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Soil Related Constraints for Sustainable Intensification of Cereal-based Systems in Semi-arid Central Tanzania

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1. Introduction

In Tanzania agriculture plays a key role largely for food security and general livelihood of rural communities where 80 percent of people lives and relies on agriculture as a major economic enterprise (URT, 2001). However, land degradation, reflected in soil fertility depletion and declined vegetation cover, is still a major biophysical constraint to sustained agricultural productivity in many Africa countries (Hengl et al. 2015). The situation is worse in semi-arid plains which experience unreliable rainfall, repeated water shortages, periodic famine, high grazing pressure and increased cultivation of marginal areas (Kangalawe and Lymo, 2013). The extent and rate of soil degradation in semi-arid areas in Tanzania is still under debate as there are no reliable data. Soils in semiarid areas are losing their ability to provide food and essential ecosystem services. Apart from climate related effects, it is well known that soil fertility depletion is the primary cause of this reduction in ecosystem services (Vanlauwe et al., 2015). Reversing the trend of declining soil productivity, profitability, and sustainability of farms, it requires greater access to affordable yield-enhancing inputs, including participatory development of integrated soil fertility management methods and even markets where farmers can sell their surplus production (Toenniessen et al., 2008).

To address the challenges noted above, FAO and other global institutions (e.g., OXFAM, DFID, and USAID) are advocating agricultural intensification. It is estimated that agricultural intensification alone may increase crop production by 80% in developing countries (FAO, 2011a&b). Sustainable intensification requires, among other things, better use of land resources upon which production depends. This is critical given that most of the arable land in Africa has soil related problems due to losses of nutrients and land cover (Hengl et al. 2015). In this context improved land management is critical to overcome soil related constraints to sustainable food production and in targeting agricultural interventions. However, limited availability of site-specific nutrient and land management guidelines for semiarid zones in Tanzania undermines efforts to target technologies in the specific biophysical conditions in which smallholder farmers operate. Technologies adopted under these circumstances are risky as they may fail to address key drivers of enhanced crop production or land degradation. This study therefore characterized soils in Kongwa and Kiteto districts to assess fertility status and drivers of land degradation so as to inform the development of integrated land management options for sustainable intensification under the Africa Research in Sustainable Intensification for the Next Generation (Africa RISING) program. This approach will also help to link soil management recommendations to soil conditions and in targeting interventions.

2. Study Sites and Methodology

Africa RISING project sites are located in Kiteto and Kongwa districts between latitude -4.41^0 and -6.26^{0}S and longitude 36.07^0 and 37.08^0 E. Land Degradation Surveillance Framework (LDSF) methodology was used for data collection (Vågen, 2014). This is a hierarchical field survey and sampling protocol using sentinel sites of 100 km^2 (10 x 10 km) which are randomly selected and within each sentinel site 16 tiles (2.5 x 2.5 km in size) were randomly created and random centroid locations for clusters within each tile are generated (Fig. 1). Each cluster consists of 10 plots, with randomized centre-point locations falling within a 1 km^2 area. Each plot is 0.1 ha and consists of 4 subplots of 0.01 ha in size which was used to collect soils for analysis (plant nutrients, carbon levels, infiltration rates and soil types) and ecological data (land use types, tree cover and density). Baseides LSDF, nine profile pits were dug in selected sites in five villages (Molet, Mlali, Laikala, Manyusi and Njoro), described and soil samples were collected from natural horizons for laboratory analysis and soil classification. The profile pits were located on sites where on-farm experiments (mother sites) were laid out. Soil samples from the profile pits were analyzed for routine analysis of chemical and physical soil properties following standard methods according to Page et al. (1982) and Klute (1986) respectively. Descriptive statistics were used to compare results between sites while existing guidelines and monographs (Landon, 1991; Baize, 1993) were used to compared soil chemical properties and rank them as low, medium or high accordingly. Soils were classified according to Reference Soil Groups (RSG) with principal and supplementary qualifiers according to the FAO-Legend “the World Reference Resource Base” (WRB, 2014).

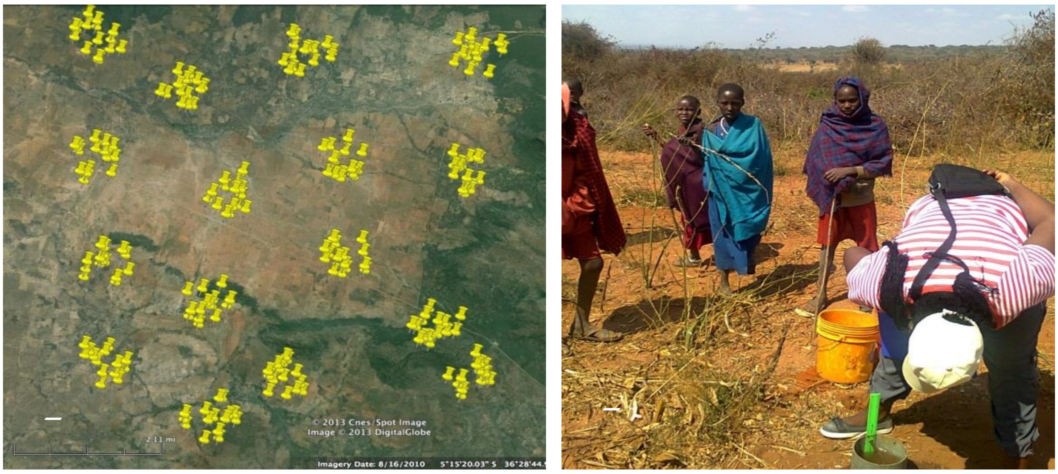

Fig. 1: Google map of the sentinel site in Njoro village, Kongwa district showing 16 clusters of plots within a 10 km x 10km block (a) and infiltration measurement (b).

Kongwa and Kiteto districts are located in the agroecological zone E2, characterised by undulating to rolling plains and plateaux with elevation ranging from 500 to 1200 meters above sea level. Rainfall is monomodal to weakly bimodal with precipitation ranging from 500 to 800 mm per year but the exact amount varies widely between locations. The onsets of rains are unreliable with reliability of 2 out of 7 years. Crops grown in the zone are sorghum, maize (Zea mays), cassava *(Manihotesculenta)*, sweet potato *(Ipomoea batatas)*, finger millet *(Eleusine coracana)*, pigeon pea *(Cajanuscajan)*, groundnut *(Arachis hypogaea)*, simsim *(Sesamu mindicum)*, sunflower *(Helianthus spp)*, tobacco *(Nicotiana tabacum)*, cotton *(Gossypium spp)*, sisal *(Agave sisalana)*, cowpea *(Vigna unguiculata)* and castor *(Ricinus communis)*. The yields of these crops are very low (1-1.5 t/ha for maize compared to a potential yield of 4.5t/ha) due to declined soil fertility and frequent crop failures associated to droughts (Kimaro et al., 2012).

3. Results and Discussion

3.1. Vegetation conditions

Analysis of land use types revealed that 14% of land (890 ha) in the Njoro sentinel is under cultivation. The rest (5652 ha) is grazing lands and forests dominated by Acacia woodlands and grasses. Tree density is low (84.3 stems ha^{-1}) compared to 268.9 stems ha^{-1} for shrubs, reflecting high clearance of trees for cultivation and supply of fuelwood and charcoal. Over a period of 23 years (1987-2010), cultivated land in Kongwa and Kiteto districts is reported to increase by 31% while the areas under forest and shrubs/thickets declined by 38.8% (Kimaro et al., 2012). If not checked scarcity of biomass energy lead to farmers using crop residues for cooking as noted in Molet and Laikala. This practice accelerates land degradation through nutrient exports from farmland. The carrying capacity for livestock exceeded 1 livestock unit per 2.5ha, which is the maximum density of unimproved natural grazing lands typical in the study sites. Manyusi site resembles Njoro with regards to natural vegetation stand. However, the situation is different in the rest of trial sites (Mlali, Moleti and Laikala) where there has been over 90 per cent natural vegetation clearing due to several factors including cultivation, fuel wood collection and charcoal making and for building materials. The extent of natural vegetation clearing between the sites seems to correlate with age where settlement started. The villages of Mlali, Moleti and Laikala appeared to have started longer the Njoro and Manyusi which seem to be newly settled areas.

3.2. Aridity indices

Table 1 present analysis of climatic factors in the study sites using aridity index, which is a ratio of annual precipitation and evapotranspiration $(AI = P/ET)$. This index differentiate excess moisture to dry or insufficient moistures from one location to another during a particular year. Thus it reflects weather variation over the years and it provides an operational tool for the production analysis. Rainfall and evapotranspiration are dominant climatic element influencing crop yield in semiarid zones. Thus aridity index is important parameters that guide selection of crops that best suit specific areas given the available moisture balance.The AI in this study revealed that Moleti has steppe characteristics while other villages are semi-arid with very short growing period of 2-3 months. The dominant rainfall water loss is by evapotranspiration which is above 90% for all sites and run off levels showed notable differences between sites (Table 1)

Table 1: Aridity indices on African RISING sites in Kongwa and Kiteto districts, Tanzania

Village	Evaporation (mm/year)	Evaporation ratio (%)	Aridity Index	Aridity index class	Runoff (mm/yr)	Run off ratio (%)
Mlali	679	92.8	0.48	Semiarid	53	7.8
Molet	705	91.9	0.50	Steppe	62	8.8
Laikala	679	92.8	0.48	Semiarid	53	7.8
Manyusi	584	95.2	0.40	Semiarid	29	4.9
Njoro	559	96.0	0.41	Semiarid	23	4.1

Rainfall distributions in the area (data not shown) show that Moleti and Mlali sites have relatively longer growing period than Njoro. Also the rainfall surpasses evapotranspiration demand for about 3-4 months in Moleti site compared to 1 month observed in Njoro site. Under these condition soils moisture and prolonged drought often drive for crop production. However, studies in the Sahel region suggest that retention of trees in agricultural holds potential to ameliorate microclimatic conditions to mitigate the impacts extreme temperature and drought on crop production in arid and semiarid areas (Sanou et al. 2011).

3.3. Soil classification and its fertility status

Soils were classified in all experimental sites whereby out of 9 soil profiles classified, 4 were Luvisols, 4 Lixisols and 1 Vertisols. These names reflect inherent soil chemical and physical properties. Luvisols have high base saturation (> 50 %) and CEC clay (>24 $cmol_{(+)}$/kg clay). Lixisols are strongly weathered soils compared to Luvisols. They have moderate to high base saturation >50 %, and CEC clay < 24 $cmol_{(+)}$/kg clay. Vertisols which are mainly found in depressions are churning heavy clay soils with high proportions of swelling clays. The range of soil pH (5.9-6.3) was in the medium acidity which is suitable for crops growth (Table 2). However, solubility and availability of some micronutrients, especially Zn, Fe, Mn, Cu and Bo; may decrease at pH 6.5 -7. Thus these soil micro-nutrients need to be the focus of nutrient management strategy in the study sites. Overall soil nutrients and organic carbon levels were very low, signifying that soil fertility is a second most liming factor for crop production after moisture (Table 2). According to Landon (1991), nitrogen (< 0.1%) and phosphorus (< 7 mg/kg) levels will results in deficiency symptoms to crops if not corrected. The use of naturally occurring Minjingu phosphate rock products such as Minjingu mazao, a fertilizer material easily soluble irrespective of soil pH and rich in micronutrients can mitigate soil nutrient deficiency in the soils. Soil K level was within the sufficient range (>0.7 $Cmol_{(+)}K$/kg soil) as noted in other studies in central Tanzania (Kimaro et al. 2009; Masawe et al. 2012). Most soils have organic carbon (OC) of 0.5%, which is very low and typical in semiarid soils in the tropics. Low OC in these soils reflects removal of crop residues through grazing, firewood collection and as hay for draught animal. Inputs of manure, conservation agriculture and/or integration of leguminous tree/shrubs are land management approaches, which can help to build soil OC, improve soil fertility, and supply fodder and fuelwood in the areas. For highly degraded soils such as those in this study, building soil OC play a significant role in improving soil structure, water retention, availability of plant nutrients and micro-fauna.

Table 2: Chemical Properties of the Top (0-15 cm) Soil

Village	pH	EC	OC	N	P	K	CEC
	(H_2O)	(dS/m)	(%)	(%)	(mg/kg soil)	($Cmol_{(+)}$/kg soil)	($Cmol_{(+)}$/kg soil)
Molet	5.9	0.09	0.51	0.04	4.67	0.66	7.25
Mlali	6.2	0.08	0.50	0.05	5.38	0.86	6.32
Njoro	6.3	0.06	0.54	0.05	6.39	0.80	8.72
Manyusi	6.2	0.12	0.72	0.08	7.16	0.76	8.20
Laikala	6.3	0.06	0.32	0.05	5.16	0.51	7.89

4. Conclusions

This study characterized soils in Africa RISING study villages in Kongwa and Kiteto districts to assess fertility status and drivers of land degradation so as to inform the development of integrated land management options for sustainable intensification of farming systems. Several factors accelerating land degradation in the sites were identified and analysed. These include drought, cultivation of crop with little or use of fertilisers; soil hardpans reflected by poor water infiltration rates and root penetration, and overgrazing which negatively affect vegetation cover and soil OC levels. Overall impacts are of these factors is soil nutrient mining and high erosion (water and windy) due to continuous cropping and loss of vegetation cover. Limited availability of biomass energy for cooking and pasture of sufficient quantity and quality also accelerate nutrient mining through crops harvest for firewood and fodder supply. Therefore, soils in the study sites requires integrated approach to address multiple nutrient deficiencies, build up OC, mitigate moisture limitations and address other physical constraints for sustainable land productivity. These include organic (manure) and inorganic amendments (especially N and P) and agroforestry options to integrate leguminous trees/shrubs in farmland so as to improve vegetation cover, soil health, supply fodder and fuelwood as well as increasing resilience to climate change.

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References

Barrett, C.B. Reardon, T., Webb, P. 2001. Nonfarm income diversification and household livelihood strategies in rural Africa: Concepts, dynamics, and policy implications. Food Policy 26, 315–33.

Berry L and Townshend. 1972. Soil conservation in the semi-arid regions of Tanzania, a historical perspective.Geographical Annaler, 54, 9A, 241-53.

FAO. 2011a. Save and grow: A policymaker's guide to the sustainable intensification of smallholder crop production.

FAO. 2011b. The State of the World's Land and Water Resources, for Food and Agriculture: Managing systems at risk.

Hengl, T., Heuvelink, G. B. M., Kempen, B., Leenaars, J.G. B., Walsh, M. G., Shepherd, K. D., Sila, A., MacMillan, R. A., Jesus, J. M, Tamene L., and Tondoh, J. E. 2015. Mapping Soil Properties of Africa at 250 m Resolution: Random Forests Significantly Improve Current Predictions. PLOS ONE | DOI:10.1371/journal.pone.0125814. 26pp

Kimaro, A.A., Sileshi G. W., Mpanda M., Swai, E., Kayeye H., Nyoka B. I., Majule A. E., Perfect J. and Kundhlande G. 2012. Evidence-based Scaling-up of Evergreen Agriculture for increasing Crop Productivity, fodder Supply and Resilience of maize-mixed and agro-pastoral farming systems in Tanzania and Malawi. Jumpstart report to IITA. 68p

Kimaro, A.A., V.R. Timmer, S.O.A. Chamshama, Y.N. Ngaga, and Kimaro, D.A. 2009. Competition between maize and pigeonpea in semi-arid Tanzania: Effect on yields and nutrition of crops. Agricultural Ecosystems Environment 134:115–125.

Klute, A. (ed.). 1986. Methods of soil analysis part 1. Physical and mineralogical methods.Second Edition.ASA, SSSA Book Series 5, Madison, Wisconsin.1173 pp.

Massawe et al., 2012. Soil survey report for NAFAKA sites in Dodoma and Manyara Regions.

Page, A.L. Miller, R.H., and Keeney D.R. (Eds.) .1982. Methods of Soil Analysis, part 2, Chemical and Microbiological Properties Second Edition.ASA, SSSA Monograph no. 9, Madison, Wisconsin.1143 pp.

Sanchez, P.A. and Swaminathan, M.S. 2005. Hunger in Africa: The link between unhealthy people and unhealthy soils. Lancet, 365, 442–444.

Sanou, J., Bayala, J., Teklehaimanot, Z and Bazi, P. 2011. Effect of shading by baobab (Adansonia digitata) and ne´re´ (Parkia biglobosa) on yields of millet (Pennisetum glaucum) and taro (Colocasia esculenta) in parkland systems in Burkina Faso, West Africa. Agroforestry Systems. DOI 10.1007/s10457-011-9405-4.

TOENNIESSEN, G., ADESINA, A., and DEVRIES, J. 2008. Building an Alliance for a Green Revolution in Africa. Annals of the New York Academy of Sciences, 1136: 233–242.

UN 2014. United Nations Human Settlements Programme (UN-Habitat). The State of African Cities: Re-Imagining Sustainable Urban Transitions; UN-Habitat: Nairobi, Kenya, 2014.

URT (United Republic of Tanzania) .2001. Agricultural Sector Development Strategy (ASDS), Government of Tanzania.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising J., Merckx R., Nziguheba, G., Wendt J., and Zingore, S. 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. Soil, 1, 491–508.

Vlek, P.L.G. 1990. The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fert. Res., 26, 327–339.