard *et al*., 1996). Soil texture was determined by laser diffraction method using calgon as a dispersing agent and ultrasonification for four minutes. Sulfur and available soil P were analyzed by wet chemistry based on Mehlich 3 extraction procedure, pH was determined in water (1:2.5 soil–water (w/v) suspensions) at the Crop Nutrition Laboratories in Nairobi, Kenya.

Metrics and threshold values

Unlike traditional analysis that focuses on individual soil physical and chemical variables, this study focus~~s~~ed on integrative metrics including the soil structural stability index (~~SSI~~St), SOC, total N, available P, S and their stoichiometric ratios (Table S2). The St is an important indicator of degradation and the sufficiency of SOM to maintain soil structural stability (Pieri, 1992). Here, St was calculated as proposed by Pieri (1992) for the ~~top~~ 0-20 cm and 21-50 cm depths ~~and lower depths~~ separately:

$$St = 100 \times \frac{SOM\ (\%)}{Clay\ (\%) + Silt\ (\%)}$$

~~SSI~~ St ≤5% indicates a structurally degraded soil due to extensive loss of SOC; 5% < ~~SSI~~ St < 7% indicates a high risk of structural degradation; and St > 7% indicates low risk (Pieri 1992).

The SOC content is considered as a 'universal indicator' of soil fertility, overall quality and a broader indicator of ecosystem response to environmental change (Loveland & Webb, 2003; Musinguzi *et al*., 2013). The SOC pool is also the most reliable indicator for monitoring soil degradation (Lal, 2015). According to Lal (2015) SOC concentrations should be kept above 1.5% to reduce risks of soil degradation. Other reviews have concluded that 2% SOC is the critical concentration for large changes in the functionality of soils (Loveland and Webb, 2003; Musinguzi *et al*., 2013). The critical concentrations of total N, available P and S that limit crop production have been reported to be 0.15%, 11 mg/kg and 10 mg/kg, respectively (Table S2), and these values are used for inferences regarding nutrient limitations in this study~~y~~.

In ecological interactions, stoichiometric ratios are known to be more critical than the actual concentration of the individual elements. For example, the soil C:N ratio is a sensitive indicator of N limitation of plants and soil microbial decomposer communities (Mooshammer *et al*., 2014). Low soil C:N ratios often accelerate microbial decomposition and N mineralization, creating an environment not conducive for SOC sequestration. According to Mooshammer *et al*. (2014) the threshold C:N ratio is between 20:1 and 25:1 in organic and mineral soils. When C:N > 25 soil microbial growth can be N-limited, whereas C:N < 20 implies C limitation. The N:P ratio is also an important indicator of N limitation. According to Koerselman & Meuleman (1996) vegetation N:P > 16:1 indicates P limitation, while N:P < 14:1 indicates N limitation in the soil. When vegetation N:P is between 14:1 and 16:1, plant growth is co-limited by soil N and P (Koerselman & Meuleman, 1996). The C:P ratio also plays an important role in the availability of P for plant uptake. At low C:P ratios, bacteria mobilize more P thus enhancing plant P uptake. At high C:P ratios microbial biomass P becomes stable as bacteria immobilize P, and this reduces P availability for plant uptake (Zhang *et al*., 2018). Low C:P ratios are often interpreted as indications of C limitation relative to P in a given LUC. Globally, a C:N:P ratios of 186:13:1 seems to be a well-balanced ratio for soils (Cleveland & Liptzin, 2007; Wang *et al*., 2014).

Statistical analysis

In order to determine whether ~~SSI~~St, SOC, N, P and the C:N:P:S stoichiometry of bulk soils vary with LUC and climate, a linear mixed modelling procedure was applied using soil depth, LUC and climate as fixed effects and plot as the random effect. Model parameters and their 95% confidence intervals (95% CI) were estimated using the restricted maximum likelihood method. For statistical inferences, the 95% confidence intervals (CI) were used to complement P. Means were judged to be significantly different from one another if their 95% CI were non-overlapping. ~~Since inferences based on the mean alone can be misleading if the probability distribution of responses is not known, the cumulative probability distributions of St, SOC, N, P, S and the stoichiometric ratios were determined.~~ Then~~ the~~ probability of exceeding the critical values of St, SOC, N, P and S were estimated from their probability distributions in the different LUCs. In the literature, critical values and thresholds of stoichiometric ratios are not available for soils. Therefore, in this analysis stoichiometric ratios were not compared against critical values.

A number ~~pf~~ of studies have found significant relationships between SOC, N, P and S (Cleveland & Liptzin, 2007; ~~McGroddy *et al*., 2004;~~ Tipping *et al*., 2016; Yang *et al*., 2010). The relationship between C and N has been shown to be isometric in soil samples (Yang *et al*., 2010). In order to determine whether or not such relationships exist, regression analysis was conducted taking the logarithms of SOC (%), total N (%), available P (%) and S (%) in the top 20 cm soil following Cleveland & Liptzin (2007), Manzoni *et al*. (2010) and Tipping *et al*. (2016). Reduced major axis (RMA) regression was performed in preference to ordinary least square regression (OLS) because of its superior performance in situations where both variables were measured with error. RMA is also preferred over OLS when neither variable can be regarded as dependent or independent (Warton et al., 2006). Any significant relationship that approached isometry (slope = 1) was interpreted as an indication of close coupling (parallel impoverishment or enrichment) of soil N, P and S with SOC. The slopes were compared using their 95% CLs to establish whether or not the LUCs significantly differ in the degree of coupling between N, P and S with SOC.

Spearman's rank correlation was used to examine the association between soil clay, silt, pH, SOC, N, available P, S, stoichiometric ratios, above-ground biomass carbon, SOC stocks and the observed probabilities of disturbance variables including fire, grazing and cutting of trees (Methods S2).

RESULTS

Variations in St, SOC, total N, available P and S across sites

The frequency distributions of St, SOC, total N, available P and S concentrations and C:P and N:P ratios were positively skewed, and their median values were much lower than their means (Figure 2). Across the 29 sites, significant variation was observed in St (Figure 3a), SOC (Figure 3b), total N (Figure 3c), available P (Figure 4a), S (Figure 4b), SOC stocks (Figure 4b) and stoichiometric ratios (Figure 5). Across 4468 sample plots, there was a 52% likelihood of severe soil structural degradation (St ≤ 5%). A further 27% of the sampled plots also had high risk of structural degradation (St = 5-7%). SOC concentrations in the 0-20 cm depth were significantly lower than the critical value of 2% on 10 out of the 29 sites (Figure 3b). Across sample plots, the probability of SOC concentrations falling below the critical value of 1.5% was 0.49. The probabilities (φ) of soil total N, available P and S concentrations falling below their critical values were 0.95, 0.70 and 0.83, respectively (Table 1). Across the sample plots, SOC stocks in the 0-20 soil depth were significantly correlated with total N ($r = 0.937$; $P < 0.0001$) and S ($r = 0.765$; $P < 0.0001$) but not with available P.

Variations in St with LUCs and climatic zones

Across all sites, the St recorded in the 0-20 cm depth was significantly lower than values considered sufficient for SOC to maintain structural stability. The probability of structural degradation was higher in shrubland and woodland compared to cropland and grassland (Table 1). Average values of St also significantly varied with LUC (Figure 6a) and climatic zones (Figure 7a). Only 3 out of the 29 sites had St was significantly higher than 7 (Figure 3a). In the 0-20 cm depth, St was significantly lower on crop land than on grassland and bushland (Figure 6a). It was also significantly higher on arid sites than on humid sites at both 0-20 and 21-50 cm depths (Figure 7a). St showed significant negative correlation with grazing land ($r = -0.373$; $P = 0.047$).

Coupling of SOC, total N, available P and S concentrations

The regressions analysis of SOC, N and S revealed highly significant ($P<0.0001$) linear relationships with slopes close to 1 (Table 2). The RMA slopes of the regression of SOC on N and S were ≥1 indicating isometric (near isometric) relationships. Near isometric relationships were also revealed between total N and S in all LUCs. The slopes for the regression of SOC on available P were also not significantly different from 1 except on cropland (Table 2), where P appears to have been decoupled from SOC.

Variations in SOC, total N, available P and S with LUCs and climatic zones

The 0-20 cm depth had significantly ($P<0.001$) higher SOC concentrations than the 21-50 cm depths across LUCs (Figure 6b) and climate zones (Figure 7b). On average SOC was higher in grassland and cropland than in all other LUCs (Figure 6b). The probability of SOC concentrations being less than the critical value of 1.5% was highest ($\varphi = 0.63$) in woodland and lowest in grassland ($\varphi = 0.42$) soils (Table 1). The highest value of SOC stocks (63 Mg/ha) was recorded in grasslands in humid areas whereas the lowest (24.5 Mg/ha) was in cropland in arid areas (Table S3). Across LUCs, SOC stocks were extremely low (<30 Mg/ha) in arid sites.

Concentrations of total N significantly varied with soil depths, LUCs and climate zones; concentrations being higher in the 0-20 cm than 21-50 cm depth across LUCs (Figure 6c) and climates (Figure 7c). N limitation occurred with greater probability (φ) in woodland ($\varphi = 0.99$) and forestland ($\varphi = 0.97$) than in cropland ($\varphi = 0.92$) and grassland ($\varphi = 0.90$) (Table 1).

Soil available P concentrations significantly ($P<0.001$) varied with soil depth, LUC (Figure 6d) and climate (Figure 7d). Spatial variability in P concentrations was much higher (CV = 157%) compared total N and S concentrations (CV = 67-68%). The probability of available P concentrations falling below the critical value was highest in shrubland (0.78) and lowest (0.59) in cropland soils (Table 1). Available P concentrations were significantly higher on cropland than forest land (Figure 6d) and on subhumid sites than on arid sites (Figure 7d).

Soil ~~sulphur~~ S concentrations significantly varied with LUC (Figure 6e) and climate (Figure 7e) but not with soil depth. Grassland soils had significantly higher S concentrations compared to all other LUCs (Figure 6e). Among the LUCs, woodland soils had the highest probability (0.86) of containing S concentrations below the critical value of is 10 mg/kg (Table 1). The S concentrations were also significantly lower on semiarid and arid sites than humid sites (Figure 7e).

Variations in stoichiometric ratios with LUCs and climatic zones

Contrary to our initial hypothesis, the C:N:P:S stoichiometry significantly varied with LUCs and climate. Across LUCs and climatic zones, C:N ratios were lower in the 0-20 cm depth than in the 21-50 cm depth (Figure 6f; 7f). Crop land had significantly ($P<0.001$) lower C:N ratio than all other land uses, but it did not significantly differ among the other LUCs (Figure 6f). Among the climatic zones, arid sites had significantly ($P<0.001$) lower C:N ratios than semiarid, subhumid and humid sites. (Table 3; Figure 7f).

The C:P ratio were generally higher in the 21-50 cm depth than 0-20 cm (Figure 6g). Grasslands had significantly higher C:P than all other LUCs (Figure 6g). Humid and subhumid sites had higher C:P ratios than arid sites (Figure 7g). The N:P ratios significantly varied with soil depth, LUC and climatic zones. Generally, the 21-50 cm depth had higher N:P ratios than the 0-20 cm depth (Figure 6h). Grasslands had significantly ($P<0.001$) higher N:P ratios than all other LUCs (Figure 6h). Arid sites had significantly lower N:P ratios than subhumid and humid sites (Table 3~~Table 3~~).

The C:N:P and C:N:P:S ratios in the top 20 cm varied with LUC and climatic zones (Table 3~~Table 3~~). Among the LUCs, the highest C:N:P ratio was recorded in grassland (191:12:1) and the lowest in woodland (120:7:1) (Table 3~~Table 3~~). The highest C:N:P:S ratio was recorded on cropland and the lowest in shrubland (Table 3~~Table 3~~). The N:P and N:S ratios were significantly positively correlated with SOC (Table S4). The C:P and N:P stoichiometric ratios were also significantly positively correlated with soil clay, silt and S contents (Table S4).

DISCUSSION

This study has revealed high frequency of soil structural degradation, low SOC concentrations and N limitation across various LUCs in southern Africa. ~~Cultivated soils are often believed to be more degraded in comparison to forestland, which is usually used as the baseline in typical chronosequence studies (Tully *et al.*, 2015). Contrary to conventional wisdom and our initial hypothesis, SOC, total N and available P concentrations were also higher in grassland and cropland~~

~~than in woodland and forestland across southern Africa. This novel but seemingly counterintuitive finding has plausible explanations.~~ Although cultivated soils are often believed to be more degraded in comparison to forestland, the risks of soil structural degradation were higher in forestland than in cropland. Contrary to our initial hypothesis, SOC and total N concentrations were also lower in woodland and forestland than in grassland and cropland across southern Africa. This finding is consistent with empirical evidence from elsewhere that C levels in intensively managed agricultural and pastoral ecosystems can exceed those under native conditions (Six *et al*., 2002). The higher SOC and N concentrations on crop land could be linked to nutrient addition from fertilizers and manure, and nitrogen fixing trees planted on crop land.

The lower SOC and total N concentrations recorded in woodland and forestland in the study area may be attributed to various factors. First, tree roots being long-lived and coarser than typical grass roots may contribute less to SOM than grass roots (Post & Kwon 2000, Guo & Gifford 2002). The extensive rooting systems of grasses and phytolith accumulation in grassland protects SOM from mineralization leading to increased SOC concentration (Liddicoat *et al*, 2010). Grasslands in southern Africa are often used as communal grazing areas, and as such they may be enriched in SOC from livestock manure inputs.

~~Another possible reason is that~~ Trees generally deposit more C as litter to the forest floor, which decompose very slowly. The litter is often burnt by annual bush fires, which are common in southern Africa (Ryan and Williams, 2011; Sileshi & Mafongoya, 2006). The effects of repeated fires on SOC and N can be both severe and cumulative. According to a 10 years' long study in a subhumid miombo woodland in Zambia, fire reduced topsoil SOC and N at three out of four sites (Chidumayo & Kwibisa, 2003). Similarly, a study on a subhumid savannah site in Zimbabwe revealed 40–50% increase in C stocks due to fire exclusion compared to annual burning (Bird *et al*., 2000).

The N and S concentrations were tightly coupled, and their limitations were more widespread in woodland and forest land than grassland. This is probably because tree species in southern

African woodlands have 50–60% N re-absorption from leaves prior to leaf fall (Timberlake & Chidumayo, 2011). High C:N ratios in plant biomass combined with moisture deficits during the 5-7 months long dry season a year may also result in slow N cycling (Timberlake & Chidumayo, 2011). Across LUCs, SOC, total N and available P decreased with aridity. The low SOC in semiarid and arid areas could result from rapid turnover of SOM due to high temperature or low moisture, which limits decomposition.

This study also revealed coupling of N and S with SOC. The coupling may arise from the isometric relationship between C and N (Yang *et al*., 2010), and the fact that plants are the major source of SOC and N (Cleveland & Liptzin, 2007). The high correlations between SOC, N and S suggest strong coupling irrespective of LUC or climate. This highlights the fact that SOM build up could be slow due to N, P and S limitations in southern Africa. Assuming a C:N ratio of 12 in SOM, storing 1 Mg/ ha C would require approximately 0.08 Mg/ha N and 20 Mg/ha P in organic forms (van Groenigen *et al*., 2017). This means that significant N inputs are needed in southern Africa to achieve the C sequestration rates envisioned in the “4 per mille” aspiration of COP21.

Analysis of stoichiometric ratios indicated that SOC, N and S concentrations are very~~alarmingly~~ low on most sites. During natural ecosystem development, it usually takes centuries or millennia to induce stoichiometric shifts. However, such shifts are expected to be accelerated by increases in anthropogenic disturbance and climate change. The C:N:P ratio found across LUCs are comparable with ratios for bulk soil reported by Cleveland & Liptzin (2007), Griffiths *et al*. (2012) and Tian *et al*. (2010). According to Cleveland & Liptzin (2007) the C:N:P stoichiometry in soil remains relatively stable at 186:13:1 on the global scale. This was very close to the value we recorded in grassland (191:12:1). Griffiths *et al*. (2012) found a C:N:P ratio of 219:18:1, which was closer to our value for humid climates (204:12:1). Tian *et al*. (2010) found a C:N:P ratio of 134:9:1, which was very close to the value we found for forest land (132:8:1).

~~The C:N and C:P stoichiometry found here indicates that SOM is lost at a faster rate than it is formed on the majority of sample plots.~~ The very high proportion of sampled plots with low St, SOC and total N especially in forestland, woodland and shrubland indicate high risks of soil structural degradation and N limitations if used for low input agriculture. ~~Low input agriculture, such as those practiced in southern Africa, results in low yields, and this has triggered clearing of more forest land to off-set the yield gap. However, the land has been shown to become unproductive within a few years after forest clearing probably because it is inherently nutrient deficient.~~ This emphasizes that clearing of native vegetation into cropland will be unsustainable as it will speed up SOC losses and soil degradation without necessarily increasing crop production. ~~The greatest impact of this will be on food security and greenhouse gas (GHG) mitigation as nutrient limitations will impede crop productivity, biomass accumulation and subsequently SOC sequestration.~~ Therefore, significant changes in policies and practice are needed to reverse the current trend of unsustainable land management. On crop land~~,~~ the strategy should be on increased legume integration (e.g. intercropping and agroforestry) and integrated soil fertility management to increase N inputs and promote build-up of SOM. Henry *et al*. (2009) cites a number of studies that demonstrate synergetic effect between mineral fertilizers and organic amendments leading to higher yields and SOC content. In that regard, investment in N fertilizer and manure could be targeted to soils currently having low C stocks, for example, those degraded due to long periods of cropping. These soils are usually strongly depleted in SOC and the sink is nearly empty so that C inputs are more likely to be translated into additional storage more quickly (van Groenigen *et al*., 2017).

On grassland, controlled grazing and reseeding with ~~nitrogen~~ N fixing trees and herbaceous fodder legumes can speed SOM build-up. Since most African rangelands are now over-stocked, more emphasis should also be placed on improving grazing management in communal grazing areas.

In woodland and forest land, an urgent need is to slow down the rate of conversion to cropland. This is particularly important to mitigate the release of carbon from the soil and biomass into the atmosphere (Scholes, 1996). ~~According to Scholes (1996) if half of the carbon in the top 30 cm soil and all the carbon in woody biomass were released in just half of the existing miombo woodland, the mean rate of release would be around 0.2 Pg C per year, which is over 20% of the global carbon~~

~~released from land-use change.~~ Therefore, there are really no strong arguments in favor of converting woodland into agricultural land. Another key strategy for slowing soil degradation is fire management. Much controversy still surrounds the sustainability of indigenous fire management practices. This controversy is a result of a discord between official fire policies and indigenous fire management practices (Sileshi & Mafongoya, 2006). Low-intensity, early and patchy burning has been recommended to reduce the detrimental effect of fire on forests and soil function (Chidumayo & Kwibisa, 2003; Ryan & Williams, 2011).

CONCLUSION

Based on the analyses above it is concluded that soil structural degradation, low SOC concentrations and N and S limitations are widespread in southern Africa. If the current trend is left unchecked, it can undermine soil carbon storage, ecosystem functions and food security. We recommend significant increases in legume integration on cropland, slowing down the rate of conversion of woodland into cropland, improved control of late season fires and controlled grazing and reseeding of grasslands with fodder legumes. Since, there is high spatial variability in SOC and soil nutrients between sites, we also recommend that site-specific studies be conducted to develop targeted land management interventions. Our results only provide a snapshot of soil SOC and soil nutrients, and therefore they should be interpreted with caution regarding temporal changes. However, the result may provide a valuable baseline for monitoring future shifts in SOC and stoichiometric ratios.

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SUPPORTING INFORMATION

Supplementary tables

Table S1 Distribution of the sentinel sites, land use and vegetation types

Table S2. Critical ranges of St, SOC, N, P and stoichiometric ratios

Table S3. Estimated amount of SOC stocks

Table S4. Correlation coefficients for the association between soil variables

CONFLICT OF INTEREST

The authors declare no conflict of interest

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CAPTIONS TO FIGURES:

Figure 1. Distribution of sentinel sites (a), schematic representation of the hierarchical structure of the site-cluster-plot-subplot sampling design employed in this study (b) and sampling plot (0.1 ha) layout with the four subplots (C, 1, 2, 3 each 0.01 ha) from where soils were sampled (c)

Figure 2. The frequency distribution of St (%), SOC (%), total N (%), available P (mg/kg) and S (mg/kg) concentrations, and stoichiometric ratios in the 0-20 cm soil depth across sites.

Figure 3. Variation in St (%), SOC (%) and total N (%) in the 0-20 cm soil depth across sites and climatic zones. Site names are preceded by the country name abbreviated as: Ang = Angola, Bot = Botswana, Mal = Malawi, Moz-Mozambique, Zam = Zambia and Zim = Zimbabwe. Error bars represent 95% confidence limits (CL) of means. The dotted lines represent the upper (black) and lower (red) critical values of St and SOC.

Figure 4. Variation in soil available P (mg/kg), S (mg/kg) concentrations and SOC stocks in the 0-20 cm soil depth across sites and climatic zones. Country names have been abbreviated as in Figure 3. The dashed lines in (a) and (b) represent the critical values of total N and available P, respectively.

Figure 5. Variation in stoichiometric ratios in the 0-20 cm soil depth across sites. Country names have been abbreviated as in Figure 3. Error bars represent 95% confidence limits (CL) of means. The dashed lines in (a), (b) and (c) represent the critical values of C:N, C:P and N:P, respectively.

Figure 6. Variation in soil structural stability index (St in %), SOC (%), total N (%), available P (mg/kg) and S (mg/kg) concentrations, and stoichiometric ratios with and soil depth and land use

category (Grass = grassland; Crop = cropland; Bush = bushland, Shrub = shrubland; Forest = forestland and Wood = woodland). Error bars represent 95% confidence limits (CL) of means.

Figure 7. Variation in soil structural stability index (St in %), SOC (%), total N (%), available P (mg/kg) and S (mg/kg) concentrations, and stoichiometric ratios with the Koppen-Geiger climatic zones and soil depth. Error bars represent 95% confidence limits (CL) of means.

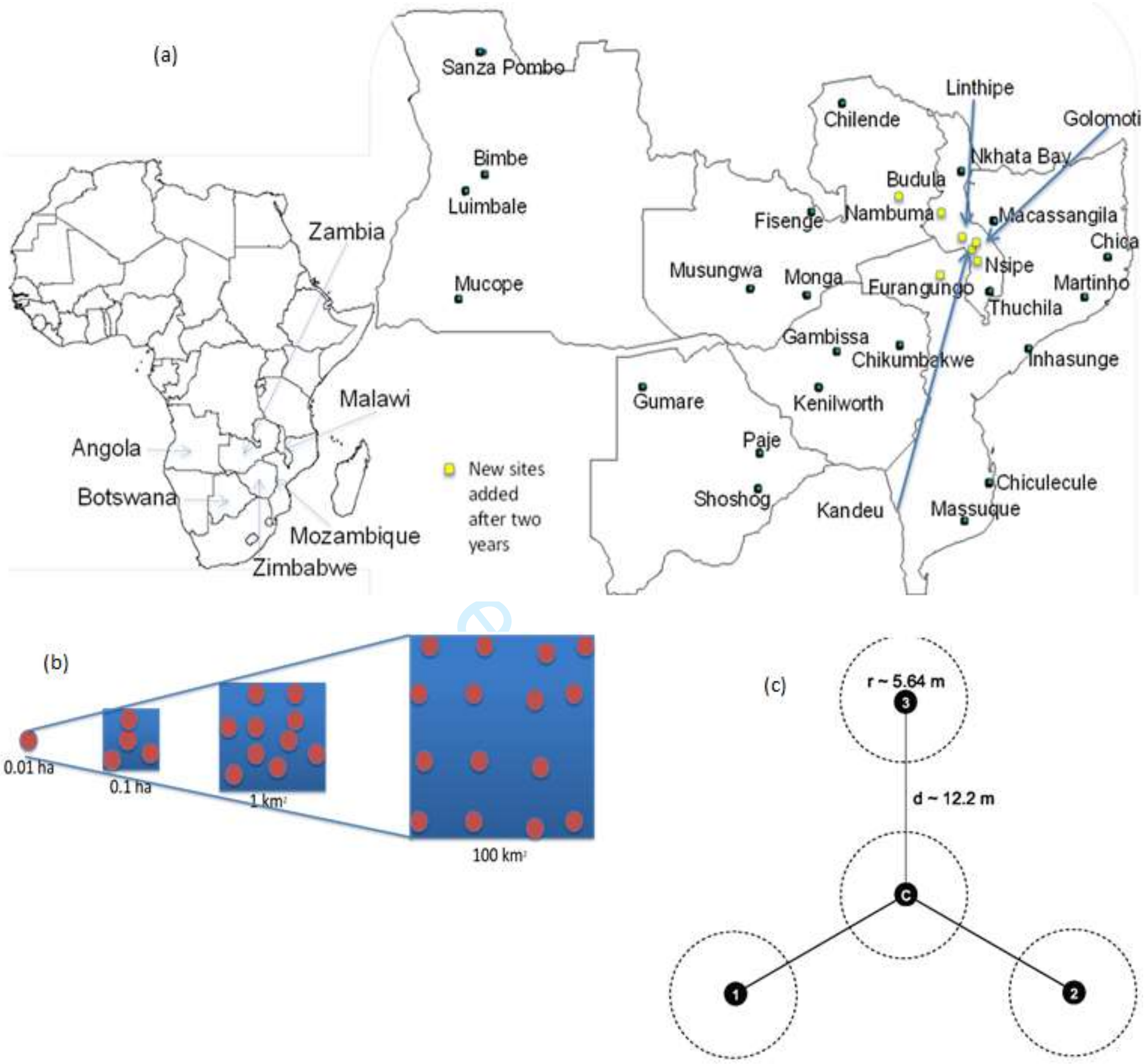
(a)
Sanza Pombo
Bimbe
Luimbale
Mucope
Zambia
Malawi
Angola
Botswana
Mozambique
Zimbabwe
Chilende
Linthipe
Golomoti
Nkhata Bay
Budula
Fisenge
Nambuma
Macassangila
Chica
Musungwa
Monga
Nsipe
Furangungo
Martinho
Thuchila
Gambissa
Chikumbakwe
Inhasunge
Gumare
Kenilworth
Paje
Shoshog
Kandeu
Chiculecule
Massuque
New sites added after two years
(b)
0.01 ha
0.1 ha
1 km²
100 km²
(c)
r ~ 5.64 m
3
d ~ 12.2 m
C
1
2

Figure 1

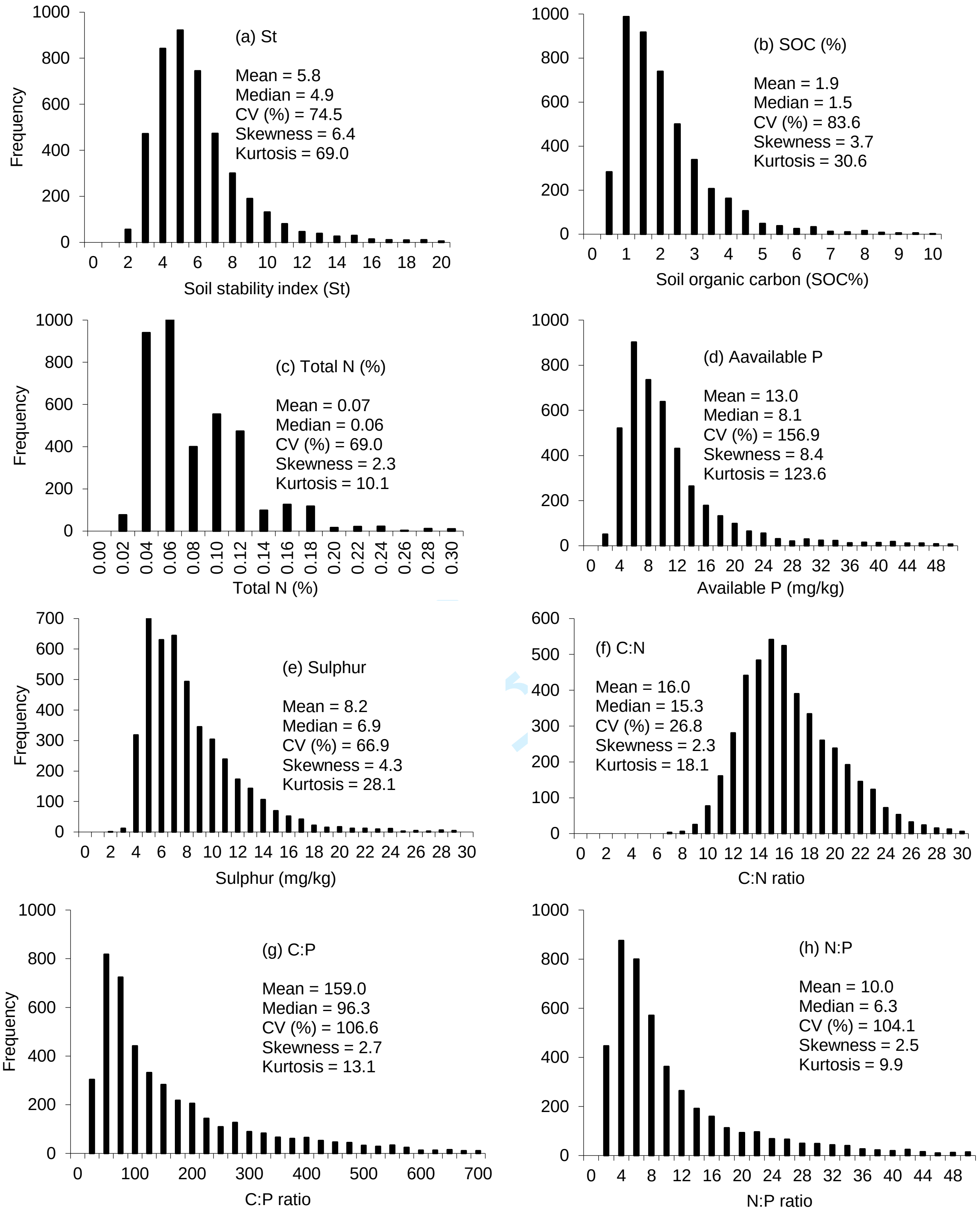
(a) St
Mean = 5.8
Median = 4.9
CV (%) = 74.5
Skewness = 6.4
Kurtosis = 69.0
Frequency
Soil stability index (St)
(b) SOC (%)
Mean = 1.9
Median = 1.5
CV (%) = 83.6
Skewness = 3.7
Kurtosis = 30.6
Soil organic carbon (SOC%)
(c) Total N (%)
Mean = 0.07
Median = 0.06
CV (%) = 69.0
Skewness = 2.3
Kurtosis = 10.1
Frequency
Total N (%)
(d) Aavailable P
Mean = 13.0
Median = 8.1
CV (%) = 156.9
Skewness = 8.4
Kurtosis = 123.6
Available P (mg/kg)
(e) Sulphur
Mean = 8.2
Median = 6.9
CV (%) = 66.9
Skewness = 4.3
Kurtosis = 28.1
Frequency
Sulphur (mg/kg)
(f) C:N
Mean = 16.0
Median = 15.3
CV (%) = 26.8
Skewness = 2.3
Kurtosis = 18.1
C:N ratio
(g) C:P
Mean = 159.0
Median = 96.3
CV (%) = 106.6
Skewness = 2.7
Kurtosis = 13.1
Frequency
C:P ratio
(h) N:P
Mean = 10.0
Median = 6.3
CV (%) = 104.1
Skewness = 2.5
Kurtosis = 9.9
N:P ratio

Figure 2.

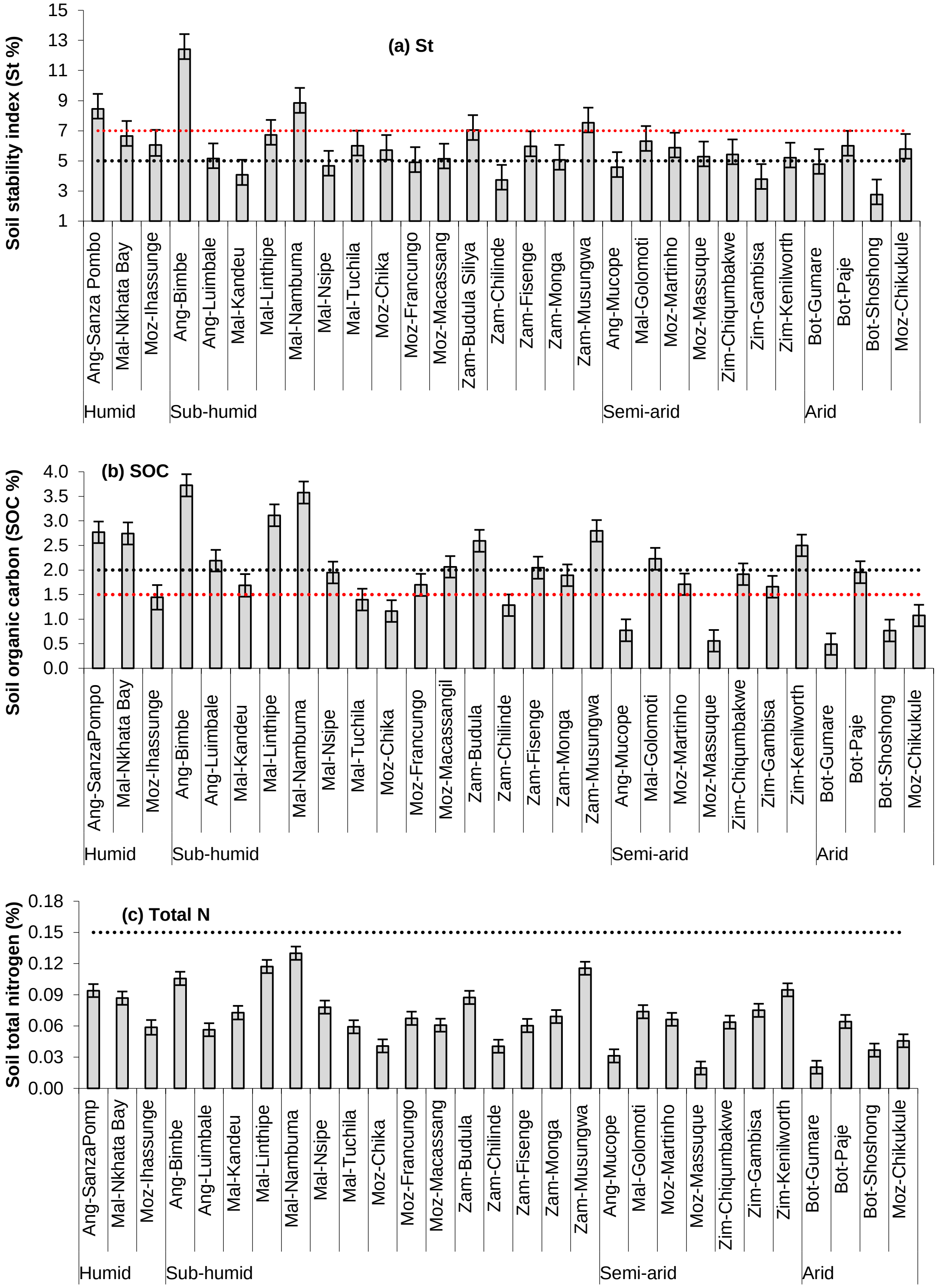
(a) St
Soil stability index (St %)
15
13
11
9
7
5
3
1
Ang-Sanza Pombo
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula Siliya
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbakwe
Zim-Gambisa
Zim-Kenilworth
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid
(b) SOC
Soil organic carbon (SOC %)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Ang-SanzaPompo
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassangil
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbakwe
Zim-Gambisa
Zim-Kenilworth
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid
(c) Total N
Soil total nitrogen (%)
0.18
0.15
0.12
0.09
0.06
0.03
0.00
Ang-SanzaPomp
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbakwe
Zim-Gambisa
Zim-Kenilworth
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid

Figure 3.

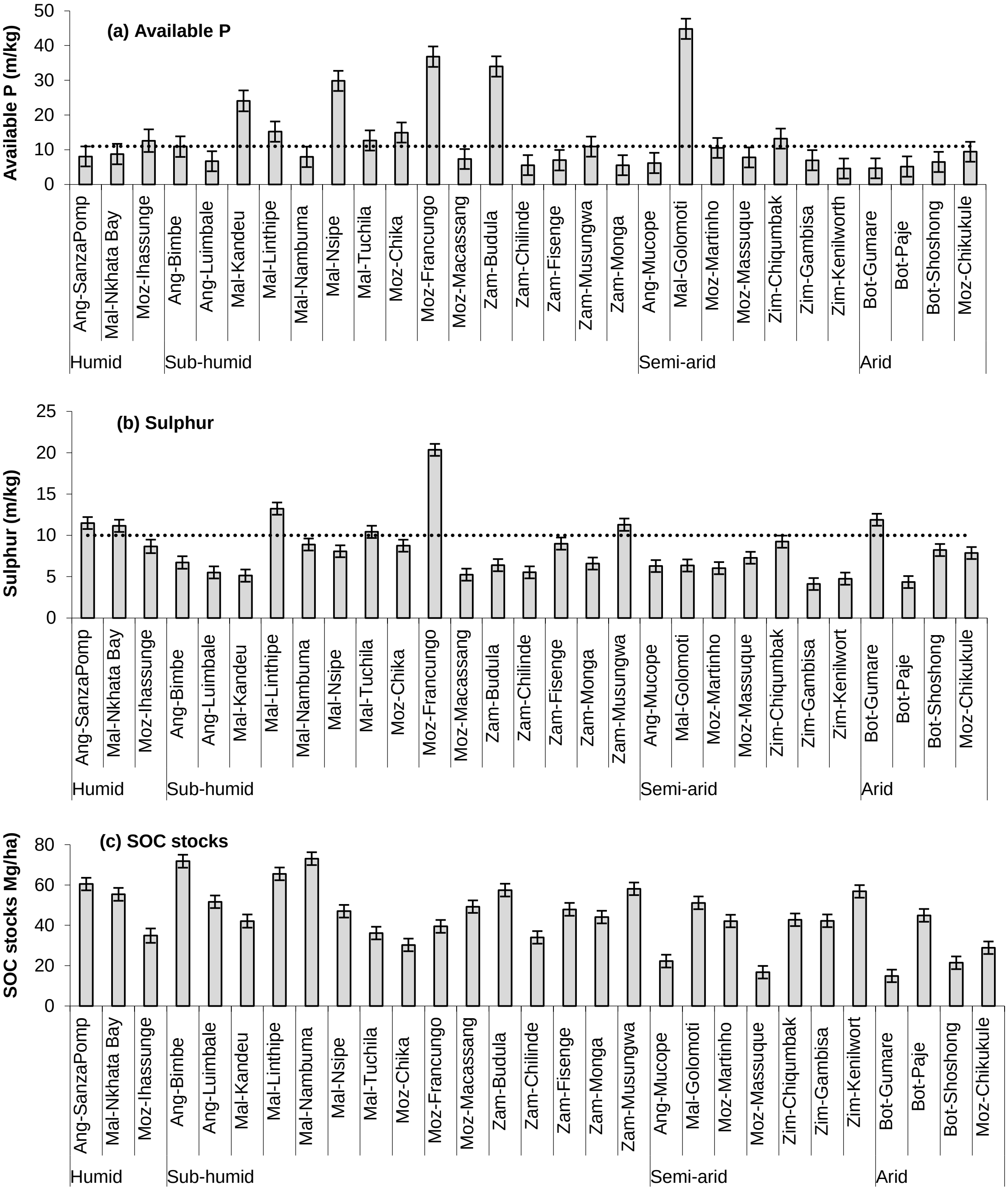
(a) Available P
Available P (m/kg)
0
10
20
30
40
50
Ang-SanzaPomp
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Musungwa
Zam-Monga
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbak
Zim-Gambisa
Zim-Kenilworth
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid
(b) Sulphur
Sulphur (m/kg)
0
5
10
15
20
25
Ang-SanzaPomp
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbak
Zim-Gambisa
Zim-Kenilwort
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid
(c) SOC stocks
SOC stocks Mg/ha)
0
20
40
60
80
Ang-SanzaPomp
Mal-Nkhata Bay
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbak
Zim-Gambisa
Zim-Kenilwort
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid

Figure 4.

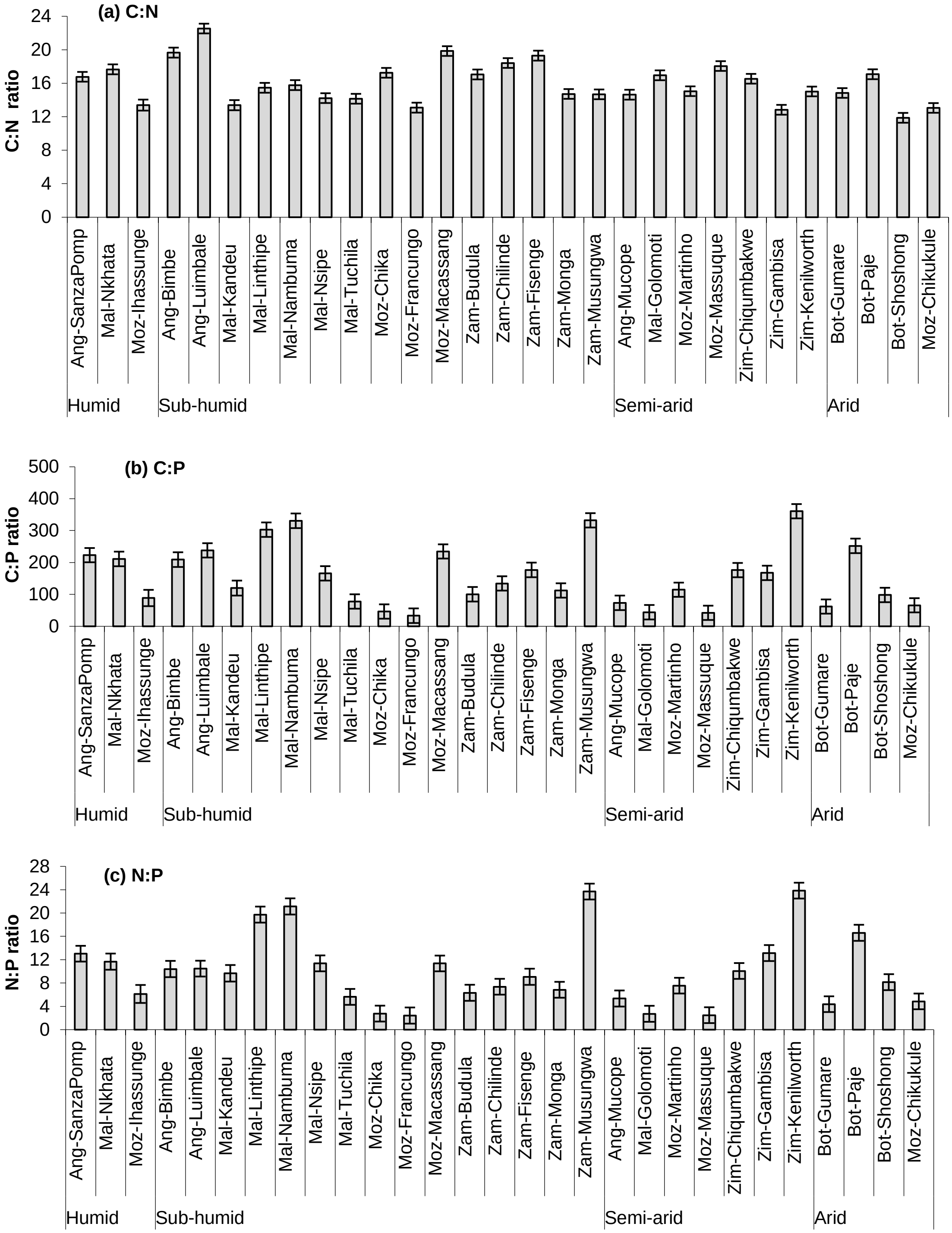
(a) C:N
C:N ratio
0
4
8
12
16
20
24
(b) C:P
C:P ratio
0
100
200
300
400
500
(c) N:P
N:P ratio
0
4
8
12
16
20
24
28
Ang-SanzaPomp
Mal-Nkhata
Moz-Ihassunge
Ang-Bimbe
Ang-Luimbale
Mal-Kandeu
Mal-Linthipe
Mal-Nambuma
Mal-Nsipe
Mal-Tuchila
Moz-Chika
Moz-Francungo
Moz-Macassang
Zam-Budula
Zam-Chilinde
Zam-Fisenge
Zam-Monga
Zam-Musungwa
Ang-Mucope
Mal-Golomoti
Moz-Martinho
Moz-Massuque
Zim-Chiqumbakwe
Zim-Gambisa
Zim-Kenilworth
Bot-Gumare
Bot-Paje
Bot-Shoshong
Moz-Chikukule
Humid
Sub-humid
Semi-arid
Arid

Figure 5.

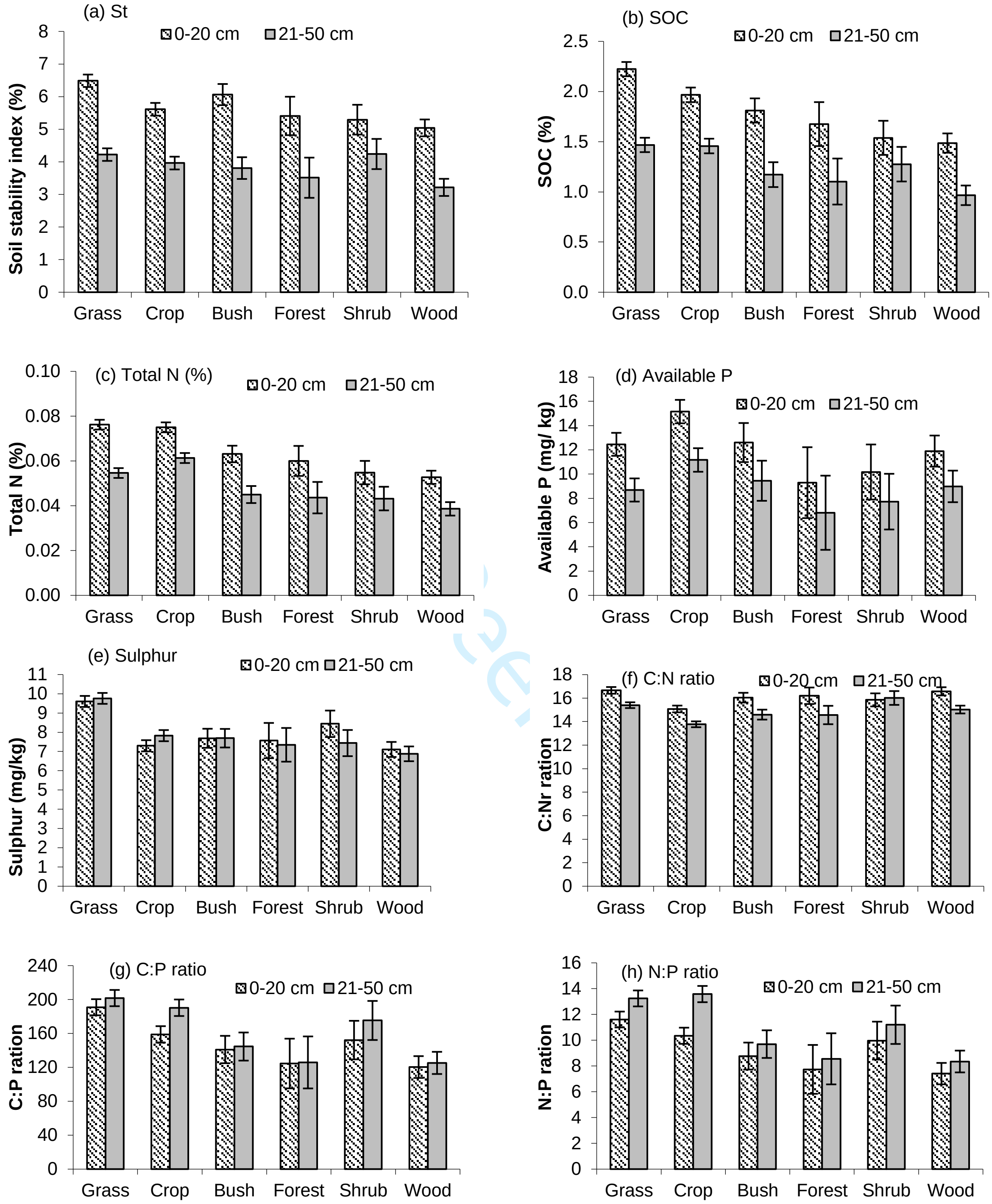
(a) St
▨0-20 cm ▩21-50 cm
Soil stability index (%)
0
1
2
3
4
5
6
7
8
Grass
Crop
Bush
Forest
Shrub
Wood
(b) SOC
▨0-20 cm ▩21-50 cm
SOC (%)
0.0
0.5
1.0
1.5
2.0
2.5
Grass
Crop
Bush
Forest
Shrub
Wood
(c) Total N (%)
▨0-20 cm ▩21-50 cm
Total N (%)
0.00
0.02
0.04
0.06
0.08
0.10
Grass
Crop
Bush
Forest
Shrub
Wood
(d) Available P
▨0-20 cm ▩21-50 cm
Available P (mg/ kg)
0
2
4
6
8
10
12
14
16
18
Grass
Crop
Bush
Forest
Shrub
Wood
(e) Sulphur
▨0-20 cm ▩21-50 cm
Sulphur (mg/kg)
0
1
2
3
4
5
6
7
8
9
10
11
Grass
Crop
Bush
Forest
Shrub
Wood
(f) C:N ratio
▨0-20 cm ▩21-50 cm
C:Nr ration
0
2
4
6
8
10
12
14
16
18
Grass
Crop
Bush
Forest
Shrub
Wood
(g) C:P ratio
▨0-20 cm ▩21-50 cm
C:P ration
0
40
80
120
160
200
240
Grass
Crop
Bush
Forest
Shrub
Wood
(h) N:P ratio
▨0-20 cm ▩21-50 cm
N:P ration
0
2
4
6
8
10
12
14
16
Grass
Crop
Bush
Forest
Shrub
Wood

Figure 6

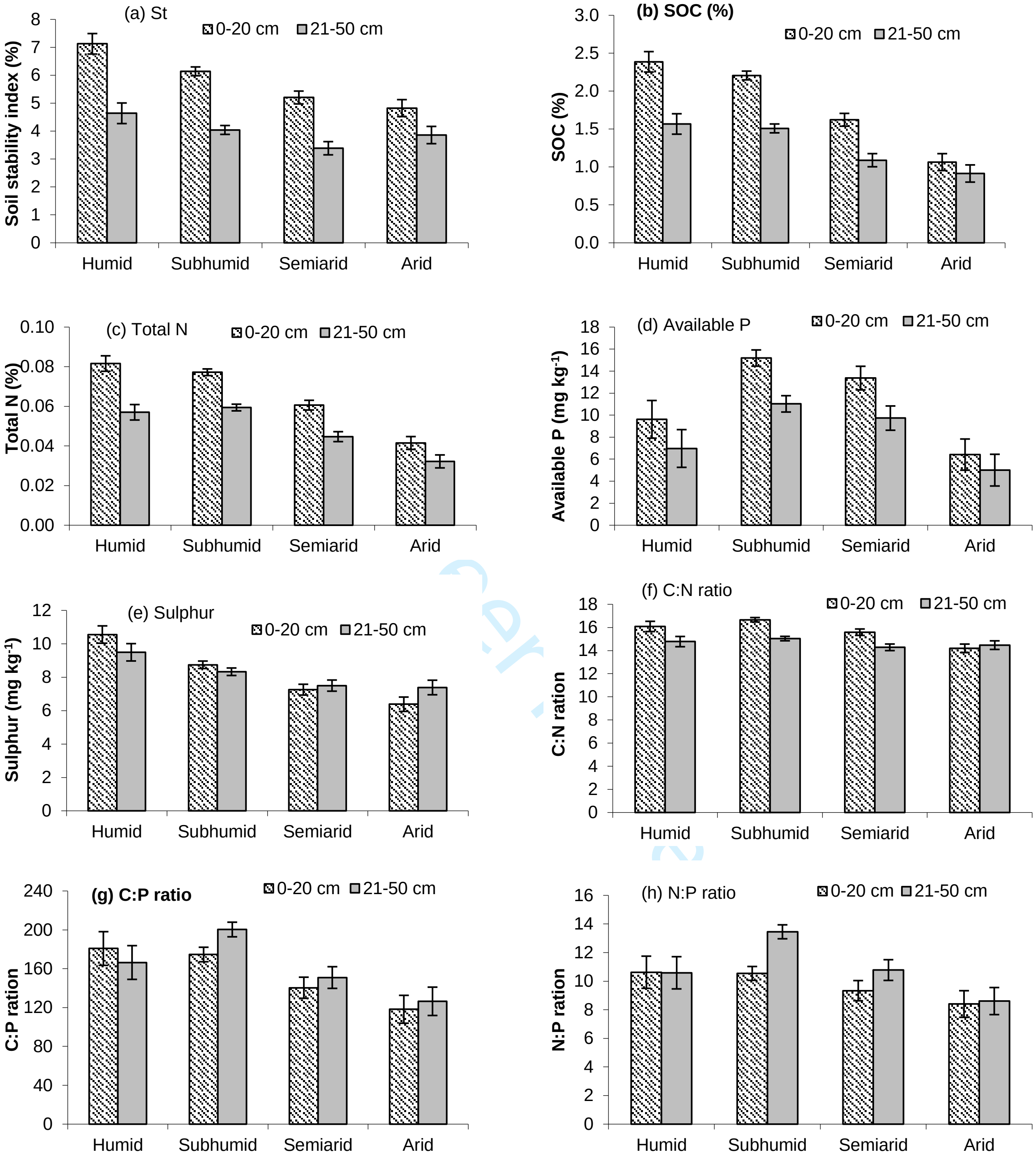
(a) St
▨0-20 cm ▩21-50 cm
Soil stability index (%)
0
1
2
3
4
5
6
7
8
Humid
Subhumid
Semiarid
Arid
(b) SOC (%)
SOC (%)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
(c) Total N
Total N (%)
0.00
0.02
0.04
0.06
0.08
0.10
(d) Available P
Available P (mg kg^{-1})
0
2
4
6
8
10
12
14
16
18
(e) Sulphur
Sulphur (mg kg^{-1})
0
2
4
6
8
10
12
(f) C:N ratio
C:N ration
0
2
4
6
8
10
12
14
16
18
(g) C:P ratio
C:P ration
0
40
80
120
160
200
240
(h) N:P ratio
N:P ration
0
2
4
6
8
10
12
14
16

Figure 7

Table 1. Probabilities (φ) of St, SOC, N, P and S falling below their critical values in the 0-20 cm soil

Variable and critical value	Cropland	Grassland	Shrubland	Bushland	Forestland	Woodland	Overall
St <5%	0.47	0.47	0.60	0.52	0.57	0.62	0.52
SOC <1.5%	0.45	0.42	0.63	0.51	0.53	0.61	0.49
SOC <2%	0.63	0.58	0.75	0.69	0.71	0.77	0.66
N <0.15%*	0.92	0.90	0.98	0.96	0.97	0.99	0.95
P <11 mg/kg*	0.59	0.73	0.78	0.72	0.75	0.75	0.70
S <10 mg/kg*	0.80	0.69	0.82	0.77	0.81	0.86	0.83

* These are indicative values below which crop production becomes critically limited.

Table 2. Reduced major axis (RMA) slopes of the regression of N and SOC, available P and SOC and S and SOC concentrations in the 0-20 cm soil depth. Regression was conducted on a log-log scale.

Regression	Landuse	RMA slope†	R^2
SOC vs total N	Cropland	1.10 (1.08 – 1.12)	0.874
	Grassland	1.12 (1.10 – 1.14)	0.898
	Shrubland	1.13 (1.06 – 1.19)	0.793
	Bushland	1.13 (1.10 – 1.17)	0.875
	Forestland	1.04 (0.98 – 1.10)	0.884
	Woodland	0.98 (0.96 – 1.01)	0.869
SOC vs S	Cropland	1.48 (1.43 – 1.54)	0.544
	Grassland	1.41 (1.36 – 1.46)	0.580
	Shrubland	1.55 (1.43 – 1.66)	0.656
	Bushland	1.59 (1.49 – 1.68)	0.551
	Forestland	1.68 (1.49 – 1.88)	0.483
	Woodland	1.61 (1.52 – 1.69)	0.487
Total N vs S	Cropland	1.35 (1.30 – 1.40)	0.492
	Grassland	1.26 (1.22 – 1.30)	0.615
	Shrubland	1.37 (1.26 – 1.49)	0.525
	Bushland	1.40 (1.32 – 1.48)	0.540
	Forestland	1.61 (1.43 – 1.80)	0.512
	Woodland	1.63 (1.55 – 1.71)	0.537
SOC vs available P	Cropland	-0.75 (-0.71 – -0.79)	0.016
	Grassland	0.98 (0.93 – 1.03)	0.027
	Shrubland	1.03 (0.90 – 1.16)	0.020
	Bushland	0.95 (0.87 – 1.03)	0.079
	Forestland	1.29 (1.09 – 1.50)	0.043
	Woodland	0.89 (0.83 – 0.95)	0.035

* RMA slope significantly lower than 1 indicates the relationship is not isometric.

†Estimates were based on a sample sizes of 1370 plots in cropland, 1427 in grassland, 249 in shrubland, 494 in bushland, 150 in forestland and 779 in woodland.

Table 3. Variation in mean stoichiometric ratios with land use and climatic zones in the 0-20 cm depth

	Land use	C:N	C:P	N:P	C:S	N:S	P:S	C:N:P	C:N:P:S
Land use	Cropland	15:1	159:1	10:1	145:1	10:1	3:1	159:10:1	145:10:3:1
	Grassland	17:1	191:1	12:1	135:1	8:1	2:1	191:12:1	135:8:2:1
	Bush land	16:1	141:1	9:1	132:1	8:1	2:1	141:09:1	132:8:2:1
	Shrub land	16:1	152:1	10:1	115:1	8:1	2:1	152:10:1	115:8:2:1
	Forestland	16:1	125:1	8:1	129:1	8:1	1:1	124:8:1	129:8:1:1
	Woodland	17:1	120:1	7:1	125:1	8:1	2:1	120:7:1	125:8:2:1
Climatic zone	Humid	16:1	181:1	11:1	127:1	8:1	1:1	181:11:1	127:8:1:1
	Subhumid	17:1	174:1	11:1	152:1	9:1	3:1	175:11:1	152:9:3:1
	Semiarid	16:1	140:1	9:1	127:1	8:1	2:1	140:9:1	127:8:2:1
	Arid	14:1	118:1	8:1	89:1	7:1	1:1	119:8:1	89:7:1:1