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Benefits and trade–offs of legume–led crop rotations on crop performance and soil erosion at various scales in SW Kenya

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"... I cannot conceive of the time when knowledge of soils will be complete. Our expectation is that our successors will build on what has been done, as we are building on the work of our predecessors."

R. S. Smith, 1928.

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Table of Contents

List of figures

List of tables

List of abbreviations

ASTM: American Society for Testing and Materials

BNF: Biological nitrogen fixation

C: Carbon

DEM: Digital elevation model

ELD: Economics of Land Degradation

ER: Enrichment ratio

ETM: Enhanced Thematic Mapper

ET: Evapotranspiration

FAO: Food and agricultural organization

GDP: Gross domestic product

GHG: Greenhouse gas

GUEST: Griffith University Erosion System Template

ICRAF: International Centre for Research in Agroforestry

IITA: International Institute for Tropical Agriculture

IPCC: International Panel of Climate Change

ITPS: International Test Pilots School

KALRO: Kenyan Agriculture and Livestock Research Organization

KeNADA: Kenya National Data Archive

LegumeCHOICE: Legume Conception of HOusehold Innovations for Creating legume Expansion

LISEM: LImburg Soil Erosion Model

LUCIA: Land Use Change Impact Assessment

MidDRIFTS: Mid Diffuse Reflectance Fourier Transform Spectroscopy

MIRS: Mid–infrared Spectroscopy

MoFED: Ministry of Finance and Economic Development

N: Nitrogen

NDVI: Normalized Difference Vegetation Index

NIR: Near–Infrared Spectroscopy

N.S: Not significant

PVC: Polyvinyl chloride

SARVI: Soil–Adjusted and Atmospheric Resistant Vegetation Index

SAVI: Soil–Adjusted Vegetation Index

SEMMED: Soil Erosion Model for Mediterranean Regions

SfM: Structure from Motion

SIDA: Swedish International Development Cooperation Agency

SSA: Sub–Saharan Africa

UNDESA: United Nations Department of Economic and Social Affairs

UNEP: United Nations Environment Programme

UNU/INRA: United Nations University/ Institute for Natural Resources in Africa

USD: United States Dollars

WEPP: Water Erosion Prediction Project

WMO: World Meteorological Organization

WOCAT: World Overview of Conservation Approaches

WUE: Water Use Efficiency

Chapter 1. General introduction

1.1 Overview

Sub–Saharan Africa (SSA) faces the challenge of chronic food insecurity, with an estimated 23.2 per cent of its population being food insecure (Ströh de Martínez et al., 2016). Agriculture is the main source of livelihood for the majority of smallholders in SSA (Alobo Loison, 2015), and plays a central role in achieving increases in food security in consideration of the expected doubling of its population over the next 20 years (Cleland, 2013; Wold Bank, 2017).

Agricultural productivity in this region is often low due to poor inherent soil fertility and prohibitively high cost of agricultural inputs (Sanchez, 2002; Vanlauwe et al., 2010). Growth in agricultural production has largely been achieved through area expansion, often with degradation of natural resources (Pretty et al., 2011; Ordway et al., 2017). Thus, expansion of cropland in the future will predictably affect the remaining ecosystems, their biodiversity and services (Tiziano, 2016). In view of this, especially in highly populated areas, the scope for further expansion is limited and intensification on existing agricultural land is needed (Ronner, 2018). However, it must be highlighted that the intensification of agriculture has also led to the degradation and exhaustion of soil and land resources (Tiziano, 2016).

Soil degradation is a "global pandemic" (DeLong et al., 2015), and has become a very serious problem in densely inhabited agricultural regions, posing a threat to future food security (Tiziano, 2016). In SSA, soil degradation has led to a decline in crop productivity, and has been linked to hunger and poverty (Tully et al., 2015). Of the 11% of the earth's land surface occupied by agriculture, 25% are already highly degraded (FAO, 2011). Soil degradation includes loss of soil cover as well as soil erosion by water and wind, salinisation, acidification and compaction. Among these, erosion is the dominant form of soil degradation (Troeh, 1991; Oldeman, 1997) in SSA.

In East Africa, soil erosion by water occurs mainly in the highlands where slopes range between 10 and 55% (Athanase, 2013; Nyawade et al., 2019). Annual crop yield reduction due to soil erosion in SSA ranges from 2 to 40% (Lal, 1995), and this poses a dire situation as per capita food production, particularly in East Africa, has declined over the past 45 years (Sanchez, 2002). Several studies on soil erosion on smallholder farms in Kenya have shown that, soil erosion by water causes soil loss at a rate of 60 to 244 Mg $ha^{-1}yr^{-1}$ (Tongi, 1990; Gachene et al., 1997; Khisa et al., 2002; Nyawade et al., 2018). Many farmers are aware of causes, indicators and consequences of erosion in the landscape (Okoba and Sterk, 2006), hitherto, lack of adequate soil cover particularly in the widespread maize–based systems adds to soil vulnerability to erosion (Chaplot et al., 2005). The relevance of this vulnerability is further reiterated given that more than 2.1 million ha of Kenya's 5.3 million ha of all crops harvested area was occupied by maize (FAOSTAT 2018).

Legumes play an essential role in SSA farming systems, providing a range of economical and biophysical benefits, one of them being erosion control (Giller and Cadisch, 1995). In fact, integration of legumes in farming systems has been proposed as a potential pathway for sustainable intensification (Tilman et al., 2011; Garnett et al., 2013), which is principled on yielding more output per unit of land, labour and capital, while negative environmental effects are reduced and ecosystem services preserved (Vanlauwe et al., 2014). Despite this major potential contribution of legumes, soil erosion still threatens the soil resource and sustainability of agriculture (Govers et al., 2017).

Slope length and gradient play a critical role in water erosion proportionate to the energy factors that maximise surface runoff (Bagio et al., 2017). Slope length in particular exponentially increases the speed and volume of runoff water to disaggregate soil and transport sediments (Bagarello and Ferro, 2010). Lal (1997) asserted that the effects of slope length on runoff and soil erosion are complex and confounded by site–specific conditions. In Africa, few studies have been conducted on slope length, often not under typical land tenure conditions e.g. neglecting crucial small–scale topography and local drain direction, or limited to short slopes of a few meters.

Soil conservation measures that reduce the impact of slope gradient and length such as terraces, grass filter strips, and hedgerows, although recognised for their efficacy, are implemented only if providing added value or incentive is obtained. Among the trade–offs of these measures are labour cost and availability (Saint-Macary et al., 2010) and competition with crops for space, water and plant nutrients (Tuan et al., 2014). Targeting soil conservation measures at specific parts of the slope instead of the entire slope length can reduce installation costs and minimise competition between crops and auxiliary plants like legumes, which increases the likelihood of implementation.

Among the major threats to crop production are drought and water stress caused by climatic variability and change. Climate change and variability poses a risk to food security in Kenya through their effect on rainfall and soil moisture (Ochieng et al., 2016). Unfavourable weather conditions often cause farmers to plant outside the optimum planting window. In view of this, exploring the effect of management practices provides an insight on feasible options that can contribute to increase yields. Planting date and selection of crop varieties with adequate vegetation period are two major strategies used globally for crop adaption and mitigation to manage unfavourable growth conditions (Baum et al., 2019), such as drought and water stress.

Simulation models have become useful impact assessment tools in agricultural decision making, e.g. regarding management of available water use. Models can simulate responses of crops to soil and weather conditions as well as water and fertilizer input (Jones et al., 2016).

In the management of drought and water stress conditions models can, for example, help in identifying an appropriate planting window since the climatic effect on crop performance and yield can be evaluated over a longer term. Moreover, models are capable of simulating crop growth of genotypes in different environments. Thus, models can project scenarios over longer times and wider areas that could not be tested in field trials.

1.2 Soil erosion in sub–Saharan Africa

Soil erosion by water and wind is one of the global environmental menaces (Wessels et al., 2007) that threatens land productivity and environmental quality (Oldeman, 1991; Montgomery, 2007; Montanarella et al., 2016). Problems related to soil erosion have become a global concern to countries; especially those in the Global South and in particular SSA appear to be under severe threat (Lal, 2001; Borrelli et al., 2017). An increasing number of studies have largely attributed this to the pressure on the land, in combination with a number of factors such as lack of suitable land management practices; raising awareness among farmers; and application of proper policies to mitigate soil erosion (Nyssen et al., 2014; Hurni et al., 2015; Haregeweyn et al., 2017).

About 494 million ha of the land in SSA are degraded (ISRIC/UNEP, 1990). Of this, 227 million ha (46%) by water erosion, and 187 million ha (38%) by wind erosion, while the remaining is caused by chemical and physical degradation (FAO and ITPS, 2015). Generally, different soil erosion processes are mainly linked to different climate zones with water erosion more common in humid areas, while wind erosion dominates in arid regions (Fenta et al., 2019). However, it must be noted that in some arid or semi–arid regions, both erosion processes contribute significantly to the total soil erosion (Du et al., 2016), depending on topography, land use and other factors. Water erosion is the most widespread soil degradation type in SSA, and Oldeman (1991) described the intensity of water erosion as very high to extreme on 45% of the total SSA area affected, moderate on about 30% and slight on about 28%.. Wind erosion on the other hand, is second in importance to water erosion in SSA (ISRIC/UNEP, 1990). The intensity of wind erosion is strong on about 5%, moderate on 48% and light on 48% of the total land area (Oldeman, 1991).

Water erosion often originates on slopes where vegetation cover is reduced, e.g. due to deforestation, overgrazing or cultivation that leaves the soil surface at least partially and temporally bare (Tuan et al., 2014; FAO and ITPS, 2015). Studies show that it is further aggravated where there has been a breakdown of soil structure or infiltration rates have been reduced (Morgan, 2005). Areas particularly affected by water erosion in SSA are the humid and sub–humid zones (FAO and ITPS, 2015). Water erosion poses the greatest threat to soils in Nigeria, affecting over 80% of the land (NEST, 1991). In Uganda, 70% of the land has been degraded by water erosion and soil nutrient depletion between 1945 and 1990 leading to more than 20% of agricultural and pasture land irreversibly degraded (FAO and ITPS, 2015).

The devastating impact of water erosion across SSA ranges from loss of agricultural lands, physical destruction such as disruption of communication routes, siltation of water bodies and financial losses to loss of human life. Almost 90% of rangelands and 80% of farm lands in the West African Sahel, Sudan, and northeast Ethiopia are seriously affected by land degradation, including water erosion. In Nigeria, gullies extended to depths of over 120 m and widths up to 2 km (Adeleke and Leong, 1980).

Wind erosion is a natural process that occurs frequently in the arid and semi–arid parts of SSA. FAO and ITPS (2015) reported that its occurrence at a particular site is a function of weather events interacting with soil and land management through the effects of weather on soil structure, tilth and vegetation cover. Studies show that wind erosion becomes severe during the dry winter season, where a dry and hot wind from the Sahara desert locally termed

Harmattan blow sand and dust particles from the land surface and transports them over long distances across the land, and as far as the Atlantic Ocean (WMO, 2005). Over 99% of wind erosion affects dry land zones, with less than 1% occurring in humid zones. Most susceptible areas to wind erosion in SSA are the southern fringe areas of the Sahara, Botswana, Namibia, Zimbabwe, Tanzania and South Africa (Favis-Mortlock, 2005).

Wind erosion physically removes the lighter, less dense soil constituents such as organic matter, clay and silt fractions, thus removing the most fertile part of the soil and lowering soil productivity (Lyles, 1975). During drought, agricultural regions become prone to wind erosion especially, where vegetation cover is reduced. Bielders et al. (1985) affirms that wind erosion can remove up to 80 tons ha^{-1} yr^{-1} of soil, and this can lead to soil fertility decline. Off–site effects of wind erosion include covering of the landscape with wind–borne soil particles from distant sources. The amount of dust lost from the Sahel zone alone has been reported to be around or above 270 million tons yr^{-1}, corresponding to a layer of 20 mm of soil particles (WMO, 2005). Additionally, the gravity of wind erosion can be realized from the Eastern Cape Province where there are over 14,000 ha of drift sand (Barnard et al., 2002).

Most developing countries including SSA have no agreement on the extent and severity of land degradation by soil erosion as well as its impacts (Reich et al., 2001). Liniger et al. (2011) attributed this to lack of information and knowledge, serving as an obstacle for reducing land degradation, improving agricultural productivity, and facilitating the adoption of sustainable land management among smallholders. However, in some East African countries, the resource loss due to land degradation by soil erosion is believed to be extensive (Kirui and Mirzabaev, 2014). For instance, in Ethiopia an estimated annual cost of nutrient loss by water erosion from croplands amounted to ca. USD 700 million (Hurni et al., 2015). Similarly, land degradation by soil erosion posed economic cost to Kenya to the tune of ca. USD 390 million (Mulinge et al., 2016).

1.3 Processes and mechanisms governing water erosion: plot and landscape scale

Soil erosion is a natural geomorphic process which occurs when the forces of water or wind move soil particles at a spatial and temporal scale driven by the interplay of land–use, soil and topography (Chaplot & Poesen, 2012). It is a three–phase process consisting of detachment of individual soil particles from the soil body that is their original domain, their transport by erosive agents such as water and wind, and deposition (Post, 1996; Morgan, 1995).

In water erosion, detachment of soil particles is caused by the locally intense shear stress generated at the soil surface by raindrop impact (Loch and Silburn, 1996). Soil detachment was originally conceived to be exclusively the result of raindrop impact (Hudson, 1975), although the importance of overland flow or surface runoff as an erosive agent has now been recognized (Merritt et al., 2003). Meritt et al. (2003) underlines that like raindrop impact, surface runoff likewise, causes shear stress to the soil surface, which causes sediment detachment if it exceeds the cohesive strength of the soil.

The detaching power of rain is provided by the kinetic energy of the falling drop which is transferred to the soil particles as it strikes the soil particles and to water on the surface, detaching soil particles and displacing water (Gabet & Dunne, 2003). Soil particle detachment and splash depend on rainfall intensity, the size distribution of drops and their terminal velocity, the direction and steepness of slope, wind, soil conditions (texture, looseness, size and stability of aggregates, roughness of surface) and likely barriers to splash such as vegetation, litter, and gravel (Hillel, 2004). While the erosion process continuously adds sediments to the runoff, there is also erosion by rainfall impact on the deposited layer termed re–detachment (Ciesiolka et al., 1995).

Erosion by runoff of the original soil is called entrainment, and of the deposited layer, re–entrainment (Ciesiolka et al., 1995). Runoff is the main transport agent of sediments besides its capability to detach soil particles. Foster and Meyer (1972) found that the rate of detachment of soil particles by runoff is a function of the rate of sediment transport. The entrainment or scouring action of runoff is associated with stream power of the water flowing over the soil surface (Ciesiolka et al., 1995). Rose and Hairsine (1988) revealed that the rates of entrainment and re–entrainment depend on the rate of working of the shear stress exerted by the runoff water on the soil surface, which is a source of power for flow–driven erosion processes.

Early investigators of water erosion made a distinction between four main types of erosion processes namely sheet erosion, rill erosion, gully erosion, and stream–channel or in–stream erosion (Merrit et al., 2003; Hillel, 2014). Hairsine and Rose (1992) described sheet erosion as a uniform detachment and removal of soil or sediment particles from the soil surface by runoff or raindrop impact evenly distributed across a slope. Hillel (2014) argues that in reality the sheet erosion process is hardly ever uniform, and that soon after it begins the sediment–carrying runoff tends to concentrate in small rills, which wend their way downslope. Together with rill erosion, sheet erosion is classified as ‘overland flow’ erosion, detaching sediment from the soil surface profile only (Merritt et al., 2003).

Rill erosion occurs when easily noticeable channels are formed as a result of movement of water over the soil surface along preferential pathways (Rose, 1993). Schwab et al. (1993) also described rill erosion as the scouring and transport of soil by a concentrated flow of water. Loch and Silburn (1996) refer to this rill as flow channels that can be obliterated by tillage. Rill or channel initiation is counteracted by the cohesive strength of the soil and driven by the shear forces exerted on the soil (Merritt et al., 2003).

Gullies are relatively permanent steep–sided water courses that experience ephemeral flows during rainstorms (Morgan, 2005). In contrast to rill erosion, gullies are channels of concentrated flow that are too deep to be obliterated by cultivation (Rose, 1993; Loch and Silburn, 1996). A widely used definition used to differentiate gullies from rills is that gullies have a cross–sectional area of 1 m^2 or larger (Poesen, 1993). Raindrop impact is not an important factor in gully erosion in relation to flow resistance or sediment particle detachment (Bennett, 1974). Instead, gullies are associated with accelerated erosion (Morgan, 2005), and their development is controlled by thresholds, which are related to slope and catchment area rather than flow erosivity (Loch and Silburn, 1996).

Stream–channel erosion occurs when sediments are directly removed from stream banks (lateral erosion) or from the stream bed (Merritt et al., 2003). Sediment also enters the stream due to slumping of the stream bank resulting from bank erosion undercutting the stream bank. A large proportion of the sediment that is transported through the stream network can originate from the stream channel during high flow periods.

It must be highlighted that these erosion processes do not necessarily occur in isolation from one another, but rather are influenced by landscape factors and rainfall characteristics (Merritt et al., 2003). For example, the development of rill and gully erosion requires the concentration of flow and discharge that exceed critical thresholds, and as such will occur as the length of the slope increases (Loch and Silburn, 1996). Hence, Loch and Silburn, (1996) predicted that the dominant erosion process would be expected to follow a downslope sequence of splash–sheet–rill–gully.

The third phase of water erosion termed deposition, also called sedimentation, sets in when the erosive agents lack sufficient energy to transport the particles (Morgan, 2005), or when critical sediment concentration in the runoff is exceeded. Proffitt et al. (1991) affirm that deposition is a particle–size selective process, with coarser particles deposited first, leading to the deposited layer becoming finer with distance, and may develop into depositional crust where less of the finer material is then exposed to erosion (Morgan, 2005). Morgan (2005) further reiterated that areas of erosion on a hillside will become sandier and areas of deposition, valley floors in particular will be enriched with clay particles.

1.4 Relevance of soil degradation through erosion for food security in East Africa

Increased soil erosion is one of the key causes of land degradation that has rapidly depleted the soil resources in many agricultural and pastoral landscapes of East Africa, contributing to widespread degradation, which threatens food security, water security and livelihood security (Oldeman 1992; Lal 2001; Pimentel 2006; Blaikie and Brookfield 2015; Wynants et al., 2019). As reported by ELD and UNEP (2015), the productivity losses driven by soil erosion in East Africa could impede efforts to achieve food security and improved livelihood, considering that 90% of the rural population livelihood is predominantly dependent on agriculture (Kirui and Mirzabaev, 2014). This situation calls for concerted national and regional efforts to combat land degradation by soil erosion by initiating effective soil conservation programs (Fenta et al., 2019).

While the main cause of this accelerated erosion is often attributed to the loss of permanent vegetation through land use change (Fleitmann et al., 2007; Kiage 2013; Wynants et al., 2019), studies have failed to explain the socio–economic drivers of unsustainable land use change (Ananda and Herath 2003; Blaikie and Brookfield 2015). The population in East Africa has grown exponentially from an estimated 66 million in the 1950s, to 109 million in 19970s, 257 million in 2000s to 433 million in 2019 (UNDESA, 2019). More specifically, the annual population growth rates in the last two decades for Ethiopia, Kenya, Malawi and Tanzania have been between 2–3% (Kirui and Mirzabaev 2014).

Kirui and Mirzabaev (2014) argue that the continuously increasing demand for food with an increasing population in Eastern Africa have not matched increased agricultural productivity, but rather, agricultural productivity has stagnated or declined over the years leading to rapid expansion of agricultural land and reduced rehabilitation of soil fertility. Hence, singling out the problem of overpopulation and overexploitation of natural resources may hamper the understanding of the complex human–environment interactions (Lambin et al. 2001; Kiage 2013; Blake et al. 2018). Multiple biophysical factors such as topography, climate, vegetation, and soil characteristics naturally interlink to influence the intensity of soil erosion (Wynants et al., 2019).

The East African terrain was one of the most active geological areas in the world, with a distinct topography (Wynants et al., 2019), but nowadays, there are probably more active areas such as the "ring of fire" in the pacific oceans created by plate tectonics whose hosrseshoe–shaped area covers 40,000 km distance of intense volcanic and earthquake activity (Rosenberg, 2020). Slopes range between 10 and 55% (Athanase, 2013; Nyawade et al., 2019), with more suitable areas for agriculture in highlands (Trapnell and Griffiths 1960; Kurukulasuriya and Mendelsohn, 2008). It should be pointed out that arable expansion to support the food needs of a growing population tends to push arable production into higher and less suitable areas, notably steep ground which is vulnerable to erosion. The effects of slope are multiple, however, in general, any neutral movement of soil particles through rainfall impact or others will be driven by gravity hence move downward (Morgan 2005; Vanmaercke et al., 2014), therefore farming on steep slopes will accelerate the effects of soil erosion (Kirui and Mirzabaev 2014). More importantly, on steeper slopes precipitated water spends less time to infiltrate the soil and flowing water will move more rapidly, giving rise to higher amount and rapid flow of runoff which subsequently gains higher energy to erode the land (Poesen et al., 2003; Morgan, 2005).

Climate effect on soil erosion and degradation is closely linked with rainfall amount and intensity. Most areas in East Africa are characterised by a semi–arid climate with a dry season and one or two rainy seasons (Wynants et al., 2019). It worth mentioning that climate change tends to lead to greater rainfall variability and more extreme events, and this is likely to lead to greater erosion problems in the future.a Nicholson (1996) observed that during the rainy season, the rain falls in short but intensive downpours and the rainfall erosivity of these events can be very high. The role of vegetation cannot be decoupled from climate, and due to the delayed response of vegetation growth to rainfall, there is nothing to buffer the erosional energy of the first rains (Wynants et al., 2019), triggering the erosion potential to be very high in the beginning of the rainy season (Kirkby, 1980). Other studies have also shown that the arid and semi–arid lands are prone to fires which may lead to serious soil erosion owed to reduced soil cover (Voortman et al., 2000; D'Odorico, 2013).

Variations in soil structure, soil mineralogy and soil texture are natural factors that can influence erosion vulnerability of an area (Lal 2001; Morgan 2005). The low organic matter content and weak aggregate stability of many soils in semi–arid East Africa are particularly vulnerable to detachment processes. Additionally, the high prevalence of crusting and overall weak structural development of these soils predisposes them to generate high runoff (Nishigaki et al., 2017; Blake et al., 2018). In summary, the interaction between a distinct sloped topography, high rainfall erosivity, lack of vegetative cover when needed most, and fragile soils naturally exposes catchments in East Africa to high sediment yields (Walling and Webb 1996; Vanmaercke et al., 2014) and ecosystem degradation.

Land degradation has adverse effects on the productive capacity of land, and thus, on food security of farm households (Nkonya et al., 2011; von Braun et al., 2012). Soil fertility degradation in particular is considered the most important food security constraint in SSA (Verchot, et al., 2007). It is estimated that about 1 billion tons of topsoil is lost annually in Ethiopia due to soil erosion (MoFED, 2010). The annual costs of land degradation related to soil erosion and nutrient loss from agricultural and grazing lands in Ethiopia is estimated at about 3% of agricultural GDP from a combination of soil and nutrient losses (Bojo and Cossells, 1995; Yesuf et al., 2008).

The other primary effect of land degradation through soil erosion relates to food supply. Davidson and Strout (2004) showed that there is continuously decreasing cereal availability per capita in the Eastern Africa region (from 136 kg yr^{-1} in the 1980s to 118 kg yr^{-1} in 2000s) due to land degradation. Sonneveld (2002) modelled the impact of water erosion on food production in Ethiopia in which he concludes that the potential reduction in production would range from 10–30% by 2030 from a base year of 1998.

Other, non–quantified, losses include human capital costs of drought and malnutrition, rural poverty and environmental services costs due to the impact of sedimentation of streams and rivers. Most importantly, the use of fertilizer has not increased to compensate for the loss of soil nutrients via soil erosion, leading to a continuous mining of soil organic matter (Kirui and Mirzabaev 2014). Data show that fertilizer use in Malawi, Kenya Ethiopia, and Tanzania remains very low (Kirui and Mirzabaev 2014). Existing alternatives of maintaining soil fertility, such as crop rotation, green manuring, and agroforestry have also not been sufficiently and effectively adopted to compensate nutrient loss. Decreased productivity of land attributed to resource degradation contributes directly to reduced livelihoods and food security among the rural and agricultural population of Eastern Africa (UNU/INRA, 1998).

1.5 The role of legumes as potential contributers to effective soil conservation

Soil conservation is an important part of sustainable agriculture and food production, and practicing it is increasingly gaining global attention, primarily in recognition of soil degradation and sustainability (Siddique et al., 2012). Accelerated soil erosion, identified as a major cause of soil degradation (Wynants et al., 2019) poses a critical challenge to food security in the years to come. Many efforts have been made in the past and present focusing on sustainable options to address soil erosion and degradation. For example, the BMZ–funded LegumeCHOICE project led by IITA, in cooperation with ICRAF, ILRI and the University of Hohenheim focused on aspects of soil erosion mitigation by combining soil conservation strategies and improved nutrient cycling through legumes for soil conservation and sustainability.

Legumes could play a critical role in this context by delivering multiple services in line with sustainability principles (Stagnari et al., 2017). Legumes contribute to reduction of GHG emissions (Lemke et al., 2007; Reckling et al., 2014), sequestration of C (Jensen et al., 2012), increase crop diversity and reduce use of external inputs (FAO, 2011; Plaza–Bonilla et al., 2016), increase soil fertility through biological nitrogen fixation (BNF) (Giller & Cadisch, 1995; Latati et al., 2016), build up high–quality organic matter and facilitate soil nutrient circulation and water retention (Hajduk et al., 2015), and reduction of soil erosion (Giller and Cadisch, 1995; Muoni et al., 2020). Legumes also perform well in intercropping systems (Latati et al., 2016), which are very important in low–input and low–yield farming systems (Stagnari et al., 2017).

Based on these multiple functions, legumes have a high potential for conservation agriculture (Stagnari et al., 2017), and cover legumes in particular have been recommended as an effective and cost efficient soil conservation measure (Thomas, 2000). Several studies have underscored legumes as an ideal plant type for two components of conservation agriculture, namely their use as soil cover and in crop rotation systems (Mundt 2002).

Legumes have been used in soil conservation for provision of high soil cover either as growing crop (Mhlanga et al., 2015) or as crop residue or mulch (Mupangwa & Thierfelder, 2014) during and after the growing season. Morgan et al. (1998) emphasized the role of plant cover in reducing soil erosion by intercepting raindrops, thereby reducing their impact to loosen soil particles and thus reduces soil loss by splash and overland flow (Ghahramani et al., 2011). Further, the presence of high plant cover increases surface roughness (Nearing, 1995), which intercepts runoff and enhances water infiltration (Adekalu et al., 2007).

Legume mulch and litter can form high quality SOM in the soil because of their high N to C ratio, which facilitates nutrient cycling (Dhakal et al. 2016). SOM contains fulvic acids, polysaccharides and humic acids that bind soil aggregates (Boyle et al., 1989). Additionally, incorporating legume crop residues into the soil serves as nourishment for macro and micro–organisms and thus promotes soil biological activity (Bertrand et al., 2015; Ashworth et al., 2017). Watt et al. (1993) showed that microbes establish intimate contact with soil particles, root hairs and mucilage, which binds soil particles and reduces their susceptibility to soil erosion. Ramirez-Garcia et al. (2014) revealed that this distinctive feature can further be exploited by intercropping legumes with cereals, which increases root density leading to more soil binding.

Kumar and Goh (2000) observed that the rotation of crops with different rooting patterns combined with minimal soil disturbance in zero–till systems promotes a more extensive network of root channels creating macro– and micropores in the soil. Many legumes are deep rooted and can be utilized in crop rotation systems to access nutrients unavailable to other crops. Some legumes perform similar roles by mechanisms such as dissolution by root exudates, and render those nutrients available to subsequent crops (Siddique et al., 2012). Pigeon pea and other leguminous shrubs / trees with extensive rooting systems are able to access water from deep soil horizons through hydraulic lift (Meena & Lal, 2018).

1.6 Soil conservation systems in Kenya: weaknesses, challenges and trade–offs

Historically, Kenya's social and economic transition is deeply rooted in soil conservation and ecological protection, and up till date one of the main principles for Kenya's development is the preservation and sustainable development of its soil and water resources (Karuku, 2018). The first national conservation project was initiated under the Swedish International Development Agency (SIDA) in 1974, commenced in Machakos district in 1979 and was later expanded to the whole country in 1989. Ever since, soil and water conservation measures have spread to the community level, and farmer–based soil management practices and measures have been practiced and have been largely successful, but face eminent challenges.

FAO (2007) grouped soil and water conservation measures into agronomic, soil management and mechanical. The agronomic measures include increasing soil surface cover, intercropping, contour farming, cover cropping and agro–forestry, increasing soil surface roughness, and increasing both surface depression storage and infiltration. Soil management measures include application of fertilizers, manures, sub–soiling, buffer strips, crop rotation and drainage, while mechanical measures include contouring, ridging and terraces. In Kenya, the most practiced measures are: (i) Agronomic e.g. plant/soil cover, conservation farming methods, contour farming; (ii) Vegetative e.g. planting barriers (vegetative strips), live fences, windbreaks; (iii) Structural e.g. Fanya Juu, terraces, cut–off drains, and (iv) Overall management e.g. area closures, selective clearing (Karuku, 2018).

In many studies the benefits of conservation agriculture has been attributed to the mulch of crop residues retained on the field (Giller et al., 2009). However, limited availability of crop residues or mulch poses a major constraint to the success of conservation agriculture methods in soil conservation. Exceptional case to this is the application of cover crop residues which are produced on–site, unless for reason of biomass transfer (Runtunga, 1999). Smallholder farmers in Kenya often find the cost of labour for collecting, transporting and applying mulch too expensive. Similarly, lopping trees and spreading branches and leaves over the cropping area requires considerable labour. On steep slopes, the application of residue cover crops is particularly labour intensive and these materials are easily washed downhill.

In addition to unavailability and labour, mulching with crop residues may alter the flow of resources at farm scale, where competing uses of crop residues such as fodder, fuel or construction material exist (Giller et al., 2009). Bebe et al. (2002) observed a rapid expansion in smallholder milk production in the past decade by stall–fed cows in the highlands of Kenya. At the same time, there was growing development of a market for maize stover as a valuable feed resource, providing further competition for potential residues for mulch (Tittonell et al., 2007). Thus, smallholders may prioritize feeding crop residues to livestock over soil mulching (Giller et al., 2009; Naudin et al., 2014; Erenstein et al., 2015).

A number of agroforestry technologies have had enormous impacts and mitigating effects on declining agricultural productivity and natural resource degradation in Kenya. Some agroforestry trees and shrubs planted on terraces, sand and stone bunds and risers, or as hedges on contours apart from soil conservation through erosion preclusion also make productive use of areas along these structures where crops cannot be grown. One of the key challenges that hinders the potential of agroforestry trees in soil conservation is lack of quality germplasm. For instance, *Proposis juliflora* was a very good fodder tree when initially introduced in northern Kenya, but has now become an invasive weed and ecological disaster affecting crop performance (Sanchez and Jama, 2000).

Leguminous trees such as *Calliandra spp*, *Leucaena leucocephala*, *Terminalia brownii* among others have doubled and tripled crop yields when combined with inorganic fertilizers on degraded lands (Jama et al., 2006). However, a number of studies have also reported declining crop yields, on plots where trees have been intercropped with crops due to competition of perennials with crops for growth resources if not managed properly and reduction of cropping area r(Rao et al., 1998; Tuan et al., 2014). Other challenges affecting the success of agroforestry systems in soil conservation includes lack of extension services and legislation on policies that provide adequate incentives for planting trees (Karuku, 2018).

Vegetation strips are usually narrow grass strips grown across slopes, where the grass acts as a barrier to runoff, thus encouraging deposition of sediments (Morgan, 2005). Many studies have been conducted on the effect of vegetative buffer strips on runoff quality and quantity control (Norris 1993; Lee et al., 2003; Borin et al., 2010; Milan et al., 2014). Commonly planted grasses in Kenyan degraded lands include *Vetiver zizanioides* (Vetiver grass) and *Cenchrus purpureus* (Napier grass, synonym *Pennisetum purpureum*). Species such as *Cenchrus purpureus* are also used as fodder to feed livestock, and hence could compete in their use in soil conservation.

Moreover, vegetative strips also take smallholder lands out of production, especially those which do not provide any direct income to the smallholder e.g. vetiver grass, unlike Napier grass which can be cut and fed to livestock. Morgan (2005) argues that the ideal situation lies where the economic power of the grass strip equals or exceeds that lost by taking the land out of agricultural production. Construction of live fences around farms and windbreaks suffer from similar setbacks from being used in soil conservation.

Rhizomous grass species spread rapidly onto surrounding land or cropping areas when used as vegetative strips (Morgan, 2005). This makes them a nuisance and may compete for nutrient and soil moisture when they encroach neighbouring cropped fields. Kikuyu grass (*Pennisetum clandestinum*) also may concentrate flow of water (Morgan, 2005), which increases the vulnerability of the land to soil erosion.

Fanya juu is one of the widely used structural soil conservation methods in East Africa. It comprises of narrow shelves constructed by digging a ditch on the contour and throwing the soil on the upslope side to form an embankment (Thomas and Biamah, 1989). Being a modern traditional system in Kenya (Critchley et al., 1994), Fanya juu is very effective in trapping runoff, with evidence of increased crop performance (William and Hess, 1999; Mwangi, 2001). Although the effectiveness of Fanya juu has been understood, the challenge however is the high labour requirement in its construction and maintenance (Kiome and Stocking, 1993; Morgan, 2005). Fanya juu is also limited to slopes up to 17 degrees to prevent overtopping (Thomas and Biamah, 1989).

Like Fanya juu, other structural soil conservation approaches such as terraces and cut–off drains are also laborious to construct and maintain. Other limitations have been shown by poorly designed terraces which in most situations can exacerbate an erosion problem (Morgan and Hann, 2003). A minimum level of scientific and engineering knowledge is also required to successfully implement terraces, which in most cases is unavailable to smallholder farmers. For instance, bench terraces are not suitable for shallow soils because their construction can expose infertile subsoil (Morgan, 2005).

Management measures of soil conservation are implemented where uncontrolled land use has led to degradation, and where other measures have failed. Fundamental change in land management such as enclosures e.g. to protect grazing area are a requirement to allow regeneration of vegetation cover. Such measures are also essential for the rehabilitation of severely degraded areas where technical measures and other interventions are often not adequate on their own but can act in a supplementary manner (Karuku, 2018). However, Karuku (2018) claims that taking land out of use can lead to increased pressure on neighbouring land, which may also be in poor condition and vulnerable to further degradation.

Additional challenge could stem from the fact that management measures are not clear–cut, and may require great flexibility and responsiveness at initial stages and in subsequent years that follow (Karuku, 2018). WOCAT (2007) further reported on implications for land tenure that can complicate decision–making that may sour relationships between neighbours as they try to conserve their land holdings.

1.7 Approaches for investigating soil erosion

Measurement of soil erosion has been a principal target and one of the highest research priorities of scientific research communities and governmental programs globally since the beginning of the 20^{th} century (García-Ruiz et al., 2015). Toy et al. (2002) reckon that soil erosion should be measured to assess environmental impacts and conservation practices, the development of erosion prediction technologies, and the implementation of conservation policies. Several methods or approaches have been developed over time to determine soil loss at scales ranging from very small plots (<1 m^2) to large basins (> 1000 km^2).

The selection of the method used to measure soil erosion depends on the objectives, financial support, size of the study area and the characteristics of the research group with regards to the number of members and training capacity (Garcia–Ruiz et al., 2015). Nevertheless, de Vente et al. (2007) revealed that measured erosion results have not been independent of the method used, because each method tends to be related to a spatial scale or a range of spatial scales, and subsequently each method is selected to measure a particular erosion process. The methods used to quantify soil erosion include bounded and unbounded plots of different sizes, rainfall simulations, small ponds, check dams and reservoirs, erosion pins and profilometers, tracers (radioisotopes), laser, drones, satellites, and models. These methods will be objectively discussed under the headings of slope–scale plots, landscape scale and models.

1.7.1. Plot to slope scale

1.7.1.1 Bounded plots

Bounded plots are physically isolated pieces of land of known size, slope gradient, slope length and soil type from which erosion is quantified (Morgan, 2005). Plot sizes used may vary, but the widely used standard Wischmeier plot size measures 22 m in length and 1.8 m in width. The plot edges are made from stable materials that do not leak and are not liable to rust, e.g. metallic sheet, wood, concrete etc. The edges should be buried into the soil at depths that are not affected by alternate wetting and drying or freezing and thawing of the soil, whilst the opposite edges should extend 150–200 mm above the soil surface.

The downslope end is made of a collecting trough or gutter covered with a lid to channel runoff and sediment into collecting tanks. The volume of runoff is measured by emptying the tanks into calibrated buckets. For larger plots or where runoff volumes are very high a divisor or splitter tanks are connected to split the flow into equal parts, as a sample into a second collecting tank. For the splitter tank, the volume of runoff water measured is multiplied by the number of splitters. On some plots, the runoff is channelled through a flume to automatically monitor the discharge.

The bounded plot gives probably the most reliable data on soil loss per unit area, however there are several sources of error (Hudson, 1957). These include silting of the collecting trough and pipes leading to the tanks, inadequate covering of tanks against rainfall, and maintenance of constant level between the soil surface and the lip of the trough. Hudson (1993) also observed collecting tanks overflowing during extreme events, tanks floating out of saturated ground, runoff entering top of the plot, and runoff along the boundary of plots and forming rills.

1.7.1.2 Unbounded plots e.g. Gerlach troughs

The original Gerlach troughs consist of simple metal gutters, 0.5 m long and 0.1 m broad closed at both ends and fitted with a movable lid (Gerlach, 1996). The base of the gutter is connected to collecting vessels via an outlet pipe, which delivers runoff and sediment to the series collecting vessels. A second vessel collects excess runoff from the first in case of storm events. A typical set–up consists of two or more gutters placed side–by–side across the slope and groups of gutters installed at different slope lengths. Gerlach troughs are simple to make and cheap, because of this they are employed for sample measurements of soil loss at large number of selected sites over a large area.

The area contributing to runoff and soil loss is estimated to be equal to the width of the gutter multiplied by the length of the slope. This is based on the assumption that loss of runoff or sediment from the defined area can be balanced by inputs from adjacent areas (Morgan, 2005). This assumption is reasonable if the slope is straight and plane. Curved slopes pose a disadvantage for the use of Gerlach troughs, but this drawback can be offset by the flexibility of monitoring soil loss at different slope lengths and steepness within an open system (Morgan, 2005).

1.7.1.3 Sediment or silt fences

A sediment fence typically consists of a synthetic geotextile fabric that is woven to provide structural integrity with a small opening that allows water to pass through but not sediment (Robichaud & Brown, 2002). Typically, the fences are between 3 and 15 m across the hillslope, and plot lengths upslope are 5 to 61 m. Consequently, areas contributing to soil erosion may vary from 15 to 930 m^2. In case of overtop flow from storm a second sediment fence located below the first may be used to trap any sediment that overflows the first fence.

The sediment fence is installed at the base of the plot. A trench is dug along the contour with the ends of the trough gently curving uphill to prevent runoff from circumventing the sediment fence. The sediment fence is laid out along the trench covering the bottom and uphill side of the trench. The excavated soil is then used to backfill the trench. Wooden stakes driven at least 0.3 m deep into the soil and spaced 0.9 to 1.5 m apart. The sediment fence can be attached to the stake with staples or nails through a protective strip of asphalt paper.

Sediment fence are relatively inexpensive, easy to install and readily available. Various plot sizes can be used to measure hillslope erosion in different settings and to determine effectiveness of various treatments or practices. However, sediment fences may require frequent maintenance. It is effective only for sheet runoff flow, and may fail in concentrated flow areas due to low permeability. Its effectiveness can be limited at large and sloping sites.

1.7.1.4 Rainfall simulators

Rainfall simulation relies on the use of a rainfall simulator, which is designed to produce certain characteristics of rainfall such as a storm of known energy, intensity and drop–size with a uniform spatial distribution, which can be repeated on demand (Morgan, 2005). A typical setup described in Abrantes et al. (2018) comprised of the simulator, drainage rectangular soil flume, and water inflow system. Rainfall simulation is a useful method to study certain erosion–related processes such as infiltration, the evolution of hydrological and sedimentological response and penetration of the wetting front (Gonzalez–Hidalgo et al., 2004).

Rainfall simulation approaches of measuring soil erosion face criticisms because of the small area of their plots (usually < 0.5 m^2), and the particular characteristics of rainfall (Garcia–Ruiz et al., 2015). Values obtained under rainfall simulation (suspended sediment concentration in runoff) may only provide relative comparisons of the response of distinct soil types or plant covers (Garcia–Ruiz et al., 2015). De Luis et al. (2003) also showed that the spatial distribution of plants within rainfall simulation plots can condition the result.

1.7.1.5 Erosion pins and profilometers

Erosion pins and micro–profilometers are used to measure soil erosion based on changes in ground level over time (Sancho et al., 1991; Benito et al., 1992; Sirvent et al., 1997). Erosion pins are typically 250–300 mm long nails of 5 mm in diameter. They can be installed at different points covering a wide area of the field by driving the pins through a washer into the soil (Emmett, 1965). The head of the nail should be 20–30 mm above the soil surface. The erosion pins can be located at the intersections of a 1 m grid pattern as well as along rill and interrill areas to capture spatial erosion distribution and as cartographic support (Sirvent et al., 1997). Periodic measurements of the gap between the head of the nail and the washer using a depth gauge indicates the extent to which the surface has been lowered. Where the washer has become buried, the depth of the material above the washer indicates the depth of deposition. The erosion pin record is then analysed by computer to generate ground lowering contour lines.

The micro–profilometers consists of a painted wooden frame or aluminium panel of 1.10 m × 0.90 m dimension. It has two legs that have flat bottoms so that it can be placed with balance on fixed erosion pins. The bottom of the board has holes at an interval of 2 cm through which thin steel rods can slide. The body of the board has been made into a graph and calibrations have been made on it. When this instrument is placed on gullies, automatically the rods slide down and rest on the ground and a graph is drawn on the board. A picture of the profile on the board is taken with a digital camera, and imported to an image processing software. From the produced image the XY position of the steel rods are determined to generate the profiles.

The major restriction is that the measurements are very imprecise and a small reading error has very large implications (1mm depth at a bulk density of 1.0 g cm^{-3} corresponds to 10 Mg soil ha^{-1}). Nadal–Romero et al. (2011) also argues that erosion pins and profilometers overestimate the erosion rates for the entire area.

1.7.2. Landscape/catchment

1.7.2.1 Turbidity–based method

Turbidity–based methods are used in measurements of the quantity of sediment leaving a catchment along a river in a period of time, referred to as sediment yield. Recording stations are established at the exit of the catchment to measure discharge, turbidity and suspended sediment concentration using weirs, sensors and depth recorders. Sediment concentration is monitored by measuring turbidity at specific time intervals using a data logger or manually after rain events. Water samples are also taken at specific times using specially designed integrated sediment samplers. Water level at the river is measured at specific time intervals using pressure sensors.

The accuracy of turbidity method is highly dependent on the sampling frequency (Walling et al., 1992). Measurements made at specific time intervals can be extrapolated to obtain estimates covering the period between measurements. The standardized approach to do this is to establish a sediment discharge rating curve in which sediment concentration is directly proportional to the water discharge (Morgan, 2005). Slaets et al. (2014) also developed a methodology in which the optimization of the sample size provides a cost effective approach to derive reliable and long term estimates of sediments and nutrient concentrations using basic hydrological characteristics.

The turbidity method is currently the best available approach to provide estimates of suspended sediment yield, especially if high frequency data are sought (Morgan, 2005). However, such data will come at a greater cost due to routine calibration and maintenance. Moreover, the turbidity meter measurements are subject to errors associated with the influence of the particle size of the sediment load, and the presence of organic matter.

1.7.2.2 Bathymetric studies e.g. reservoir surveys, small ponds

Sedimentation rates in reservoirs, small ponds or lakes can show how much erosion has taken place in a catchment upstream, as long as the efficiency of the reservoir as a sediment trap is known (Morgan, 2005). Molina–Navarro et al. (2014) showed that bathymetric studies in reservoirs can provide information on sediment accumulation and therefore erosion rates over long periods of time extending to decades and centuries in the case of ancient reservoirs. A bathymetric study by Rapp et al. (1972) in Tanzania used repeated studies of designated transects across four reservoirs in relation to a benchmark. Depth readings were produced using manual soundings from a boat to generate a contour map of the bottom of the reservoir.

With current technological advancement, more rapid surveys can be made e.g. echo–sounders can now be used to obtain depth readings, laser theodolites or electro–distance measuring theodolites can be used to fix the position of the sounding.

However, some challenges include sources of error associated with estimates of the reservoir trap efficiency, which requires knowledge of the frequency and sediment concentration of flows that might spill away during periods of flood, and errors associated with estimating the reservoir capacity (Morgan, 2005). Valero–Garces et al. (1998) also pointed out that erosion rates derived from sedimentation comes from large catchments and it's very difficult to know the source of the sediment, although efforts have been made to study this based on the sediment composition in water from the main tributaries of the basin.

1.7.2.3 Tracers

Fallout radionuclides (FRN), including caesium–137 (^{137}Cs), excess lead–210 ($^{210}Pb_{ex}$) and beryllium–7 (^{7}Be) have been used globally as suitable materials to estimate soil erosion rates (Zapata, 2003; Mabit et al., 2008; Brandt et al., 2018). Notably, caesium–137 has been established as the most commonly used tracer in soil erosion research over the years (Wallen and Quine, 1992). The key assumptions which are fundamental to its successful application are its uniform local fallout distribution, rapid and strong adsorption onto soil particles, subsequent redistribution which reflects sediment movement, and provision of estimates of rates of soil loss from measurements of soil caesium–137 inventories (Walling & Quine, 1991; Morgan, 2005).

Several studies have used transect and the grid system of soil sampling with varying density e.g. 10 ×10 to 20 × 20 m on fields and catchments to capture spatial pattern of isotope loading. Soil samples are taken at incremental depths from erosion plots or hotspots and from reference sites, usually in either woodland, forest or grassland. Spatial variations in isotope loading in comparison with those at the reference site indicate patterns of erosion and deposition (Ritchie and Ritchie, 2001).

Whiles most other erosion measurement approaches measure sediment yield from closed system, radioisotope surveys can provide true erosion rates, including intermediate deposition areas (Garcia–Ruiz et al., 2015). However, Boardman (2006) argues that it is a time consuming approach, and that its assumptions are debatable. Thus, the loss of caesium–137 is not necessarily proportional to the loss of soil (Parson, 2011; Parson and Foster, 2011). Moreover, it is quite difficult to establish a site where no erosion or accumulation has occurred in the past 60 years, to provide a reference for values of caesium–137 determined for eroded soils (Garcia–Ruiz et al., 2015).

1.7.2.4 Satellites, laser and drones

The capacity to quantify and monitor soil erosion has greatly been enhanced by the use of aerial photographs and satellite data at the local, national and regional levels (Roux et al., 2007). Remote sensing technologies offers a timely, affordable and robust approach for investigating soil erosion at a larger spatial scale, especially in environments where intensive field methods remain a challenge (Seutloali et al., 2016). Satellite imagery covers large areas and provides detailed spectral information (Boak & Turner, 2005) as well as very high resolution (< 1 m) satellite data (Ford, 2013). Likewise, datasets produced by drones have higher resolutions (< 10 cm) (Harwin and Lucieer, 2012) and support the development of high resolution digital elevation models (DEMs) that facilitate change detection and measurement (Hugenholtz et al., 2013). The identification and mapping of soil erosion features is performed by classification technique, the use of spectral characteristics and vegetation indices (VIs) (King et al., 2005).

Classification procedures require user input in the form of training data, to guide the image processing software. In the process, the identification and mapping of soil erosion features is performed by classification algorithms in extraction of digital information based on spectral and or structural pattern recognition (Alatore and Beguería, 2009). Several classification approaches exist such as supervised, unsupervised or hybrid (combination of supervised and unsupervised classification) methods (Vrieling, 2006). These methods come in hand with mathematical algorithms to aid in the classification (Sepuru & Dube, 2018).

Mapping soil erosion from its level of formation such as sheets, rills, or gullies using remotely sensed data lies in their spectral differences (King et al., 2005). Price (1993) found a direct relationship between soil and spectral reflectance, which allows the detection of disturbed soil and the mapping of its spatial occurrence. Soil features such as its mineral composition, texture, moisture, and organic matter influences the bare soil spectral signature of different levels of soil erosion (Barnes and Baker, 2000; Sujatha et al., 2000). Hence, it is important to understand the spectral response and reflectance of the erosion features characteristics using remote sensing (Sepuru and Dube, 2018).

Apart from classification technique and spectral characteristics, vegetation indices (VIs) derived from satellite images also provide information about the earth's surface reflectance, and have been used as simple and quick feature extraction technique for soil erosion mapping (Singh et al., 2004; King et al., 2005). The Normalized Difference Vegetation Index (NDVI), since its initiation has been widely used in soil erosion research (Taruvinga, 2008; Seutloali et al., 2016; Kwanele and Njoya, 2017). Various modifications have been advocated to address the sensitivity of NDVI to non–vegetation factors (Lawrence and Ripple, 1998; Kwanele and Njoya, 2017). The Soil Adjusted Vegetation Index (SAVI) proposed by Huete (1988), and Soil and Atmospheric Resistant Vegetation Index (SARVI) developed by Huete and Liu (1994) are amongst the widely used modifications of NDVI in erosion research (Kwanele and Njoya, 2017).

Lidar (laser scanning) from both airborne and terrestrial platforms has resulted in more comprehensive and detailed measurement of bank movement (Thoma et al. 2005; Resop and Hession, 2010; Grove et al. 2013) and hillslope and gully erosion (Perroy et al. 2010; Tseng et al. 2013; Cavalli et al. 2017). Drone–based surveying can overcome some of the existing data collection shortcomings of ground surveys and manned aircraft systems, such as being limited to specific sites, high costs or the requirement of longer data collection lead–times. Drone derived data have shown potential in quantifying bank erosion and monitoring volumetric change in fluvial settings due to flooding (Cook 2017; Hamshaw et al., 2017). Hamshaw et al. (2019) applied drone–based photogrammetry to monitor long (ca. 20 km) distances of river corridors and quantify streambank erosion rates along multiple rivers in the north–eastern United States.

Major challenges related to the operation of drones may be weather related, e.g. flights are limited to specific times in coastal areas to reduce the impact of strong winds (Gonçalves and Henriques, 2015). Other challenges include platform instability, view angle, data processing tools and short flight times due to battery constraints (Elaksher et al. 2017). Drone technology is rapidly growing and new camera sensor technology, improvements in photogrammetric software and processing algorithms, and the direct georeferencing capability of GPS equipped drones should both improve the utility and performance of future systems.

1.7.3. Models

Soil erosion measurement techniques described above under 1.7.1 and 1.7.2 allow soil erosion rates to be determined at different positions in the landscape over various spatial and time scales. Obviously, it is difficult to take measurements at every point of the landscape, and to capture the rare extreme events which cause damage. Long–term measurements would be required to create an erosion database to ensure that measurements are not biased by few years of abnormal rainfall (Morgan, 2005). Consequently, long–term measurements will be required to study how erosion rates respond to soil conservation measures. Models can be used to address these short falls due to their applications under a wide range of conditions to predict erosion.

Soil erosion models are generally categorised into empirical, conceptual and physically based models (Lal, 1994; Hudson, 1995; Merritt et al., 2003), depending on the physical processes simulated, the model algorithm describing the processes and the data dependence of the model (Merritt et al., 2003).

Empirical models are based primarily on defining important factors through field observation, measurement, experimentation and statistical techniques relating erosion factors to soil loss (Petter, 1992). They are used in situations with limited data and parameter input (Merritt et al., 2003). The Universal Soil Loss Equation (USLE) and its revised version Revised Universal Soil Loss Equation (Wischmeier & Smith, 1978) are the most widely used and accepted empirical soil erosion models. Conceptual models play an intermediary role between empirical and physically based models. Whilst they tend to be aggregated, they still reflect the hypotheses about the processes governing the system behaviour. This is the main feature that distinguishes conceptual models from empirical models (Beck, 1987).

Physically based models are based on the knowledge of the fundamental erosion processes; and incorporate the law of mass conservation and energy (Bennett, 1974). The parameters used in physical–based models are measurable and therefore known (Merritt et al., 2003). Examples of physically based models include: Water Erosion Prediction Project (WEPP) (Flanagan et al., 2001), Griffith University Soil Erosion Template (GUEST) (Misra and Rose, 1996), and Land Use Change Impact Assessment tool (LUCIA) (Marohn and Cadisch, 2011).

The success or performance of any model is judged on how well it meets its objective. One reason for insisting on the accuracy of model prediction is that performance measurement is intrinsically case dependent (McIntosh et al., 2011; Bennett et al., 2013). Jetten & Maneta, (2011) showed that almost all models are calibrated based on their spatial and temporal scales, and although the objectives are different for each scale, the calibration procedures used are similar. At different scales, different data may be required for calibration and validation, often obtained from measured short to long–term plot/field/catchment experimental studies or remotely sensed data at different resolutions as discussed above in sections 1.7.1 and 1.7.2.

Models used at the plot or field scale which is regarded as a single homogeneous spatial unit vary from empirical/conceptual to physically–based process models. In the former category, processes such as transport and deposition are often not included. Temporal scale varies from individual rainfall events of runoff and soil loss to lumped annual values. Models operating at the catchment scale are generally process–based or hybrid models. Temporal scales vary again from individual rainfall events to annual totals, although most calibration is done for individual events. Models used at the so–called 'large' scale with administrative boundaries, from provinces and parts of countries to continental are partly physically based, but use variables derived from a DEM as proxies for slope angle, transport capacity and accumulation. Generally, sediment delivery ratios are used for calibration and temporal scales vary from monthly to annual totals (Jetten and Maneta, 2011), and event (minutes) for high resolution modelling (Liu et al., 2020).

Crop simulation models are equipped to dynamically describe the changes in system state in response to external drivers (e.g. management practices which includes sowing dates, weather etc.), and how those changes are affected by other components in the system (Wallach et al., 2014). Input data in simulation models related to crops make use of their genetic coefficients, which allows simulation of crop performance of genotypes (Teixeira et al. 2017). Moreover, simulation models can simulate different irrigation schemes to predict their impact on crop yield and hydrological components such as evapotranspiration and water requirement (Dallacort et al., 2010).

A major limitation in modelling soil erosion in any given area includes restrictions in understanding of the processes involved, especially in terms of the spatial distribution of soil erosion to those processes and causes (Croke and Mockler, 2001). Assessments of the quality and quantity of soil erosion models in the past show that, in general, the spatial aspect and patterns of erosion are poorly predicted (Jetten et al., 2003; Merritt et al., 2003). Furthermore, Sepuru and Dube (2018) stated that models can rarely be relied upon to give accurate predictions of absolute amounts of soil erosion. Models can only be expected to give a relative ranking of the effects of land management without adequate input data and calibration (Garen et al., 1999). Input data preparation can be a difficult task and sometimes the mechanics of operating the models are complicated (Jetten et al., 2003).

1.8 Justification of the study

Improving the current farming system and soil conservation on sloping lands in a South–Western Kenyan smallholder–catchment – Rongo – calls for an integrated approach to mitigate the water–induced soil erosion which threatens soil health and food production. In this catchment, farm lands are mostly fragmented, and typically laid out in strips in slope direction. The resulting long slopes coupled with unsustainable farming practices such as ploughing downhill have led to severe runoff and soil erosion. Furthermore, lack of adequate soil cover particularly in dominant maize–based cropping systems in these landscapes adds to erodibility, i.e. soil vulnerability to erosion. The long slope length in particular, could be a potential target factor in designing spatially explicit erosion measures largely neglected to date. This study location should be treated as a case study as the findings have general application to other similar locations in Western Kenya and beyond. Moreover, unreliable climatic trends caused by climate variability and change further impose drought and water stress and unfavourable growth conditions that affect water use efficiency and crop production. The use of agronomic management approaches such as late planting and exploitation of genetically determined vegetation periods e.g. early maturing cultivars can help crops to avoid drought, especially if the first planting fails and there is only limited time until the end of the rainy season. Cover legumes have been recommended to smallholder farmers in Kenya as a (cost-) effective soil conservation measure against erosion, but their adoption rate is still low. Most cover legumes are not accompanied by economic added value, making them unattractive to farmers in soil conservation measures. Many grain and fodder legumes offer this added value, if planted in the appropriate socio–ecological context. Soil conservation measures that reduce slope gradient and length (e.g. terraces, grass filter strips, hedgerows) are recognized for their efficacy but only implemented if providing added value or incentive is obtained. This study on one hand, focused on the combination of the concept of critical slope length and spatial design of legume–based crop fields to minimise land and labour costs in land constrained smallholder settings while optimising soil conservation and crop production. On the other hand, this study also aimed at determining the viability of late sowing, and different vegetation genotypes (early and late maturing) in order to assess their impact on grain yield production and WUE. Setting up such a study on the field would be time consuming and costly. Thus, dynamic and spatially–explicit models have become a useful impact assessment tool as they can simulate responses of crops to soil and water as well as weather and management practices, offering for example the implementation of agronomic management systems of water stress. Such measures can be an effective approach to reduce cost and crop failure.

1.9 Research objectives

The first main objective of this study was to better understand the potential of alternative smallholder selected legume–based cropping systems on the environment (runoff, erosion), sustainability of the production base (soil fertility), and food production (grain yield). The focus was to adapt different legume cropping systems to the local environment through cross–seasonal field experimentation, in order to provide evidence–based effective systems for soil conservation. The effects of different planting systems on aggregate stability, bulk density, infiltration, runoff and soil erosion and agronomic yield were assessed.

The second main objective was to investigate the impact of slope length on runoff and soil erosion under a typical smallholder maize (*Zea mays*) and common bean (*Phaseolus vulgaris*) intercropping system. This study would explore options to improve current farming systems on sloping land in a smallholder environment, combining the concept of critical slope length and spatial design of crop fields. The study includes event–based measurements of groundcover, rainfall, runoff, profile curvature as explanatory variables and maize crop yields and analysing them using a spatial statistical model on soil loss (response variable) in a slope length experiment, to assess the role of slope length compared to other factors causing erosion. Integrating slope length options and legume cropping systems results were then used to recommend management options that are effective in reducing soil erosion and show potential of adoption for effective soil conservation.

The third main objective was to evaluate the impact of different agronomic drought and water stress management strategies on sowing date and vegetation cultivars to improve grain yield and water use efficiency using modelling as a decision–support system. Following the legume cropping system, a database on management practices, soil, climate, agronomic, runoff and soil erosion was developed and used to parameterize and calibrate a landscape model. In the next steps, model scenarios evaluated the impact of sowing dates (baseline vs late planting) and vegetative genotypes (short duration crop varieties). This would allow evaluating options to identify adequate sowing periods and vegetative cultivars that can adapt into cropping cycle for increased grain yield production and improved water use efficiency.

1.10 Hypotheses

Corresponding to these research objectives, the hypotheses that guided this research were:

1. Cropping systems and management practices that promote protective soil cover through high groundcover and canopy cover will improve soil structure and enhance infiltration, thus reducing runoff and soil loss.
2. Under uniform land use and management systems on an inclined plane, runoff and soil loss will increase exponentially with slope length due to exponentially increasing flow velocity.
3. Under high rainfall variability, delayed planting and/or planting short duration crop (SDC) varieties can enable plants to escape water stress that occurs at the beginning or during the cropping season and hence reduce the risk of crop failure.

1.11 Research questions

1. Which legume types and cropping systems have the potential to contribute to soil erosion and runoff mitigation, improve soil structure and infiltration through provision of plant canopy and groundcover?
2. How will the efficacy of soil conservation measures on surface runoff and soil loss vary with the changing soil erosion processes along slope gradient?
3. Can delayed planting and combinations with short vegetation crop varieties help escape water stress at the beginning of the cropping season in order to avert the risk of crop failure?

Chapter 2. Study sites

2.1 Site selection

The study was conducted in one of the two counties in South–western Kenya, which was part of the BMZ–funded LegumeCHOICE project led by ICRAF, in cooperation with IITA and the University of Hohenheim. These were Nyaribari chache and Kitutu chache in Kisii County and Rongo and Suna West in Migori County. These four sites are characterised by steep slopes, which is of relevance for the moderate to severe erosion on most of the farms and degraded soils intensively cultivated without fallow due to small land sizes. All sites differed in access to markets in accessing agricultural inputs and marketing of their agricultural produce. In Kisii, Nyaribari chache was more distant in market accessibility than to Kitutu chache, whereas, in Migori county, market was more accessible in Rongo than Suna West. Besides, preliminary data on soils and legume interventions already existed in all the four sites. Rongo site was selected for this study as a small and not very complex watershed representative for smallholder farming systems in Kisii and Migori. Average farm size was around 0.8 ha (Jaetzold, 2009) and the ancestral form of landholdings is in narrow strips with slope lengths up to about 200 m from upper slope position towards the stream. Valleys are characterized by gentle foot slopes, so that sediments can deposit before reaching the stream.

2.2. Location, topography and soils

The on–farm studies were carried out in a small catchment (24.3 km^2) of Rongo Sub–county (Fig. 1), Migori County, located between latitude 0º45′42.84″S and longitude 34º34′20.28″E (North–West corner) and latitude 0º47′50.64″S and longitude 34º40′31.44″E (South–East corner). Elevation of the catchment ranges from 1370 to 1840 m above sea level (m.a.s.l). Topography at Rongo is hilly with a few stretches of flat land. Typically, slope inclination varies from 5 to 40%. Soils in the catchment differ in texture from sandy to clayey. At lower slope positions, Acrisols and Cambisols prevail, while upper parts are dominated by Nitosols and Phaeozems (Wielemaker and Boxem, 1982).

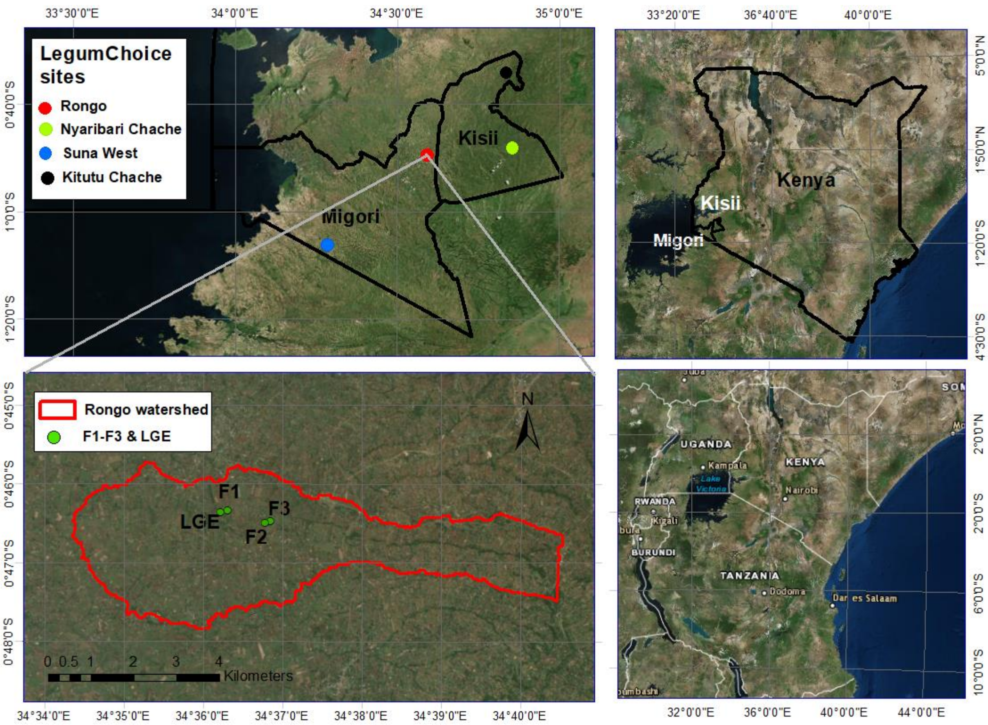

Figure 1. Study sites of the LegumeCHOICE project and locations of legume groundcover experiment (LGE) and slope length study farms F1-F3 in Rongo watershed.

2.3. Climate

Rainfall in Rongo is bi–modally distributed (long (LR) and short rainy season (SR)) permitting two cropping seasons per year. The LR occurs between March and July, the SR between September and November. Long–term annual rainfall varies between 700 and 1,800 mm. Air temperature varies from a minimum of 18 to a maximum of between 26 to 30 ˚C. Seasonal rainfall varied during our experiments with 622 mm in LR 2016, 754 mm in SR 2016, and 347 mm in LR 2017 (Fig. 2). Average air temperature also varied slightly seasonally from 22˚C in LR 2016, 21.8˚C in SR 2016, and 22.1˚C in LR 2017.

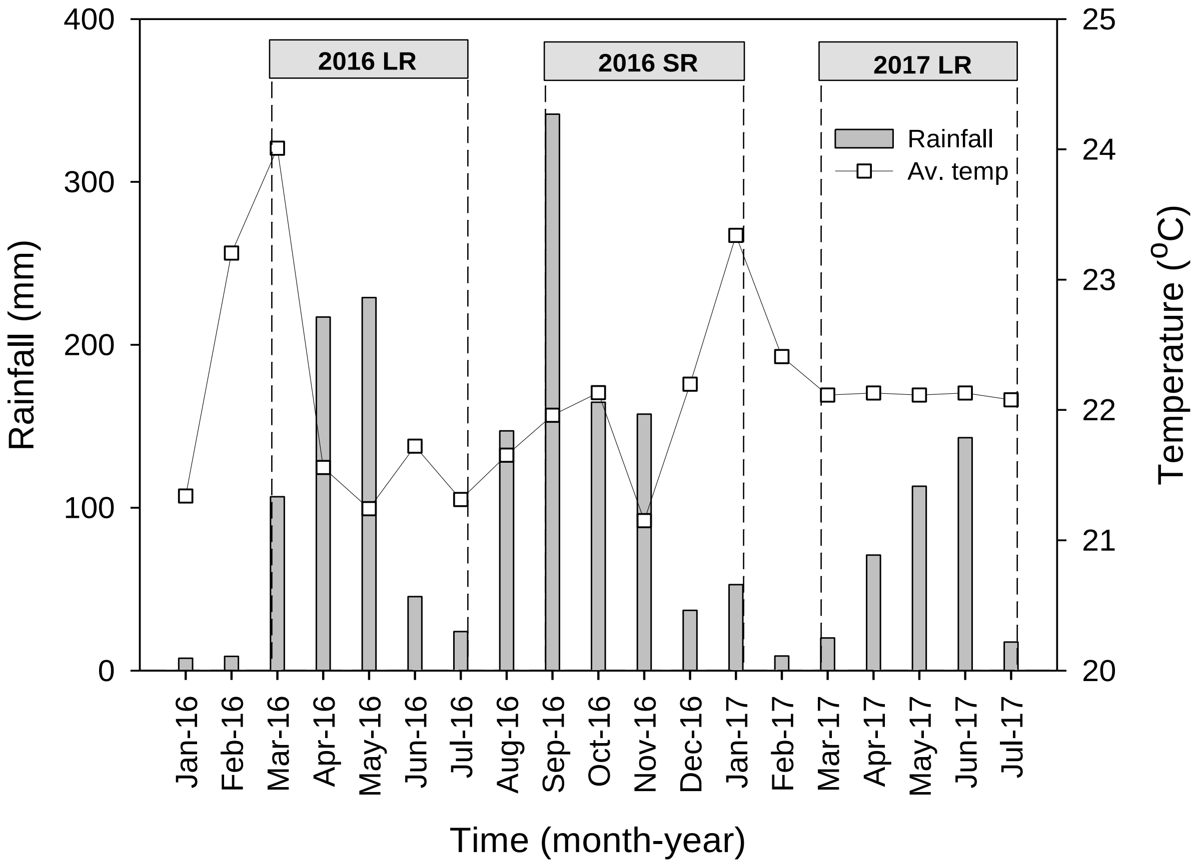

Figure 2. Monthly precipitation and average air temperature in Rongo watershed during the study period from 2016 to 2017.

2.4. Socio–cultural, land tenure and agricultural systems

Rongo Sub–County covers an area of 208.40 Sq. Km, with a population of 100,547 people (KeNADA, 2009). The main economic activities include agriculture and small scale mining. According to our focus group discussion and farmer interviews agricultural lands have been under cultivation for centuries, but commercial agriculture started about 60 years ago. Land ownership is an important aspect in agricultural development since it influences land–use patterns and the distribution of farms. The major means of land acquisition in Rongo is inheritance. Under this system, the land belongs to the male head of the household and is subdivided amongst the male children upon his death or as soon as any of the children has established an independent household. This mode of land transfer has contributed to declining sizes of individual farm units. Agricultural practices are dominated mainly by subsistence farming and characterized by lack of proper soil conservation techniques. The main interventions to control soil erosion includes cut–off drains, and planted Napier grass across slope. Given the typical spatial farm lay–out, farmers' tillage practices involve downhill ox–ploughing of plots. The watershed confines a mosaic of land use types dominated by agricultural crops (maize (*Zea mays*), sugarcane (*Saccharum officinarum*) and banana (*Musa sp*.) and planted trees, mainly Eucalyptus (*Eucalyptus grandis*). Maize, sugarcane and banana are the most popular mono crops within the catchment. In intercropped systems, the most popular main crop is maize, followed by banana (*Musa sp*.), sugarcane, cassava (*Manihot esculanta*), groundnut (*Arachis hypogaea*) and Napier grass. The major intercropped species is common bean (*Phaseolus vulgaris*) followed by groundnut. Other major intercrops are desmodium (*Desmodium intortum*), soybeans (*Glycine max*) and tomatoes (*Solanum lycopersicum*). The main cash crop cultivated is sugarcane. The main livestock kept are draught oxen, improved dairy cattle, and local cattle.

Chapter 3. Materials and methods

3.1 Experimental approach

Two separate field experiments were set up to monitor runoff and sediment loss on bounded erosion plots. The legume ground cover experiment (LGE) was established to evaluate the effectiveness of five different legume cropping systems to reduce soil loss and soil fertility degradation. The legumes used in our trial were selected by the majority of farmers for testing in the LegumeCHOICE project (Duncan et al., 2016).

The slope length experiment (SLE) aimed to assess the critical slope length to balance trade–off in runoff, erosion and yield in a maize–common bean intercrop system.

3.1.1 Legume groundcover experiment

The LGE site was located at latitude 0°46′21″ South and longitude 34°36′12″ East at an altitude of 1432 m.a.s.l. on approximately 20% slope gradient on an Acrisol (Table 1). Prior to this study the site had been managed under maize–common beans intercropping for five years. The LGE was monitored during the LR 2016, SR 2016 and LR 2017.

Plots were laid out in a randomized complete block design (RCBD) with three replicates of five treatments (Fig. 3). Each treatment plot measured 12 × 6 m, with a bounded plot of 12 × 4 m inside. The remaining 12 × 2 m plot area were used for biomass sampling at flowering/tasselling stages which could not be carried out inside the runoff plots due to its destructive nature. Plots were 2 m distant from each other. The five treatments were (Table 2): T1) *Mucuna pruriens* (Muc); T2) *Lablab purpureus* (Lab); T3) *Arachis hypogaea* (Gnt); T4) *Zea mays–Phaseolus vulgaris* (MzBn) intercrop; and T5) *Zea mays–Phaseolus vulgaris* intercrop with 5 Mg/ha *Calliandra calothyrsus* leaf mulch amendment (Mul) corresponding to about 2 cm mulch layer. Treatments were chosen to cover different legume types–grain

(Gnt), forage (Lab), tree (Mul) and cover (Muc) legumes. Farmers' practice of MzBn was selected as control. *Calliandra* shrubs are commonly planted as hedgerows and used as feed for livestock. *Calliandra* was established using seedlings in T5 across the slope during the SR 2016 (seedlings were not available during the LR 2016); *Calliandra* leaf mulch was imported and added between harvest and sowing of crops. The spacing for MzBn in T5 was not altered when *Calliandra* hedgerows were introduced. All legume species and maize were sown using the local recommended plant population (Table 2) and received a basal fertiliser dressing. Only maize was top dressed (see Table 2 for dates and rates). Fifty percent of harvested crop residues were retained on each respective individual plot and spread uniformly after harvest. Before installation plots were ox ploughed, while subsequent land preparations were done by hand hoeing as the bounded plots could not be accessed with a plough. Weeds in MzBn, Gnt and Lab were controlled by hoeing and the frequency depended on the type of cropping system. A minimum of two weeding events were conducted seasonally. *Mucuna* was not weeded, and weed control on the mulch plots was done by hand to ensure minimum disturbance of the mulch layer. Photos of field lay–out with erosion fence and crops are shown in Figure 4 below.

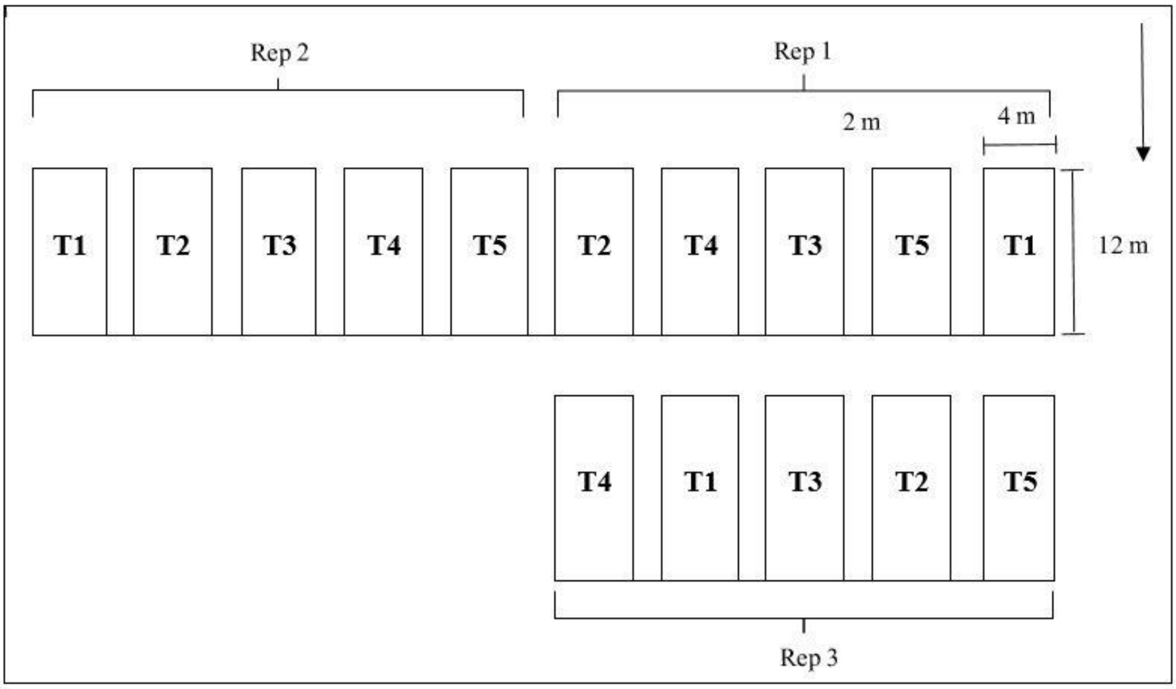

Figure 3. Design showing lay–out of LGE experimental plots. Treatments T1, T2, T3, T4 and T5 are Muc, Lab, Gnt, MzBn and Muc respectively. Arrow shows slope direction.

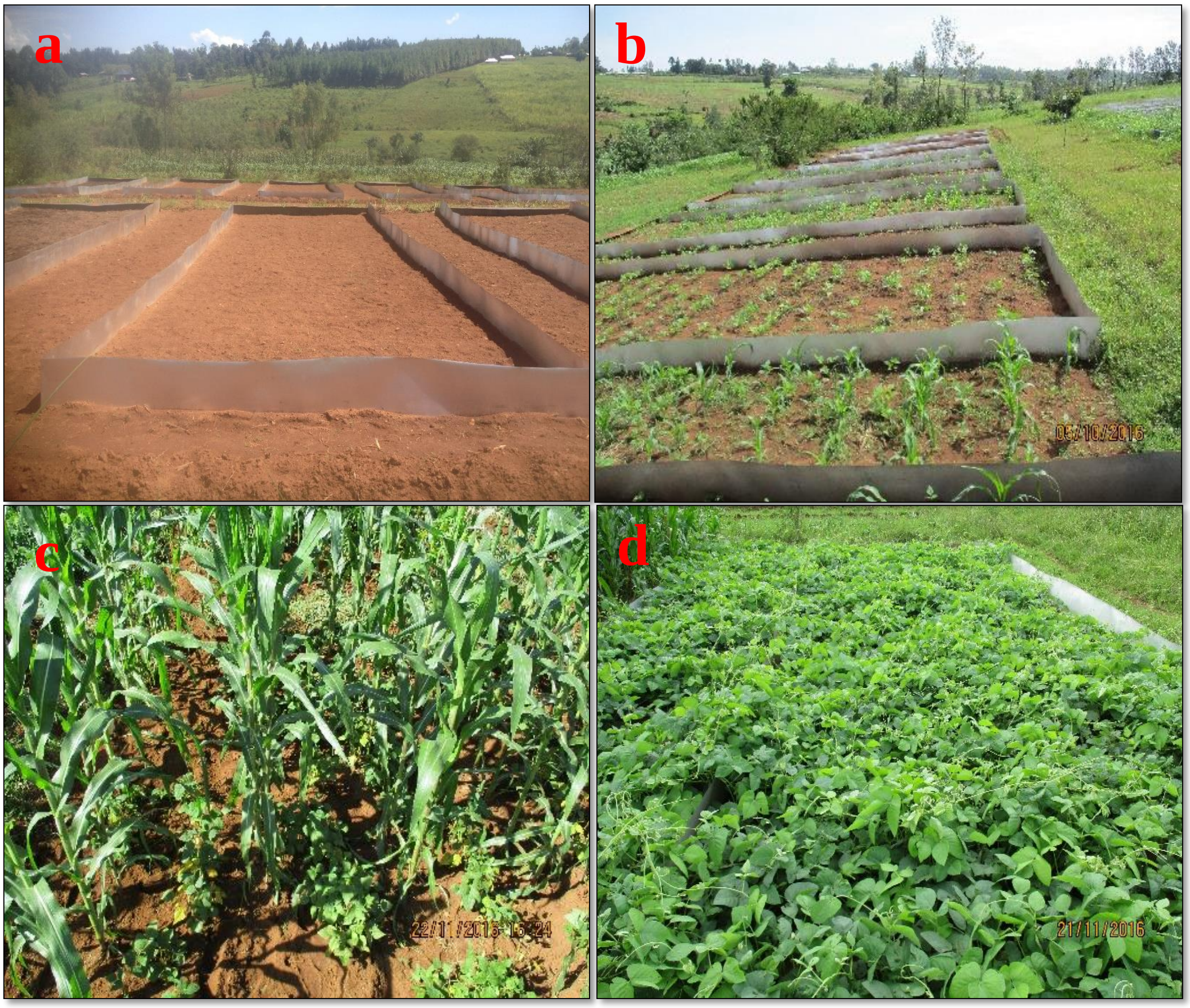

Figure 4. LGE experimental plots showing: a) plots after land preparation; b) crops at emergence stage; c) farmer practice (MzBn) at vegetative stage; d) Mucuna at vegetative stage.

Table 1. Top and sub–soil characteristics in the legume ground cover experiment on a 20% slope (n = 3).

Depth	**pH**	**Org C**	**Tot N**	**C/N ratio**	**BD**	**Avail P**	**Avail K**	**Sand**	**Silt**	**Clay**
(cm)	[]	----- [%] ------		[]	[Mg m^{-3}]	[mg kg^{-1}]	[cmol 100g^{-1}]	-------- [%] ---------		
0–20	4.75	0.99	0.10	9.9	1.32	0.89	0.02	63	12	25
20–40	4.86	0.86	0.09	9.9	1.41	0.12	0.02	56	13	31

Table 2. Spacing and fertilizer application rates per treatment for the legume ground cover experiment. Basal dressing with diammonium phosphate (18% N, 46% P_2O_5) at planting. Top dressing 28 days after planting with calcium ammonium nitrate (27% N).

Treatment	Spacing [m]	Basal dressing [kg/ha]	Top dressing [kg/ha]
1. *Mucuna pruriens,* Muc	0.5 × 0.2	50	None
2. *Lablab purpureus,* Lab	0.5 × 0.2	50	None
3. *Arachis hypogaea,* Gnt*	0.45 × 0.15	50	None
4. Common Beans in MzBn	0.75 × 0.2	50	None
Maize in MzBn	0.75 × 0.3	100	50
5. Common Beans in MzBn, Mul	0.75 × 0.2	50	None
Maize in MzBn, Mul	0.75 × 0.3	100	50
Calliandra in Mul	4.0 × 0.5	None	None

*Gnt was intercropped with maize during the SR 2016

3.1.2 Slope length experiment

The SLE assessed runoff and erosion in a maize–common bean intercrop system under three different slope lengths (SL). These were established on three farms with slightly different slope gradients (Table 3) within the watershed (Fig. 1). Farm 1 (F1) in particular contained a high amount of sand with relatively higher stone content and bulk density than farms 2 and 3. The selected farmer plots were representative of the smallholder landholding slope lengths in the area, and had been planted to maize–common bean intercrop systems for more than five years. Farm 1, 2 and 3 were located at 1462, 1486, 1495 m.a.s.l, altitude and slopes were 14, 10 and 11%, respectively. Bounded slope length plots measuring 20 (SL20), 60 (SL60) and 84 m (SL84) × 4 m were replicated twice per farm and planted to MzBn as in the previous trial (Fig. 5). Plots were installed a week after ox–ploughing downhill at the beginning of the LR 2017 (Fig. 6). Planting days slightly differed between farms, but all plots were sown before the rains started. Runoff and sediment loss were measured for all major rainfall events that generated runoff during the entire cropping season of the LR of 2017.

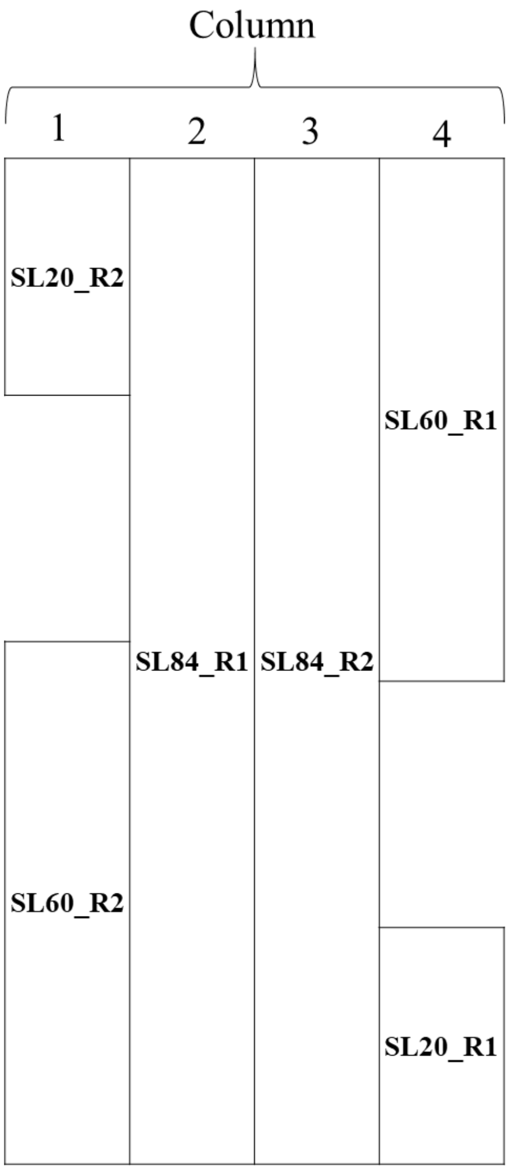

Figure 5. Design showing lay–out of slope length (SL20, SL60 and SL84 are slope lengths 20, 60 and 80 m respectively) plots on farm 2 (F2). R is replicate and 1, 2, 3, 4 are columns.

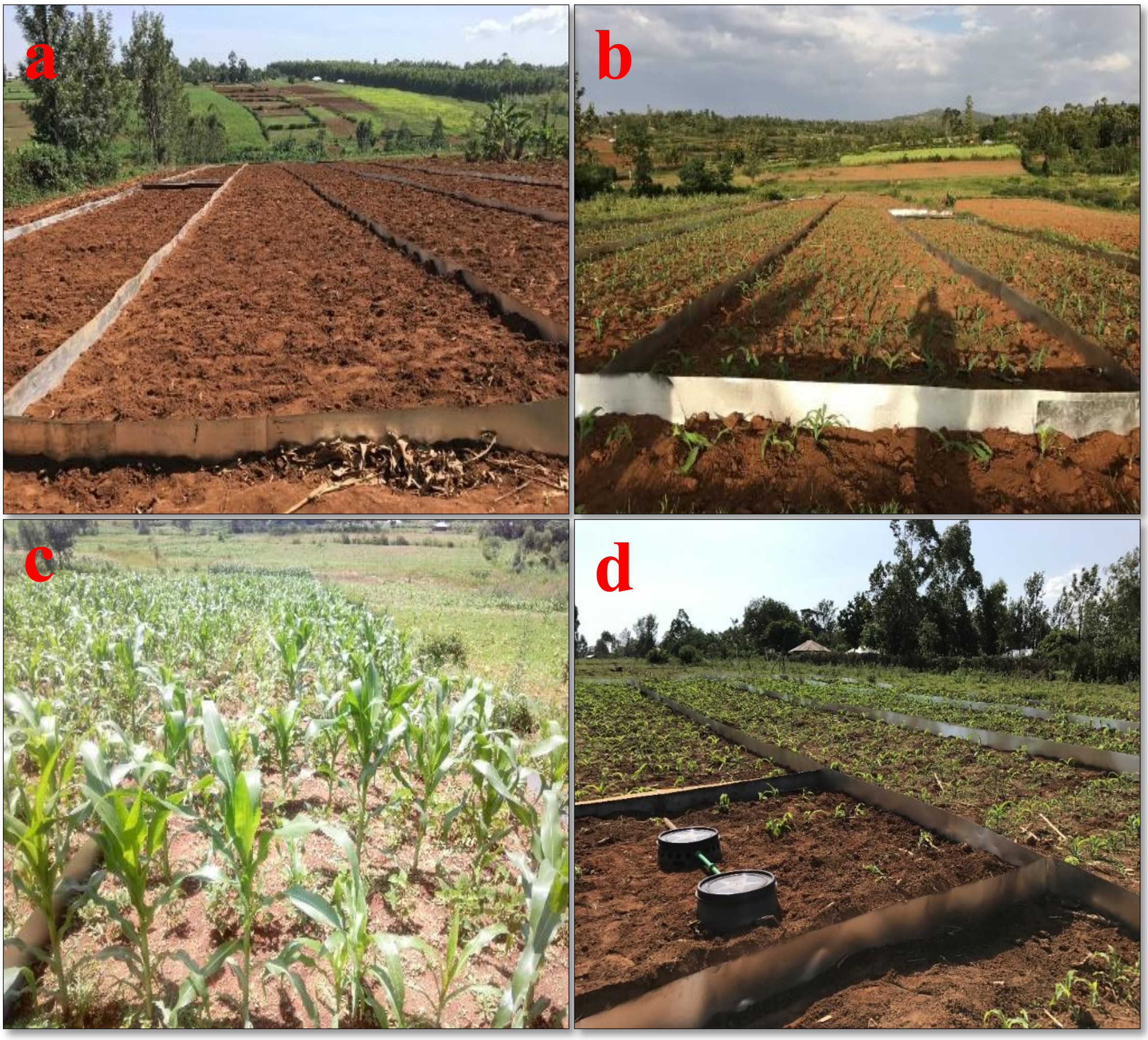

Figure 6. SLE experimental plots showing: a) plots after land preparation; b) MzBn at emergence; c) MzBn at vegetative stage; d) Sediment collection.

3.1.3 Soil transect survey

A soil survey was conducted in Rongo watershed during the 2016 LR. The objective was to outline and describe how the present land use, soil types, cropping systems and vegetation were distributed and managed in the landscape. Two transects E-W and N-S were defined and participatory transect walks were implemented with an extension officer, farmers and researchers from KALRO. Printouts of google maps of the landscape aided this. Soil samples were collected along each defined transect at 50–100 m intervals. Top and subsoil samples were extracted from auger cores based on the genetic soil horizon. Three topsoil sub-spot samples were composited into one sample for each spot; the same was done with subsoil samples. Additionally, profile pits of width 2 m were dug per genetic horizon where the auger sampling showed distinctive or representative soil characteristics. These were to aid the development of a soil map.

Table 3. Site and top soil (0–20 cm) characteristics on the slope length plots (farms).

Farm	Slope gradient [%]	Slope position	pH	Total C	Total N	C/N ratio	Avail P	Avail K	Bulk Density	Sand	Silt	Clay
			[]	------- [%]	--------	[]	[mg kg^{-1}]	[cmol 100g^{-1}]	[Mg m^{-3}]	----------	[%]	-----------
1 (n=2)	14	Upper	4.54	0.41	0.03	13.7	4.0	0.038	1.39	79	8	13
1 (n=2)		Lower	4.52	0.46	0.03	15.3	4.5	0.028	1.45	82	5	13
2 (n=2)	10	Upper	5.17	0.92	0.05	18.4	7.3	0.049	1.12	69	7	24
2 (n=2)		Lower	5.21	0.65	0.06	10.8	7.8	0.030	1.16	77	2	21
3 (n=2)	11	Upper	5.35	0.79	0.06	13.2	6.4	0.028	1.10	67	11	22
3 (n=2)		Lower	5.24	1.29	0.10	12.9	8.4	0.042	1.08	54	19	27

3.2. Field measurements

3.2.1. Soil sampling for field characterization

Soil samples were collected from each farmer plot prior to installation of the experiment. For the LGE, each experimental plot (12 × 4 m) was divided into grid cells of 4 × 4 m, and samples were augered from the middle of each cell at two soil depths (0–0.2 and 0.2–0.4 m). For the slope length study, plots were divided into upper, middle and lower slope subplots. The subplots were further divided into 4 × 4 m grid cells for sampling and for detailed slope measurements to derive slope curvature (Table A1 in appendix). Nine top and sub–soil samples, respectively, were bulked into one sample per subplot. Additionally, a profile was dug at the middle of the LGE site for detailed description (Table A2 in appendix). Samples were air–dried, sieved through a 2 mm screen and ball milled for wet chemical analysis. Soil pH was measured in 0.01 M $CaCl_2$ with soil: extraction solution ratio of 1:2.5 using an inoLab1 Labor–pH–Meter, WTW GmbH, Weilheim, Germany. Total C and N were measured by dry combustion using Flash EA 1112 Elemental Analyser, Thermo Fisher Scientific. Available P was determined by Bray 1 with a Beckman coulter Du, UV–Du 640 spectrophotometer. Plant available K was analysed by Calcium–Acetate–Lactate–extraction method using ICP–OES (Agilent 5100). Soil texture was determined by the pipette method (Böttcher, 1996), after removal of organic matter with 35% hydrogen peroxide and dispersion by agitating the sample in 200 ml of 0.05 M ammonium hydroxide.

3.2.2. Meteorological monitoring

Automatic weather stations were positioned next to legume groundcover and slope length fields to monitor rainfall, air and soil temperature, relative humidity, solar radiation and wind speed and direction. Rain gauges were set to ten minutes and other devices to hourly logging interval. Rainfall was manually measured from April to July in 2017 due to breakdown of the rain gauges. One of the rain gauges was positioned near farms 2 and 3, which were adjacent

(Fig. 1). The other was on the LGE plot, closer to Farm 1 (about 100 m away) and less than 500 meters away from farms 2 and 3. The rainfall measuring device comprised of a tipping bucket rain gauge (MD532–HOBO, UP GmbH, Germany) connected to a logger (HOBO–UA 003–64 Pendant, Onset Computer corp., USA). The rainfall intensity summarization tool (RIST) version 3.6 (Dabley and Justice, 2012) and the equation of McGregor *et al*., (1995) were used to calculate storm kinetic energy (EI_{30}):

$EI_{30} = 1099[1 - 0.72^{-1.27i}]$ …………… [Eq1]

Where, i is maximum intensity of 30 min. The kinetic energy of the rainstorms occurring on each day was summed to obtain daily kinetic energy, E. A Decagon DS–2 sonic anemometer, VP–3 humidity/air temperature sensor, and an RT–1 soil temperature sensor were connected to a data logger (Decagon EM50). Recordings were averaged to obtain representative daily data for over two years (2015–2017).

Historic precipitation data of the study region was accessed from the NASA Prediction of Worldwide Energy Resources (POWER). NASA POWER meteorological parameters are based on a single assimilation model from Goddard's Global Modelling and Assimilation Office (GMAO). The data was extracted using GPS coordinates of the study sites from https://power.larc.nasa.gov/data-access-viewer/.

3.2.3. Runoff and sediment

Bounded erosion plots for runoff and soil loss measurements were delineated with iron metal sheet inserted 20 cm deep into the soil and 30 cm left above the ground surface. A triangulated head was adjoined to the iron sheets at the lower plot end and directed into collection tanks through a 1 m long steel pipe (50 mm internal diameter). Soil loss and runoff water were collected after each rainfall. For LGE, each tank (100 L) was levelled and six holes of 2.5 cm diameter each were created equidistant from the bottom at a height of 95 cm. A polyvinyl pipe (2.5 cm diameter) connected one of the splitters to a second tank. The splitters were connected because it was not possible to collect all potential runoff from the plot. For the SLE, each tank measured 210 L with nineteen holes of 2.5 cm diameter equidistant from the bottom at approximately 140 cm height. The volume of runoff was measured by emptying the tanks into a calibrated bucket to determine the volume. For the splitter tank, the volume of runoff water measured was multiplied by the number of splitters. After collection of runoff water the wet sediments were weighed. Where > 0.5 kg of sediment had been collected during an event, an aliquot of 0.5–1 kg fresh material was dried and further processed to calculate the dry weight in kg ha^{-1}. For the slope length study, measured runoff, soil loss and sediment load apart from their absolute values were also expressed in relative terms using averages on experimental plots as reference. Sediment load (kg ha^{-1} mm^{-1}), which measures the amount of sediment transported by runoff water was computed as the ratio of soil loss to runoff (Lal, 1997). The relative soil loss under different SL's by example was calculated using equation 2.

$$R_{Sloss} = \frac{Sloss_{SL}}{Sloss_{\mu SL}} \text{.........[2]}$$

Where, R_{Sloss} is relative soil loss, $Sloss_{SL}$ is soil loss under different SL's, and $Sloss_{\mu SL}$ is mean soil loss under the different SL's.

Sediment samples were also collected during the 2016 LR and SR seasons to be analysed for C and N loss, and texture by MidDRIFTS as described in Demyan et al. (2012) after every rainfall event. 148 soil, eroded sediment (roughly 600) and 120 samples from the soil transect survey were air–dried, sieved (<2 mm) and ball milled for MIRS analysis. Calibration and validation (test set approach) were performed on the 148 top and subsoil samples collected at different locations of the watershed. The 148 soil samples were subjected to wet chemical analysis of pH, C, N, and texture. Proceeding to MIRS analysis, subsamples of the ball milled soil were scanned on a Tensor–27 mid–infrared spectrometer (Bruker Optik GmbH, Ettlingen, Germany) equipped with a gold (Au) beam splitter and a liquid nitrogen cooled mid–band mercury-cadmium-telluride detector. Three replicates from each ball milled subsample were scanned by combining 16 individual scans at a resolution of 4 cm^{-1} to obtain spectra in the mid–infrared range (4000–600 cm^{-1}). The spectra were further pre–processed in OPUS version 6.5 software package (Bruker Optik GmbH, Ettlingen, Germany) to eliminate noise at both edges of each spectrum, and to exclude regions that did not contribute to the actual soil spectra. All three replicate scans per sample were averaged and later subjected to multivariate calibration using partial least square regressions (PLSR). The derived PLSR calibrated model evaluated on accuracy by residual prediction deviation (RPD), coefficient of determination (R^2) and root mean square error (RMSE) was used to predict pH, C, and N of the eroded sediment samples.

The C and N enrichment ratio (ER), a measure of nutrient accumulation in sediment relative to the topsoil, (Hashim et al., 1998) was computed by equation 3.

$$\mathrm{ER} = \frac{\text{nutrient concentration in sediment}}{\text{nutrient concentration in topsoil}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{[Eq3].}$$

3.2.4. Aggregate stability, bulk density and infiltration

Aggregate stability, bulk density and infiltration were evaluated from the plot areas before ploughing and on all individual treatment plots before harvest per season. For both LGE and SLE, samples (3 replicates each) were collected from upward, middle and bottom positions.

Aggregate stability was measured following the flat sieve method (Cole, 1939) Undisturbed soil cores were collected using a spade from 0–20 cm soil depth. Samples were sealed in polyethylene bags and transported to the laboratory to determine the dry and wet stability of the soil aggregates by dry and wet sieving, respectively. Soil samples were air-dried at room temperature for 48 hrs. Plant roots and stones were removed from the samples. For dry sieving, four different sieves of mesh sizes 5, 4, 2, and 1 mm were used. Weighed soil (100 to 900 g) samples were passed through the nested sieves by horizontal oscillations for 30 seconds. The distributed soil aggregates were collected separately on each sieve and weighed for determination of mean weight diameter (MWD, Eq. 4) and geometric mean diameter (GMD, Eq. 5).

For wet sieving, fifty grams of soil were placed in the nested sieves (5, 4, 2, 1, and 0.15 mm) and dipped into distilled water. The sieves were moved up and down for 2 minutes at 30 cycles/minute. Remaining material in each sieve was oven dried at 105 °C for 48 hrs and weighed for determination of water stable aggregate stability, WSA (Eq. 6) (Singh & Khera, 2009).

$$\mathrm{MWD} = \sum_{i=1}^{n} x w_i \text{ --- [Eq4]}$$

$$\mathrm{GMD} = \exp\left(\frac{\sum_{i=1}^{n} w_i \log x_i}{\sum_{i=1}^{n} w_i}\right) \text{ -- [Eq5]}$$

$$\mathrm{WSA} = \%\ \text{of soil aggregates} > 2.0\ \text{mm after wet sieving --------- [Eq6]}$$

Where x is the diameter of the aggregates corresponding to the sieve mesh, w_i is the ratio of aggregate weight per sieve to the sample total weight, and n is the number of sieves used for the separation.

Bulk density was measured using nine undisturbed 110 cm^3 cylindrical cores (Blake & Hartge, 1986) per experimental plot at 0-0.2 m depth before ploughing, and per genetic horizon of the profile pit. Samples were weighed and oven dried at 105^0C until constant weight. Bulk density was computed as the ratio of the oven-dried soil mass and the volume of the core.

Infiltration rate was measured during SR 2016 and LR 2017 before the cropping season started using a double ring infiltrometer (DRI) at the middle of each treatment plot for the legume cover study. Two concentric rings having inner and outer diameters of 30 and 60 cm, respectively, and 50 cm high were driven 10 cm into the soil. The water level in the rings was maintained under falling head conditions (Gregory et al., 2005). The water level in the outer ring was maintained at the same level as in the inner ring. A fall in water level in the ring was manually topped–up and the water ponding level was maintained between 5 and 20 cm (Reynolds et. al., 2002). A decrease in water level inside the inner ring was measured as a function of time, and the volume of water that infiltrated the soil during a given time was calculated from the diameter of the inner ring and the change in water level (Arriaga et al., 2010).

3.2.5. Profile curvature

Profile curvature measures the rate at which the slope surface changes in the direction of the slope or flow line (Peckham, 2011). It indicates the shape of the surface around the sample point on a curved slope. Positive curvature values show convex slope and negative indicate concave slope. Profile curvature was derived in PCRaster software (Schmitz et al., 2016) using elevation data measured on 4 x 4 m subplots of the SL plots. A moving window of 3 × 3 cells was used to calculate the scurvature of the central raster cell by referring to the elevation of its eight neighbours (Corripio, 2003; Tarolli et al., 2012). The nine elevation data points of the window were first approximated by a type of polynomial surface (Zevenbergen and Thorne, 1987; Florinsky, 1998; Hurst et al., 2012) from which the profile curvature values were derived.

3.2.6. Plant sampling

3.2.6.1. Groundcover

Groundcover by crops and weeds was measured by taking photos from 2.5 m above ground using a digital camera mounted on a pole and held perpendicularly to the ground (Tuan et al., 2014). Three images were taken per plot at upper, middle and lower slope, covering more than half of the plot area. These images were evaluated by ‘sample point’ image analysis software (ARS-USDA, 2011). Groundcover was assessed during tillage operations, one month after sowing (< 30% groundcover), mid–season (30 – 70% groundcover) and late growing season (> 70% groundcover). The mid–season coincided with flowering period, and so groundcover was assessed before and after every weeding operation (twice per season). Cover provided by fallen leaves and weeds was also estimated by the software and subsumed.

3.2.6.2. Above ground biomass and grain yield

Above–ground biomass (AGB) and maize grain yield of the LGE and SLE were measured at physiological maturity. For LGE, AGB and grain were collected from eight central rows, each crop measuring 3 m long. AGB and grain were harvested row–wise on 54 m^2 excluding border plants from the SLE plots and weighed in the field to obtain their fresh weight. Fresh subsamples of these materials were weighed and oven–dried at 60 ºC until constant weight to determine fresh/dry conversion factors.

3.2.6.3. Biomass partitioning, plant NPK and quality

Whole plant samples were harvested in replicates of three per treatment plot at two cardinal growth points (flowering and harvest) and partitioned into root, leaf, stem and seed. For biomass assimilate weights, each plant organ was oven dried at 60 °C until constant weight to obtain dry weights. The oven–dried samples were further ball milled for analysis of plant NPK content and plant quality (lignin and polyphenol) of the different plant organs. Plant NPK was measured using inductively coupled plasma mass spectrometry (ICP–MS), whereas, lignin and polyphenol were determined by Folin–Ciocalteu method (Makkar and Becker, 1993) (Table A5 in Appendix).

3.3. Data analysis

Experimental data on the effects of different legume ground cover and slope lengths on runoff, soil loss, maize grain and AGB yields, percent ground and canopy cover, bulk density, infiltration, aggregate stability, C and N loss in sediments and enrichment ratios were subjected to ANOVA using Statistical Analysis Software program SAS version 9.4 (SAS Institute, 2016). Prior to that the data was checked for normality and homoscedasticity on model residuals using quantile–quantile (Q–Q) plots, histograms and studentized residual plots. A linear mixed model was fitted in the SAS MIXED model procedure. The log base 10 transformation was used to transform runoff and soil loss data to achieve normality of the residuals. For the slope length study, randomized complete block design (RCBD) was specified with block factors: column nested within farm and slope length plots nested within column (see Fig. 4), and their interactions as random effects on the response variables (i.e. runoff, soil loss). Repeated measurements (events) of soil erosion within the fixed effects (i.e. slope length, rainfall, groundcover, gradient and profile curvature) were accounted for by fitting an error term with power model (SP (POW)) covariance structure to the data. A similar mixed model structure was fitted for the LGE with runoff and soil loss as response variables, and groundcover, canopy cover and EI_{30} as fixed effects. Models were selected using the Akaike Information Criterion (AIC). Statistical significance of all effects was assessed at a significance level of $p<0.05$ and treatment means were compared using the PDIFF option of the LSMEAN in SAS.

3.4. Modelling process

3.4.1. LUCIA model description

The LUCIA model is both a plot–level management and spatially explicit landscape–level tool for tropical watersheds designed to quantify key interactions between management practices, plant growth, water balance, erosion and soil (Marohn and Cadisch, 2011). We simulated biophysical processes in the context of smallholder landscapes capturing the impact of slope length related soil conservation on crop growth and soil degradation. LUCIA runs on a daily time step, and at user defined pixel size, usually reflecting average plot (slope length) size in a study area. The plant growth module in LUCIA is based on the WOrld FOod STudies (WOFOST, Supit, 2003) concept, and can simulate plant growth–management–soil interactions in legume–led rotations and intercropping systems. Infiltration is built on KINEROS 2 (Woolhiser et al., 1990), while the soil erosion module is based on the Rose concept of soil erosion (Rose et al., 2007), which considers runoff entrainment–driven soil erosion dominant over rainfall–induced soil detachment (Noordwijk et al., 2008; Marohn et al., 2013; Lippe et al., 2014; Liu et al., 2019). This study focused on simulation of different sowing dates and vegetative cultivar (of different maturity) as agronomic management strategies to enhance soil water use and increased grain yield production.

3.4.2 Baseline data preparation and parameterization

3.4.2.1 Spatial maps

LUCIA requires spatial land use, soil type, area, DEM and local drain direction (LDD) map as core inputs for spatially explicit simulation. The spatial maps were created in PCRaster Nutshell software (v.4.87a) at 4 × 4 m pixel size. DEM was derived using elevation data measured on 4 x 4 m subplots of the LGE plots. A soil map already existed for the region

(Wielemaker and Boxem, 1982) and was improved to a higher resolution using soil datasets collected from transects.

3.4.2.2 Crop parameters

Parameters related to plant growth of legumes (*Groundnut, Common bean*, *Mucuna* and *Lablab*) and *maize,* e.g. biomass and grain yield, biomass partitioning at flowering and maturity, plant N, P, K, lignin and polyphenol contents of different plant organs (leaf, stem, root and seed) at flowering and maturity etc. were obtained by field investigation (see above), analysed and manually entered in LUCIA. Additional data were taken from the database provided by LUCIA, existing validated models e.g. WOrld FOod STudies (WOFOST), Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) and Van Heemst et al., (1998).

3.4.2.3. Soil parameters

The main measured soil input parameters for LUCIA were taken from the LGE and SLE experiments. These were: soil thickness defined for two depths (top and sub–soil), texture (sand, silt and clay), stone contents, soil organic carbon (Corg), total nitrogen (Nt), mineral nitrogen (Nmin), plant available P and K, pH. Soil physical parameters were derived using pedo transfer functions by Saxton and Rawls (2006), e.g. bulk density, saturated hydraulic conductivity, total pore volume and volumetric water content at field capacity and permanent wilting point. Measured bulk density values were used to evaluate results of the pedotransfer functions.

3.4.2.4. Meteorological data

Meteorological model input variables including rainfall, air and soil temperature, relative humidity, solar radiation and wind speed and direction were monitored using automated weather devices that were stationed on the LGE and SLE plots as shown in section 3.2.2.

Additionally, evapotranspiration (ET) was calculated using ET calculator software version 3.2 (FAO, 2012). Reference evapotranspiration from meteorological data is assessed in the ET calculator software by means of the FAO Penman–Monteith equation. By specifying values of the available climatic data (air temperature, air humidity, wind speed, solar radiation) ET is computed.

3.4.3 Model calibration and validation

A pixel level (4 m × 4 m area) calibration and validation was used to derive a good fit between the measured and simulated parameters. Aboveground biomass (AGB) and grain yield of crops from the LGE study were used for model calibration and validation. Calibration and validation of AGB and grain yield were achieved by comparing their simulated and measured values. Measured parameters during the LR and SR 2016 were used for calibration whereas the LR 2017 parameters were used for validation. Soil, plant and weather data for the model parameterization are shown in Table A3–A6 in appendix.

3.4.4 Model performance

The performance of the model in adequately representing measured field data was assessed using model efficiency (EF, Eq. 7), coefficient of determination (CD, Eq. 8) and root mean square error (RMSE, Eq. 9) (Loague and Green, 1991). The EF indicates how good the model simulations are. An EF of 1 signifies a perfect 1:1 relationship between the simulated and observed values, and EF < 0 is an indication that the observed mean is a better estimate than the simulated outputs. The model is regarded as good fit if EF > 0.75, and 0.36 < EF < 0.75 as acceptable (Moriasi *et al*., 2007). Studies by Pansak *et al*., (2010) and Lippe *et al*., (2014) used an EF threshold of > 0.6 as minimum performance benchmark during LUCIA and

ERODEP calibration. The RMSE measures the error associated with the simulated values. RMSE value of zero indicates a perfect simulation or fit, and smaller RMSE signify simulated values closer to the observed (Hussein *et al*., 2007). CD measures the proportion of the variance of observed data explained by the predicted data. CD value of 1 indicates a perfect prediction fit. We used CD values between 0.5 and 2 to evaluate the success of our model calibration and validation.

$$EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad [Eq\ 7]$$

$$CD = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{\sum_{i=1}^{n}(P_i - \bar{O})^2} \qquad [Eq\ 8]$$

$$RMSE = \left(\frac{\sum_{i=1}^{n}(P_i - \bar{O}_i)^2}{n}\right)^{0.5} . \frac{100}{\bar{O}} \qquad [Eq\ 9]$$

Where n is the number of samples, mean of the observed data, P_i predicted and O_i observed values.

3.4.5 Model scenarios

Crop adaptation and mitigation to water stress management strategies using late planting (sowing late in the season due to delay in rainfall vs baseline), short duration crop varieties (varying the GDD at flowering and maturity) and drought scenarios would be tested together with prevailing climatic conditions for their impact on evapotranspiration (ET), grain yield production and water use efficiency (WUE) computed as a ratio of grain yield to ET. Thus, eight scenarios were tested in each of the three cropping seasons namely, 2016 LR and SR, and 2017 LR. Since a long dry spell was experienced during the 2016 LR in particular, the rainfall in this year may not represent the normal rainfall characteristics of the region. Historical rainfall data (1982–2019) accessed from NASA POWER satellite–based agroclimatological data was analysed to compare trends in the current measured rainfall data.

1. Baseline (farmers' practice) (BL)
2. Planting date one week late (PD1WL)
3. Planting date three weeks late (PD3WL)
4. Short duration crop 10 days < baseline (SDC10)
5. Short duration crop 30 days < baseline (SDC30)
6. SDC10 planted three weeks late (SDC10+PD3WL)
7. SDC30 planted three weeks late (SDC30+PD3WL)
8. No rainfall from 50–80th day after planting (NR50-80DAP)

The baseline represents farmers' practice of planting with the first rain, which is the beginning of each cropping season starting in March (e.g. March 4 for 2016) for the long rain and September (September 9 for 2016) for the short rain. The late planting dates in the alternative scenarios (PD1WL: 11. March and 16. September for 2016 LR and SR respectively; PD3WL: 25. March and 30. September for 2016 LR and SR respectively) were chosen based on the assumption that recent rainfall variability trends caused by climate change could delay seasonal rainfall in the region (Wainwright et al. 2019). There are already existing varieties of SDC e.g. maize (DH01: 70 to 90 days to physiological maturity; long stay green trait, drought tolerant, good level of tolerance to leaf blight, common rust and ear rot) and groundnut (ICGV–9991 locally called Nyaela: 60 to 75 days to maturity) with 30 days shorter in maturity than the BL cultivar e.g. maize (H516: 100 to 110 days to mature; good husk cover, very tolerant to logging, ear rot, rust and stem and leaf blight) and groundnut (KEN–GNUT1: 100 to 110 days to mature; mid–brown in color high in oil content tolerance to rosette disease) supplied by Kenya seed company limited (https://kenyaseed.com). The SDC10 variety is not in existence, however, there is a knowledge gap regarding what hybrids to use when planting date is delayed beyond the optimum window because of weather and soil constraints. The SDC10 could provide an alternative to the BL cultivar, especially if rainfall delays few weeks from the BL planting date. No rainfall from day 50 to 80 after planting was chosen on the assumption of coincidence with the flowering period of the crops, which has been shown to be a critical phenological stage that is vulnerable to drought stress.

Table 4 below gives a detailed summary of planting date and growing degree-day to flowering and harvest of the model scenarios. Simulated water stress under the baseline condition during the three cropping seasons is shown in Figure 7.

Table 4. Scenario runs to evaluate the impact of late planting, early maturity and climate change on grain yield, ET and WUE. Crops evaluated under the cropping systems were: Muc–mucuna, Mul–maize, Gnt–groundnut, MzBn–maize, and Lab–lablab. DOY-day of year, GDD-growing degree days, flow-flowering, harv–harvest. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

			2016 LR			2016 SR			2017 LR		
#	Scenario	Crop	Sowing date (DOY)	GDD flow [°C days]	GDD harv [°C days]	Sowing date (DOY)	GDD flow [°C days]	GDD harv [°C days]	Sowing date (DOY)	GDD flow [°C days]	GDD harv [°C days]
1	BL	Muc	63	750	1870	252	750	1870	423	750	1870
		Mul	63	700	1480	252	700	1480	423	700	1480
		Gnt	63	720	1635	252	720	1635	423	720	1635
		MzBn	63	700	1480	252	700	1480	423	700	1480
		Lab	63	720	1635	252	720	1635	423	720	1635
2	PD1WL	Muc	70	750	1870	259	750	1870	430	750	1870
		Mul	70	700	1480	259	700	1480	430	700	1480
		Gnt	70	720	1635	259	720	1635	430	720	1635
		MzBn	70	700	1480	259	700	1480	430	700	1480

		Lab	70	720	1635	259	720	1635	430	720	1635
3	PD3WL	Muc	84	750	1870	273	750	1870	444	750	1870
		Mul	84	700	1480	273	700	1480	444	700	1480
		Gnt	84	720	1635	273	720	1635	444	720	1635
		MzBn	84	700	1480	273	700	1480	444	700	1480
		Lab	84	720	1635	273	720	1635	444	720	1635
4	SDC10	Muc	63	700	1750	252	700	1750	423	700	1750
		Mul	63	640	1360	252	640	1360	423	640	1360
		Gnt	63	660	1510	252	660	1510	423	660	1510
		MzBn	63	640	1360	252	640	1360	423	640	1360
		Lab	63	660	1510	252	660	1510	423	660	1510
5	SDC30	Muc	63	600	1500	252	600	1500	423	600	1500
		Mul	63	525	1110	252	525	1110	423	525	1110
		Gnt	63	550	1260	252	550	1260	423	550	1260
		MzBn	63	525	1110	252	525	1110	423	525	1110

		Lab	63	550	1260	252	550	1260	423	550	1260
6	SDC10+PD3WL	Muc	84	700	1750	273	700	1750	444	700	1750
		Mul	84	640	1360	273	640	1360	444	640	1360
		Gnt	84	660	1510	273	660	1510	444	660	1510
		MzBn	84	640	1360	273	640	1360	444	640	1360
		Lab	84	660	1510	273	660	1510	444	660	1510
7	SDC30+PD3WL	Muc	84	600	1500	273	600	1500	444	600	1500
		Mul	84	525	1110	273	525	1110	444	525	1110
		Gnt	84	550	1260	273	550	1260	444	550	1260
		MzBn	84	525	1110	273	525	1110	444	525	1110
		Lab	84	550	1260	273	550	1260	444	550	1260
8	NR50-80DAP	Muc	63	750	1870	252	750	1870	423	750	1870
		Mul	63	700	1480	252	700	1480	423	700	1480
		Gnt	63	720	1635	252	720	1635	423	720	1635
		MzBn	63	700	1480	252	700	1480	423	700	1480
		Lab	63	720	1635	252	720	1635	423	720	1635

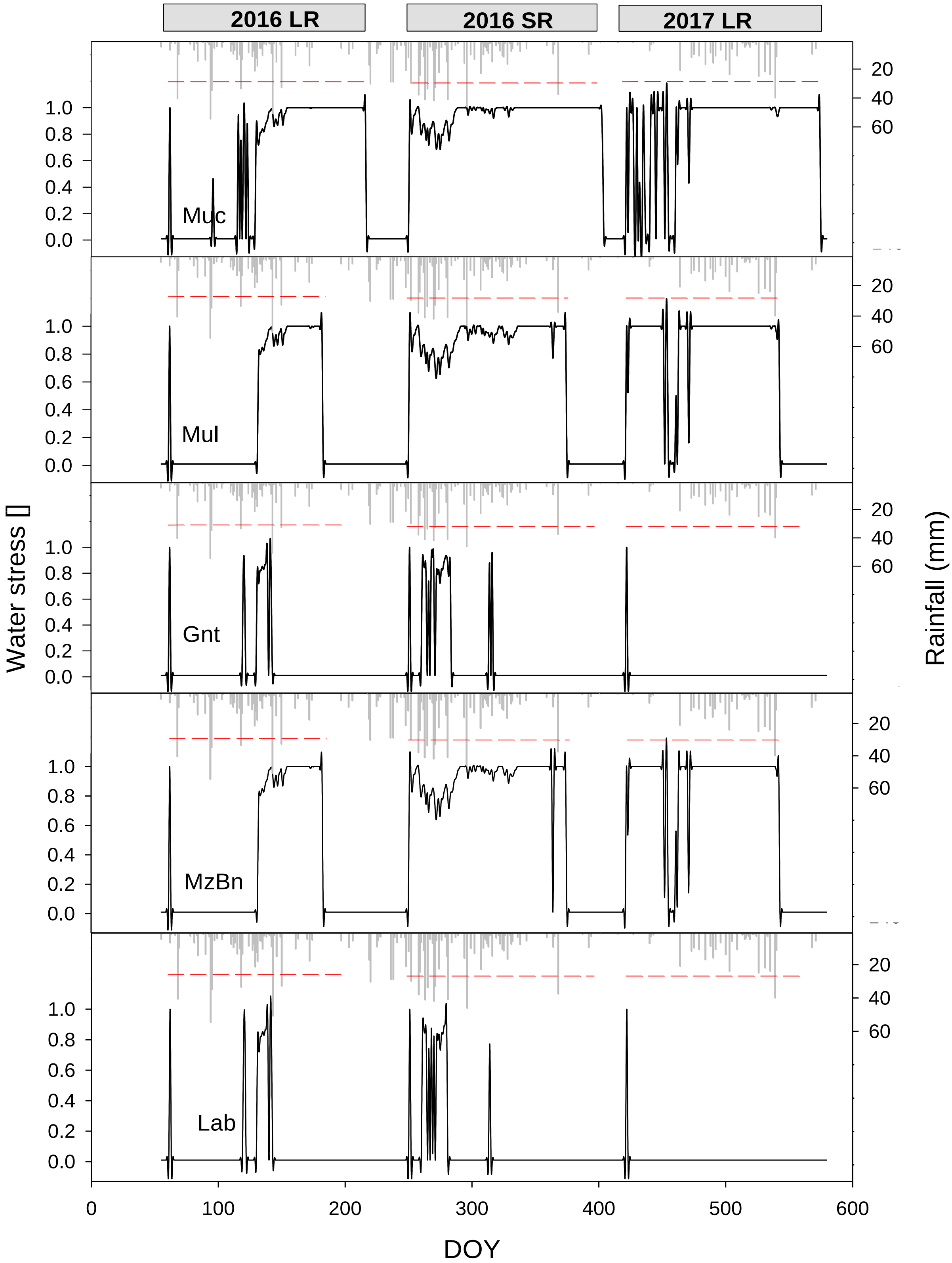

Figure 7. Simulated water stress by LUCIA model under different cropping systems for baseline (BL) cropping seasons LR, SR 2016 and LR 2017. Relative water stress is calculated as plant water supply over demand with 0 indicating maximum stress and 1 full supply. Rainfall is plotted as grey columns. Horizontal dotted line shows growing period per season for each crop.

The simulated water stress of Gnt and Lab was mostly zero (0). This was not observed on the field, but could be due to low biomass allocation in root, stem, leaf and harvestables. The allocated biomass to these various plant organs during parameterization and calibration was reasonable and fitted the simulated AGB and grain yield well to the measured values.

Chapter 4. Results and discussion

4.1. Effects of legume–led planting systems on runoff and soil erosion at the plot level

4.1.1. Results

4.1.1.1. Event–based runoff and soil loss dynamics under the different planting systems

The temporal evolution of event–based runoff and soil loss produced during the three cropping seasons is presented in Figs. 8 and 9, respectively. In the LR16, runoff was clearly lowest of all seasons and evenly distributed among events. Under Mul, runoff was always significantly lower than under all other treatments except for the last two events. The highest runoff occurred on event 7 (24.08.16) for all treatments except Gnt. Statistical spread was very low among replicates.

In the SR 16, runoff was highest of all the seasons with majority of the highest events occurring at the beginning of the season, whereas the lowest runoff events occurred at the mid and latter part. Runoff was still among the lowest, but not as clearly as in the LR 16, except after event 6. The statistical spread was high among the replicates with highest runoff and low among the events with lowest runoff.

The trend in the LR 17 was quite different from the previous two seasons. First, the season began with low runoff events, followed by high events, interspersed with periods of low and high runoff. Most of the lowest runoff events occurred under Mul. From event 8 onward the lowest runoff occurred under Mul and Muc to the end of the season. The highest runoff

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occurred mostly under Lab and Gnt, and MzBn at the latter part of the season. Again, the highest statistical spread occurred among the replicates with the highest runoff.

In contrast to runoff, soil loss started in the LR 16 with high occurrences for Gnt and MzBn. The lowest soil loss occurred under Mul except event 7 similarly to the runoff observations. The first low soil loss event in SR 16 contrasted the corresponding high runoff. Following that, high soil loss occurrences coincided with the high runoff events. From event 5 to the end of the season, low soil loss incidences corresponded to the low runoff amounts. The statistical spread among the replicates was very low for the low soil loss events.

In LR 17, soil loss amounts at the beginning of the season were low in accordance with the runoff dynamics. The highest soil loss occurred under event 7, which was also similar to runoff. However, soil loss was thereafter low to the end of the season, contrasting the intermixed low and high runoff dynamics. Soil loss was highest under Lab in most of the events, and lowest under Mul and Muc.

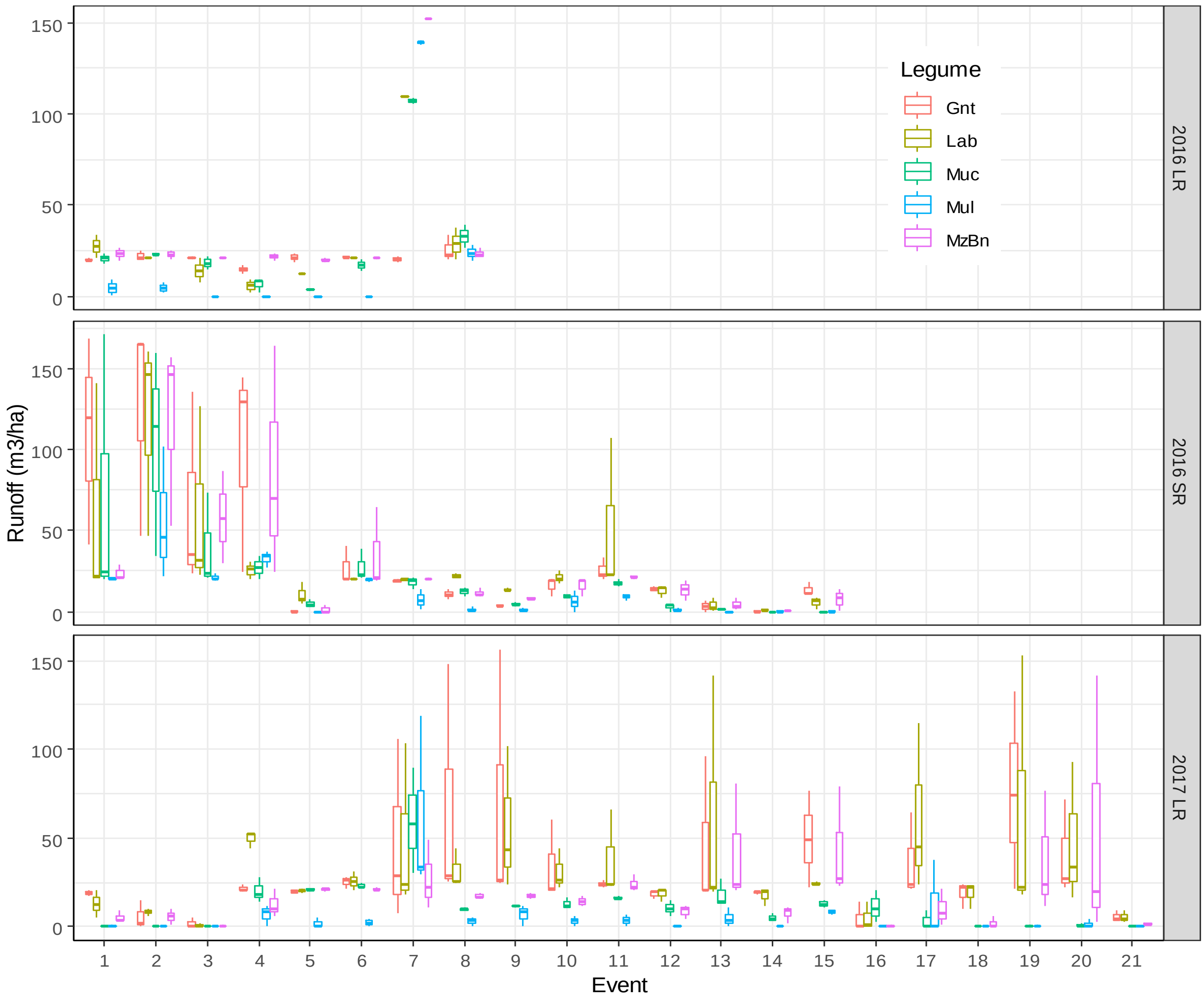

Figure 8. Event–based runoff under different cropping systems for cropping seasons 2016 long and short rain (2016 LR, 2016 SR) and 2017 long rain (2017 LR) . Error bars show standard deviation among replicates (n=3). Muc: Mucuna; Lab: Lablab; Gnt: Groundnut; MzBn: Maize common bean intercrop; Mul: MzBn under mulch.

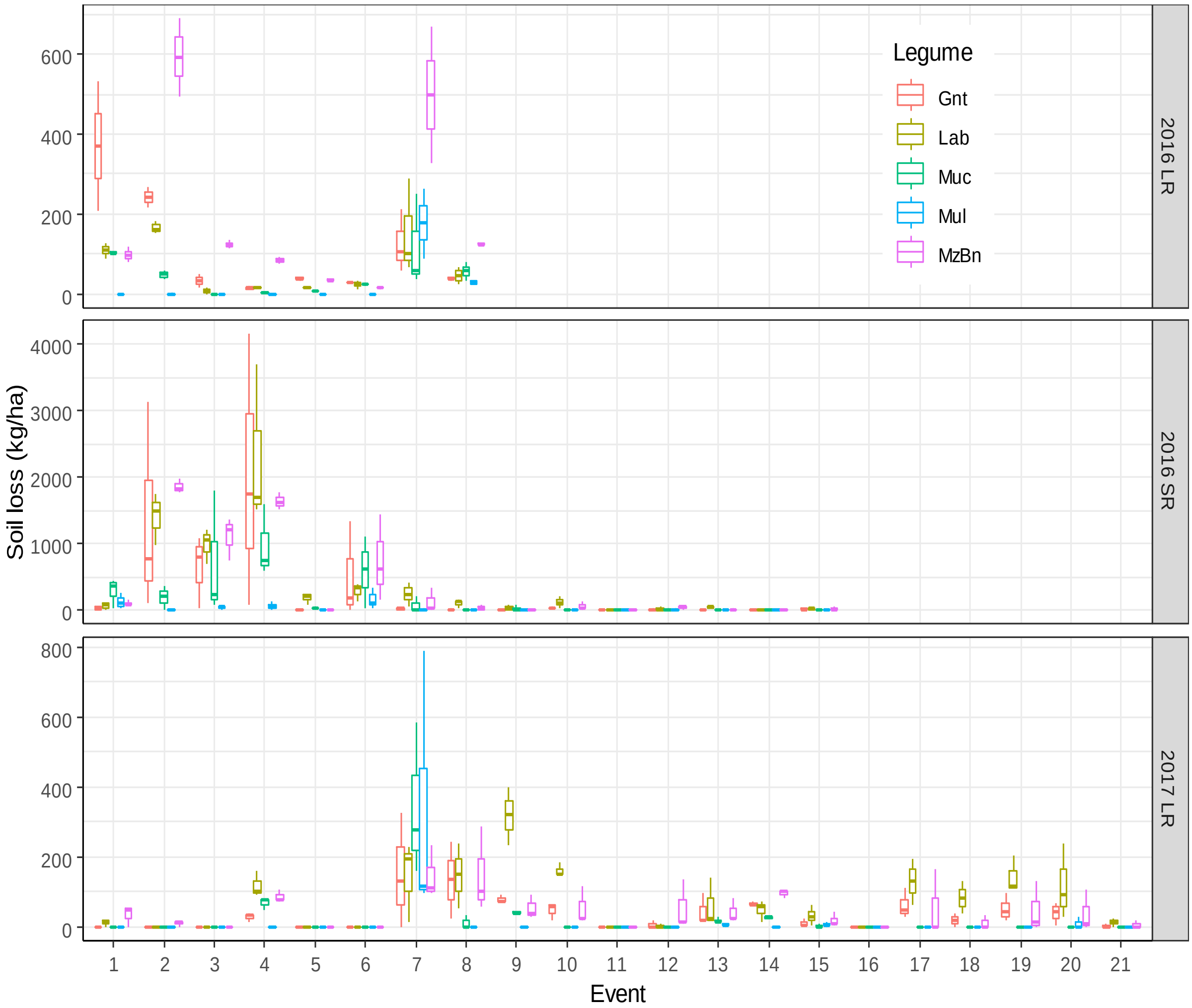

Figure 9. Event–based soil loss under different cropping systems for cropping seasons 2016 long and short rain (2016 LR, 2016 SR and 2017 long rain (2017 LR). Error bars show standard deviation among replicates (n=3). Muc: Mucuna; Lab: Lablab; Gnt: Groundnut; MzBn: Maize common bean intercrop; Mul: MzBn under mulch.

Seasonal cumulatives of the event data showed that in LR 2016 runoff under MzBn, Lab and Muc significantly exceeded Mul by 43, 28 and 25% respectively, whereas, soil loss under Muc, Lab, Gnt and MzBn increased by 86, 93, 95 and 97% respectively over Mul (Fig. 10). In the following season (SR 2016), Mul still proved effective in lowering runoff. Lab and MzBn showed increased runoff by 61 and 59% respectively over Mul, and soil loss under Lab, MzBn and Gnt significantly exceeded Mul by 92, 92 and 90% respectively. Lab and Gnt produced higher runoff over Mul in 2017 LR as well. Higher soil loss generation under Lab amounted to 77% increment over Mul.

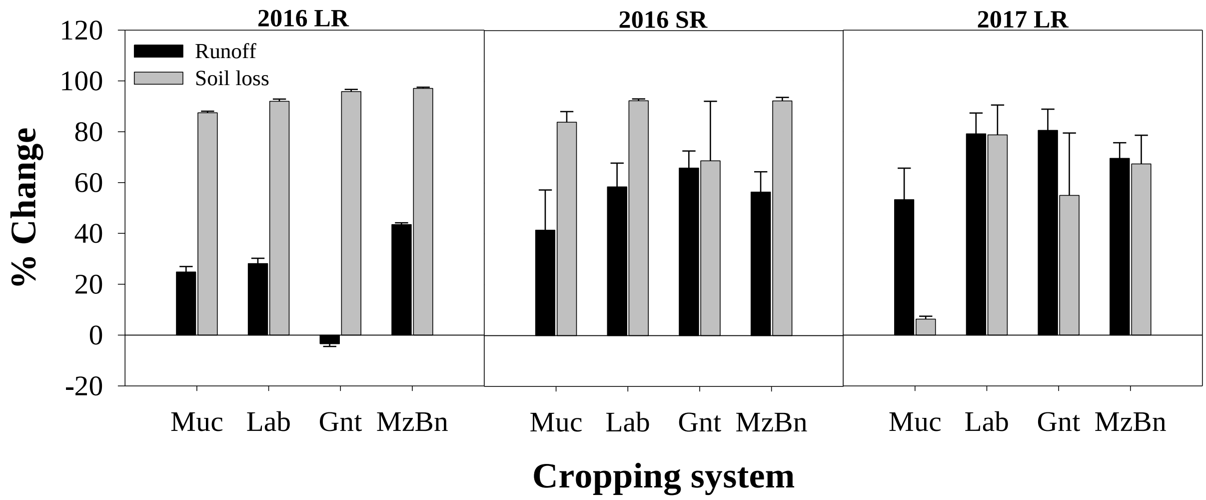

Figure 10. Runoff and soil loss (in %) by Mul relative to the other cropping systems. Muc: Mucuna; Lab: Lablab; Gnt: Groundnut; MzBn: Maize common bean intercrop; Mul: MzBn under mulch.

4.1.1.2 Impact of rainfall and groundcover on runoff and soil loss

Groundcover in the LR 2016 reached 15% for Gnt, 30% for Lab and 20% for MzBn, while vigorous Muc growth covered up to 70% by the end of the season (Fig. 11). As *Calliandra* leaves in Mul decomposed, cover decreased from 95 to 20% by the end of LR 2016. A dry spell from June to August 2016 generally hampered biomass and litter production leading to low cover. In the SR 2016 and LR 2017, under more propitious rainfall conditions, *Mucuna* reached up to 99% groundcover, followed by MzBn (79%), Gnt (45%), and Lab (20%) while the established *Calliandra* compensated for decomposition of mulch after the second month of establishment. In the last two seasons, most runoff and soil erosion occurred during intensive rain events when groundcover was low, particularly after land preparation. Furthermore, most of the runoff and soil loss also occurred immediately after weeding operations when the significant groundcover contribution by weed (4 to 45% groundcover; Fig. 11) was reduced.

Ranking of soil loss between treatments at the end of each cropping season reflected soil cover (Muc > Mul > MzBn > Gnt > Lab) except for MzBn which was highest in soil loss in LR 2016, and second highest in SR 2016 and LR 2017 despite relatively high ground cover.

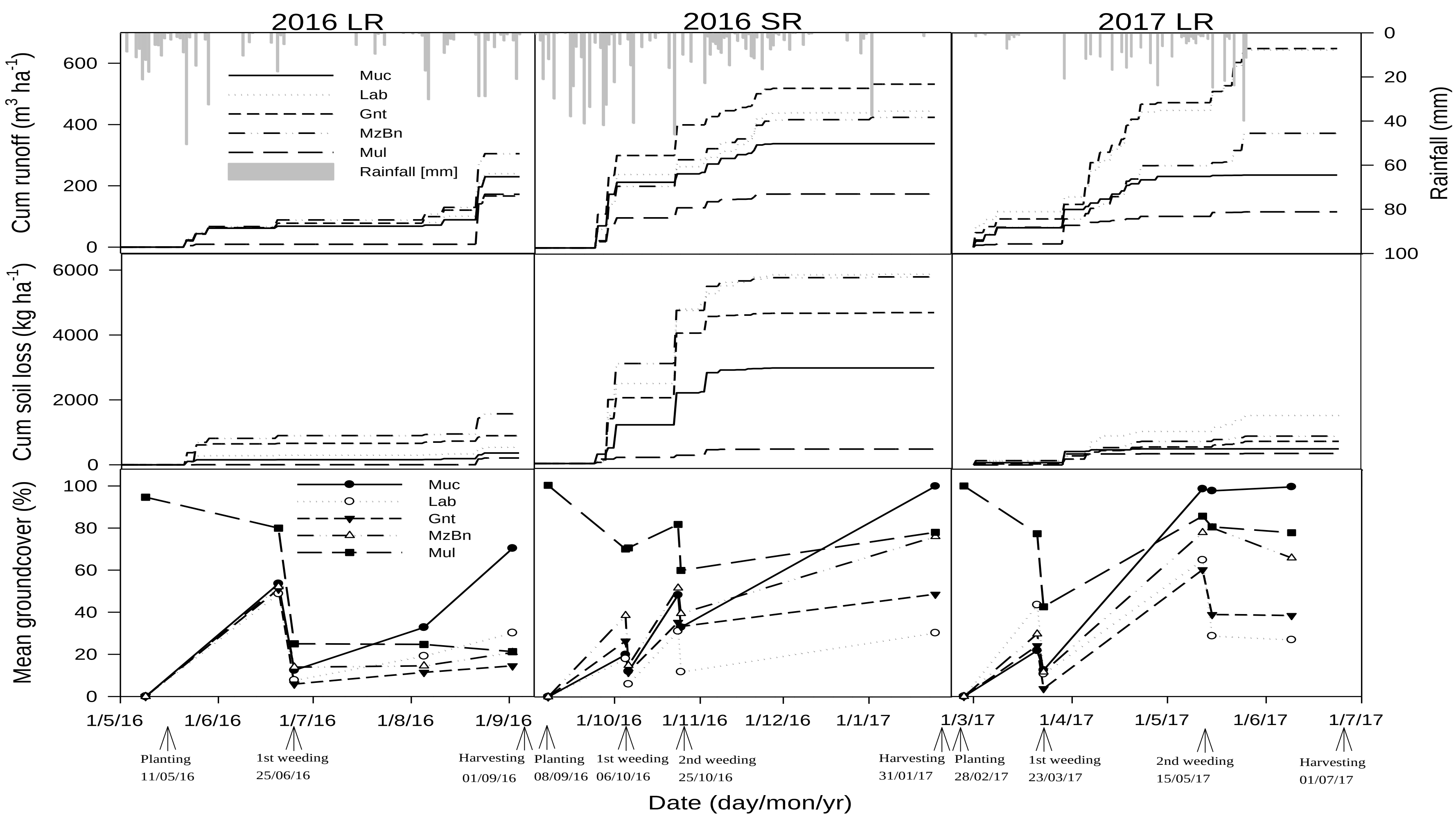

Figure 11. Daily rainfall, cumulative runoff and soil loss (n=3), and mean percent groundcover (n=3) with time under different plant cover for the LR and SR 2016, and LR 2017. Muc: mucuna; Lab: lablab; Gnt: groundnut; MzBn: maize-beans; Mul: maize-bean under mulch. Markers on the x-axis indicate weeding events.

4.1.1.3. Ground and canopy cover development under the different cropping systems

Looking at average ground (cover by plants, weed, mulch and litter) and canopy cover (cover by only plants) over all three seasons, both differed among the cropping systems ($p<0.05$) (Fig. 12). There were no differences among the cropping systems in canopy cover from emergence until flowering, while groundcover under Mul was significantly ($p<0.05$) higher due to the dead plant material mulched between the rows.

At flowering of maize as a reference plant, canopy cover under Muc was significantly ($p<0.05$) higher than for the other cropping systems except MzBn, and showed greater ($p<0.05$) groundcover among the cropping systems except Mul and MzBn. The mulch treatment showed significantly higher canopy cover than and the two attained significantly higher canopy cover than Lab and Gnt. Concerning groundcover, Mul was significantly higher than all except Muc. The growth in plant canopy at maturation revealed a similar trend as observed at flowering stage.

Ground and canopy cover increased further under all cropping systems from flowering to maturation, being higher ($p<0.05$) under Muc compared to the other cropping systems. No differences were found between groundcover of Lab and Gnt, and MzBn and Mul, but MzBn and Mul produced higher groundcover than Lab and Gnt. A significantly higher canopy coverage was reached under Muc at maturation, and this was followed by Mul and MzBn, which were similar but also significantly different from Lab and Gnt.

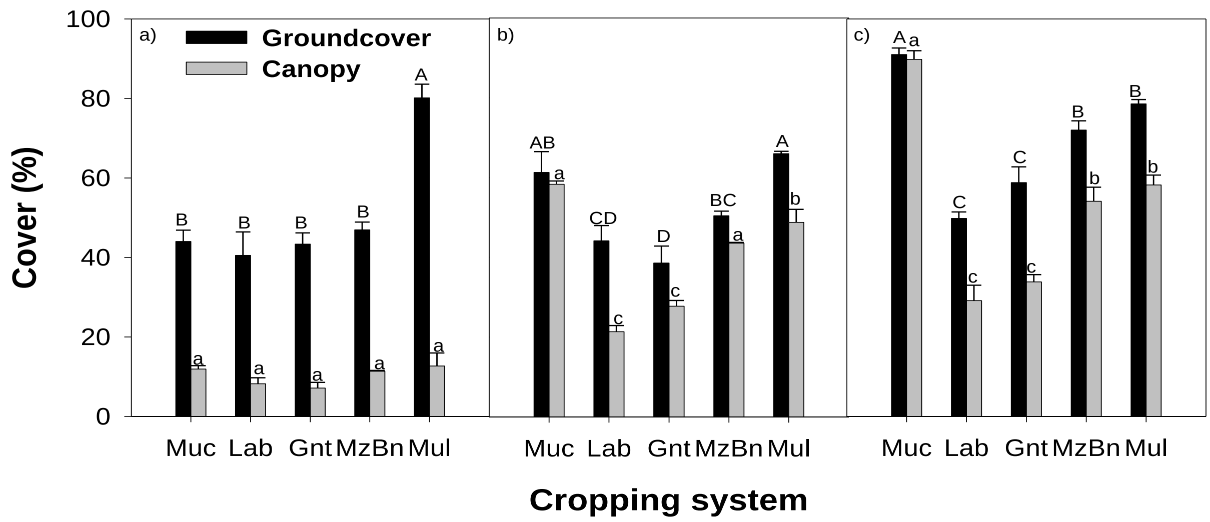

Figure 12. Ground and canopy cover of different cropping systems at different growth stages: a) Vegetative stage, b) flowering stage, c) maturation stage. Data presented as pooled averages of the three cropping seasons (LR, SR 2016 and LR 2017). Different letters stand for statistical significance ($p<0.05$). Muc: Mucuna, Lab: Lablab, Gnt: Groundnut, MzBn: Maize–common bean intercrop, Mul: MzBn under mulch. Error bars show deviation between seasons (n=3).

4.1.1.4 Assessing the relative impact of groundcover, canopy cover and rainfall intensity on soil loss

The trends in ground and canopy cover among the cropping systems were similar over all seasons. Evaluating the impact of groundcover, canopy cover and rainfall intensity (EI_{30}) on soil loss revealed that groundcover showed the strongest effect in the statistical model that best predicted soil loss, selected by AIC (Table 5). Rainfall erosivity showed relatively stronger effect than canopy cover.

Table 5. Influence of ground cover, canopy cover and rainfall intensity (EI_{30}) on soil loss (in log-transformed scale) in LR and SR 2016 as determined by a linear mixed model. Absolute magnitude of B-value indicates explanatory power, and sign indicates direction.

		Standardized coeff.		Confidence limit	
Dependent variable	Explanatory variable	*B–value*	St. error	Lower	Upper
Soil loss	(Constant)	1.7967	0.1383	1.4776	2.1158
	Groundcover [%]	-0.2229	0.0655	-0.3570	-0.0887
	Canopy cover [%]	-0.0480	0.0809	-0.2109	0.1148
	EI_{30} [MJ*mm/ha*hr]	0.1798	0.0859	0.0035	0.3560

4.1.1.5. Influence of different plant types on aggregate stability, bulk density and infiltration

Proportion of large dry aggregates (> 5 mm) was significantly higher under Mul than under Gnt, Lab and Muc at the end of SR 2016, while MzBn was intermediate (Fig. 13, left). For the smaller aggregate sizes, no significant differences were observed. Mean weight diameter (MWD) and geometric mean weight (GMW) of aggregates under Mul were significantly ($p<0.05$) larger than under Gnt. During both long rainy seasons, no significant differences were measured (Table A7 and A8 in appendix). No significant differences in water stable aggregate and structural indices were observed among cropping systems. Dominant aggregate size was 1–0.15 mm (Table A9 in appendix).

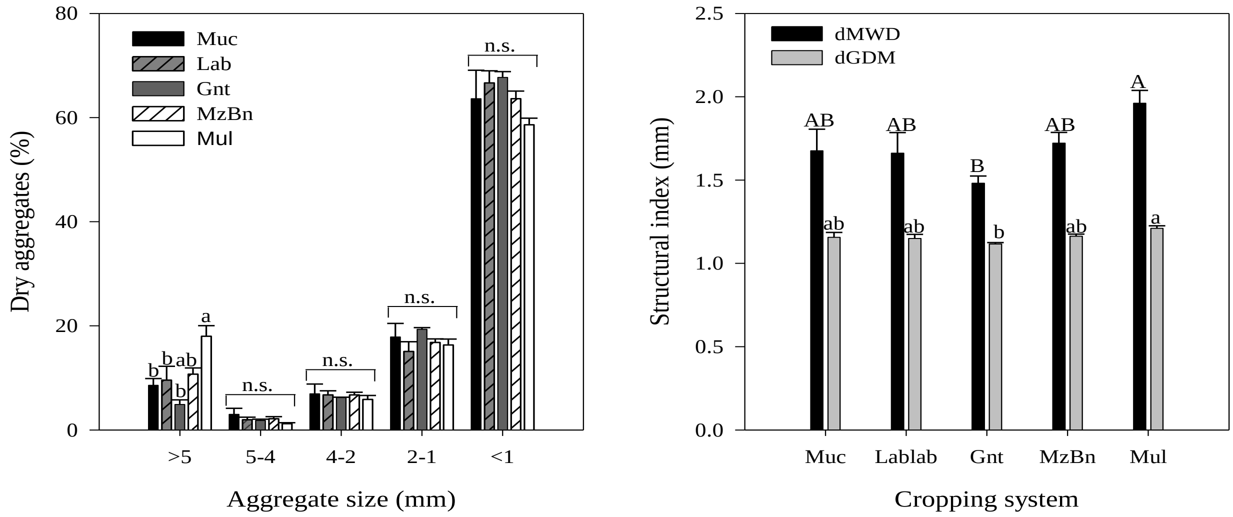

Figure 13. Effect of different legume cropping systems on dry aggregate size distribution (left), mean weight diameter (dMWD) and dry geometric mean diameter (dGMD) measured in SR 2016 (right) at the end of the season before harvest (n = 3). Muc: Mucuna; Lab: Lablab; Gnt: Groundnut; MzBn: Maize common bean intercrop; Mul: MzBn under mulch.

There was no significant ($p<0.05$) difference in soil bulk density among treatments at the end of the LR 2016, SR 2016 and LR 2017 cropping seasons (data not shown).

The impact of cover legumes on infiltration began to emerge in the LR 2017 when infiltration under Mul was significantly higher ($p<0.05$) than under Lab and Gnt (Fig. 14).

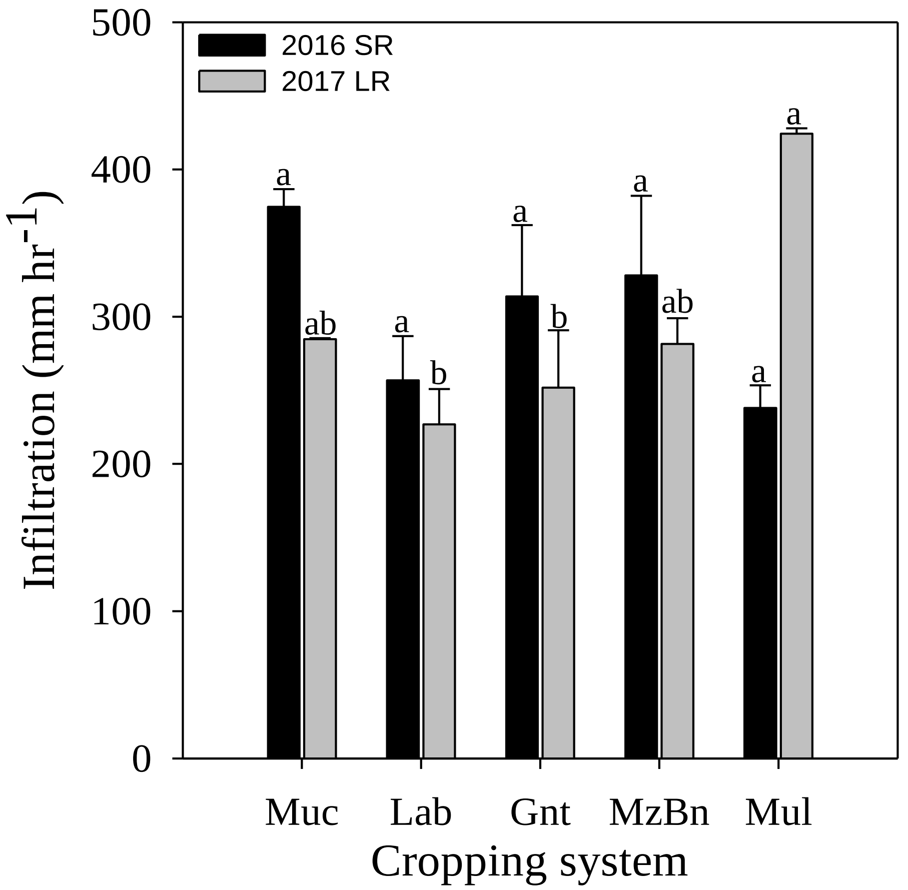

Figure 14. Effect of cropping system on infiltration rate in the SR 2016 and LR 2017, measured at the end of the cropping seasons prior to harvest. Different letters indicate significant differences between treatments at p<0.05 level. Infiltration was not measured in LR 2016. Muc: Mucuna; Lab: Lablab; Gnt: Groundnut; MzBn: Maize common bean intercrop; Mul: MzBn under mulch.

4.1.1.6 Sediment concentration, C and N content of sediments and enrichment ratio

Seasonal average sediment concentrations (the mass of sediment per volume runoff water in kg m^{-3}) in the SR 2016 generally exceeded those in LR 2016 (Fig. 15). The lowest sediment concentration for LR 2016 season was recorded under Mul (1 kg m^{-3}) and Muc (2 kg m^{-3}). But only Mul showed significantly lower sediment concentration (2 kg m^{-3}) than Lab (17 kg m^{-3}) in the SR 2016.

Total seasonal C and N losses in eroded sediments under Mul (0.74 kg C ha^{-1}, 0.07 kg N ha^{-1}) were significantly ($p<0.05$) lower than under Gnt (11.04 kg C ha^{-1}, 1.01 kg N ha^{-1}) and MzBn (15 kg C ha^{-1}, 1.31 kg N ha^{-1}) during LR 2016 (Fig. 15). Similarly, total seasonal C (3.90 kg C ha^{-1}) and N (0.33 kg N ha^{-1}) in eroded sediment were reduced under Mul in the following season (2016 SR) compared to Lab (88.41 kg C ha^{-1}, 7.98 kg N ha^{-1}) and MzBn (55.61 kg C ha^{-1}, 5.23 kg N ha^{-1}). Seasonal average C and N losses per erosion event (numbers of accounted events that generated run-off differed between treatments) ranged from 0.74 kg C ha^{-1} (Mul) to 3.20 kg C ha^{-1} (MzBn) and 0.07 kg N ha^{-1} (Mul) to 0.28 kg N ha^{-1} (MzBn), respectively, in LR 2016. In SR 2016, the average C and N losses ranged from 3.26 kg C ha^{-1} (Mul) to 9.82 kg C ha^{-1} (Lab) and 0.27 kg N ha^{-1} (Mul) to 0.88 kg N ha^{-1} (Lab) respectively. Adding up LR and SR 2016, annual carbon losses by soil erosion ranged between 5 (Mul) and 92 kg C ha^{-1} (Lab) and nitrogen losses between 0.4 (Mul) and 8 kg N ha^{-1} (Lab) per year.

Average C and N nutrient enrichment ratios exceeded 1, but showed no significant differences among the cropping systems (data not shown).

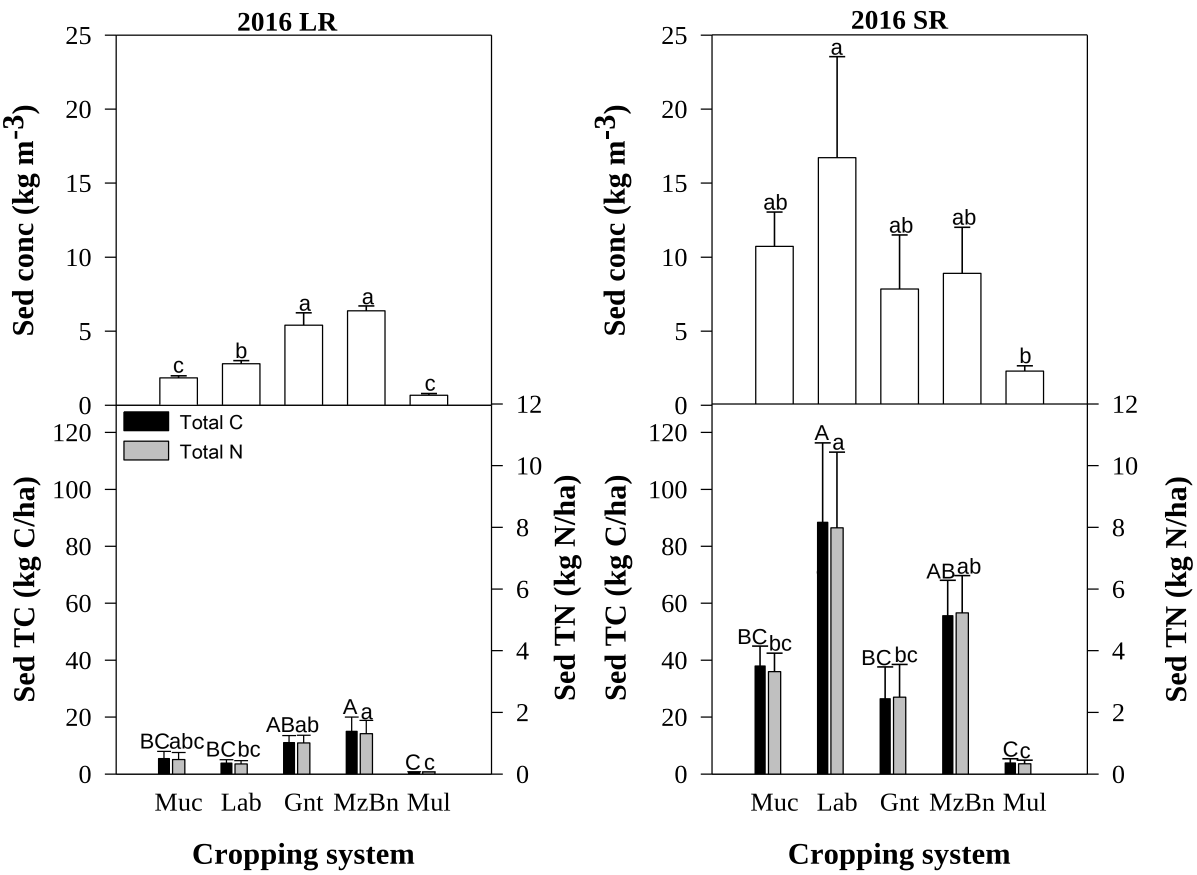

Figure 15. Average sediment (Sed) concentration and sediment total C and N under different cropping systems during the 2016 long and short rains. Muc: mucuna; Lab: lablab; Gnt: groundnut; MzBn: maize-common beans; Mul: maize-common beans under mulch. Columns with different letters are statistically different at p<0.05.

4.1.1.7 Above–ground biomass and crop grain yield

AGB was larger in the LR 2017 season than in the LR 2016 and SR 2016 (Fig. 16). There was no difference in AGB among treatments in LR 2016. In the SR 2016 season, Gnt produced the larger AGB than Lab and MzBn, while Lab produced the smallest. In the LR 2017 season, MzBn and Mul produced the largest AGB followed by Muc.

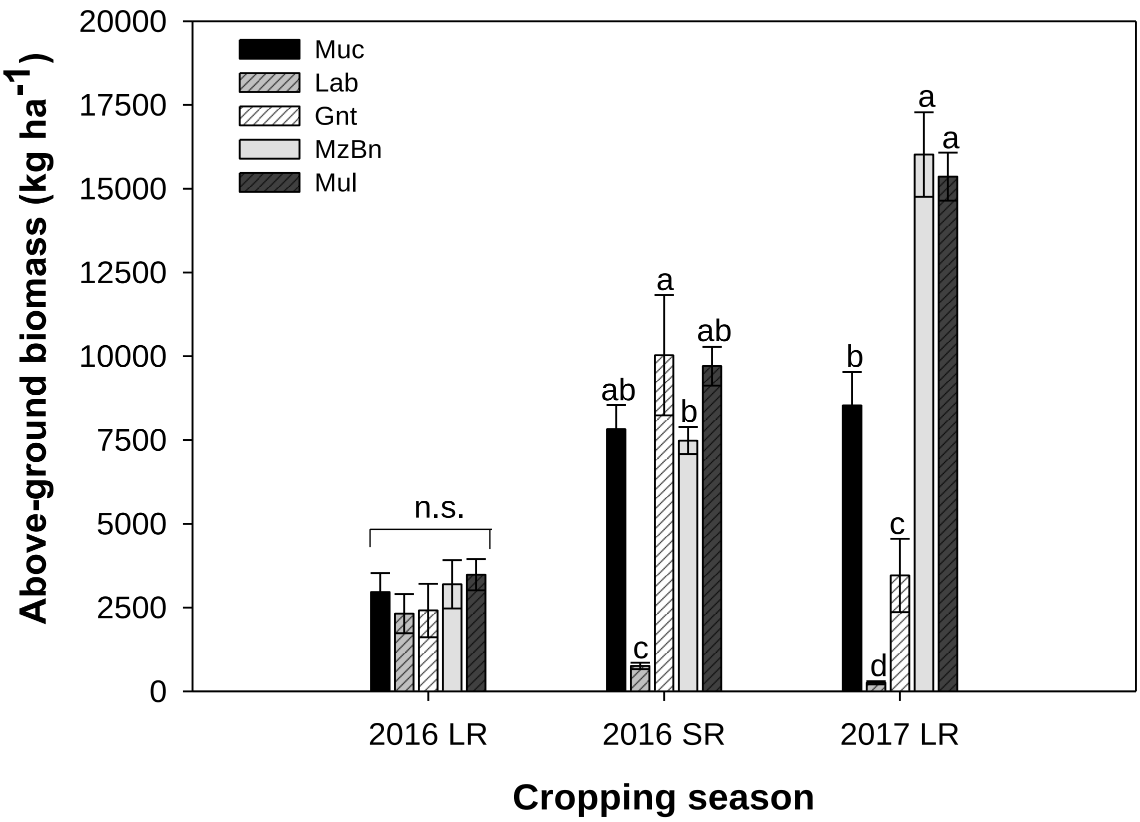

Figure 16. Effect of treatments on above-ground biomass during the 2016 long rains (LR 2016) and short rains (SR 2016), and the LR 2017. Groundnut was intercropped with maize during the SR 2016 season. Means with different letters in the same cropping season are significantly (p<0.05) different from each other. Error bars are standard error of mean. Muc: mucuna; Lab: lablab; Gnt: groundnut; MzBn: maize-common beans; Mul: maize-common beans under mulch.

Treatment had a significant effect on maize and legume grain yields during the SR 2016 and LR 2017 (Table 6). *Mucuna* produced higher grain yield than the other legumes. Common bean showed no differences in grain yield between Mul and MzBn during SR 2016 and LR 2017. Maize yield was, however, higher in Mul than MzBn in SR 2016, but not in LR 2017.

Table 6. Average grain yield (kg ha^{-1}) and standard errors of legumes and maize at physiological maturity during the 2016 short rains and 2017 long rains based on Muoni et al. (2019a). Statistical significances are indicated with different letters (p<0.05) for legume[(a, b)] and maize[(A, B)]. Groundnut was intercropped with maize during the SR 2016.

		----------- Cropping season ------------	
Treatment*	**Crop**	**SR 2016**	**LR 2017**
Muc	Mucuna	1625 ± 507a	3433 ± 253a
Lab	Lablab	209 ± 8b	80 ± 17b
Gnt	Groundnut	73 ± 46b	418 ± 152b
MzBn	Common bean	79 ± 22b	229 ± 51b
Mul	Common bean	108 ± 32b	240 ± 82b
Gnt	Maize	3361 ± 343B	–
MzBn	Maize	3070 ± 246B	7260 ± 580A
Mul	Maize	4339 ± 610A	4697 ± 576A

* Muc: mucuna; Lab: lablab; Gnt: groundnut; MzBn: maize-common beans; Mul: maize-common beans under mulch.

4.1.2. Discussion

4.1.2.1. The role of plant canopy and groundcover on runoff and soil loss

Under the studied planting systems, *Calliandra* mulch or agroforestry system (Mul) most effectively reduced runoff and soil loss followed by Muc in agreement with our first hypothesis. Mechanisms behind this reduction are absorption of kinetic energy of raindrops by the cover material, reduced splash erosion and overland flow velocity. The soil cover also decreases runoff velocity and enhances ponding and infiltration (Vermang et al., 2015) and prevents surface sealing (Valim et al., 2016). The current study has enhanced our understanding of the relative influence of ground and canopy cover on soil erosion. The mixed effect model (Table 5) indicates that groundcover was the main factor controlling soil loss among the planting systems. Groundcover provision by Mul at planting ensured soil protection from the high intensity rainfall. This is critical for soil conservation strategies during the first erosive events when canopy cover of biomass is still low. However, the effect of the Calliandra mulch lasted only until mid–season when the mulch was mostly decomposed. Other shrub legumes with high lignin/ polyphenol e.g. *Acacia angustissima* (Mafongoya, 1995) could be tested to ensure that the mulch effect remain into the next season. The low soil erosion observed under Muc could be due to its fast establishment (5–6 weeks after emergence and lasting until maturity) and vigorous biomass production, which substantially conferred greater soil protection than Lab, Gnt and MzBn. These findings demonstrate that Gnt and MzBn were vulnerable to erosion because of their initial low groundcover (Fig. 11), leaving the soil exposed to the impact of raindrops for a long time. The repeated cultivation measures (i.e. seedbed preparation and twice weed control per cropping season by hoeing) practiced by farmers in this region and also in our studies contributed to breakdown of soil aggregates and decreased surface cover by crop residues as shown by Tuan et al., (2014) in NW Vietnam, augmenting erosion risk (Engel et al., 2009) through enhanced crusting, runoff and reduced roughness. The multiple field operations could also be responsible for the lack of the observed significant differences in water stable aggregates among the cropping systems as the multiple field operations breakdown soil aggregates and facilitate surface sealing that reduces infiltration (Cogo et al., 1983). Surface seal formation is dependent on the extent of the breakdown of surface aggregates, which depends on soil structural stability (Wick et al., 2014; Gelaw et al., 2015). The observed WSA values were categorized as low (23–26%) according to the classification scale of structural quality of water stability of soil aggregates (Bartlová et al., 2016).

By reducing runoff and soil loss, groundcover also played a dominant role in the reduction of overall C and nutrient losses in eroded sediment. Farmers' practice, sole lablab and groundnut treatments with relatively lower groundcover recorded the largest amounts of C and N losses per year due to their considerably greater total soil loss. The reason for reduced canopy cover in Lab especially in the SR 2016 and LR 2017 was pest infestation, which subsequently resulted in high soil loss.

4.1.2.2. Potential use of cover legumes in soil erosion mitigation Runoff and sediment loss dynamics as influenced by different crop types

The impacts of soil erosion are commonly experienced especially where: i) no effective soil and water conservation measures are undertaken on steep slopes (Gachene et al. 1997; Mboya *et al*., 1999); ii) there is high effective rainfall erosivity; and iii) lack of timing of conservation measures. Loss of plant nutrients and organic matter through eroded sediments are high as these are closely associated with the erodible finer fractions of soils (Ghulam et al., 1995). Some studies have shown the important role of incorporating herbaceous N_2–

fixing legumes into cropping systems in the maintenance and improvement of soil fertility (Giller et al., 1997).

In this study, soil loss was reduced by legume planting systems that provided adequate cover at the beginning of the cropping season. The type of legume and crop management strategy is therefore decisive because legumes differ in their potential to establish a cover canopy in time and thus, control soil erosion (Khisa et al., 2002). Moreover, vegetation cover has fundamental effects on soil properties such as stability of the aggregates and water permeability (Rutigliano et al. 2004).

C*alliandra calothyrsus* mulch cover (Mul) reduced soil loss and showed increased grain yield of maize over farmers' practice (MzBn) that lacked surface protection during the short rains. However, this was not the case during the LR 2017, when the shrubs were well established. Then, grain yield of maize in Mul was not different from MzBn. This could be attributed to competition for nutrient and water resources imposed by the hedgerows, although this was not evaluated. Advantages of *Calliandra* mulch include addition of soil organic matter and N release into the soil, prevention of crust formation, and increased infiltration through improvement of soil structure. In two field experiments conducted during rainy and dry season, *Calliandra* residues decomposed to about 50% of their initial mass within 40 days (Thomae 2017) releasing plant nutrients but also reducing surface cover and roughness. One more limitation in the use of *Calliandra* mulch in our case was the cost of time and labour invested in gathering or collecting the *Calliandra* residues. Despite these challenges, opportunity cost exists in using *Calliandra* residues as supplements in feeding livestock.

Most herbaceous trees and legumes are very useful as a feed source, and have shown to improve milk production in animals (Paterson et al., 2013). However, their use as fodder or mulch may face challenges related to intensive labour requirement in establishing and pruning for high quantities. Muoni et al. (2019b) affirmed that farmers show very low interest in herbaceous legumes because they prefer growing grain legumes to provide food security for their families. Stressing the usefulness of herbaceous legumes as fodder in addition to enhancing soil fertility and soil conservation could increase farmer interest, but adoption may be possible where some income can be earned from livestock (Muoni et al., 2019b).

Buckles (1995) alluded to the use of *Mucuna pruriens* (Muc) in cropping systems as the most researched herbaceous cover crop, because it produces large amounts of biomass in varied environments, exerts consistent positive results on the main crop yield, and effectively suppresses weed growth (Carsky et al. 2001). *Mucuna* could also be used as livestock feed when properly ensiled with an average pH of 5.32 (Matenga *et al*., 2003). In this study increases in AGB of *Mucuna* over *Lablab* and *Groundnut* were 28, 933, 3229 and 23, 687, 147% in LR 2016, SR 2016, and LR 2017, respectively. The high AGB of Muc was reflected in its high groundcover evaluated at different physiological stages. The low AGB during the 2016 LR compared to the subsequent seasons, and no differences in AGB among the cropping systems (e.g. between MzBn and Lab in particular) could be due to the late planting and a long dry spell during the vegetative growth stage.

Despite the principal role played by *Mucuna* in soil erosion mitigation, some studies indicate that low adoption still remains a bottleneck because *Mucuna* occupies the land without a direct economic output as its value as food and feed is not evident (Carsky & Ellitta, 2004). Other legume species such as grain legumes (e.g. groundnut in this study) have much higher adoption rates, but lower benefits for the soil (Carsky et al., 2003).

Generally, the level of soil erosion measured in this study particularly, during the long rains was relatively small (10 under Mul to 1800 kg ha^{-1} under Lab) compared to other studies due to the low rainfall amounts measured during the measuring period. This does not imply that erosion is not a major problem in this region. Thiefelder and Wall (2009) estimated 6900 kg ha^{-1} under no–till plus legume intercrop in Zimbabwe during 2005/2006 cropping season. In another study in Western Kenya, Ampofo et al. (2002) recorded > 2000 kg ha^{-1} under different crop and tillage management systems. Under a bare soil during the 2011/2012 cropping season in Southern Africa, Paterson et al. (2013) measured 52000 kg ha^{-1} yr^{-1}. The measured soil erosion during the SR in this study ranged from 200 to 6000 kg ha^{-1} under Mul and Lab respectively were within the range of measured soil loss in other studies.

4.1.2.3. C and N losses caused by soil erosion

Soil erosion decreases soil organic C and nutrients by selectively detaching and transporting fine particles (Lal 2003), resulting in the enrichment of sediments in C and nutrients relative to the *in situ* soil (Owens et al., 2002). The C and N enrichment ratio (ER) exceeded 1 under all the cropping systems, indicating pronounced losses of C and N due to soil erosion (Gachene et al. 1997). However, Mul and Muc were less enriched in C and N. Farmers' practice, sole lablab and groundnut treatments recorded the largest amounts of C and N losses per year due to the considerably greater total soil losses. The occurrence of high C and N losses from sole lablab relative to the other cropping systems was a direct reflection of the high soil loss that resulted from pest infestation, which decreased biomass cover considerably. A comparison of the C and N losses between the mulch and the other plots over the one year exposure to the highly erosive rainfall showed that the C and N losses decreased strongly under mulch. Tiscareño-López et al. (2004) asserted that the loss of nutrients is closely linked with the magnitude of runoff produced and sediment loss under each cropping system. In a similar study, Zöbisch et al. (1996) concluded that total nutrient losses in eroded sediments and in dissolved surface runoff were independent of the nutrient concentrations of the eroded soil and water, but rather dependent on the total amount of runoff and eroded soil. So, the high losses of C and N from farmers practice, lablab and groundnut cropping systems are assumed to be the result of high runoff and soil loss. Annual N input via mineral fertilizer under the farmers practice (MzBn) amounted to 81 Kg N ha^{-1}. Relating this to the annual N loss through sediments (7 Kg N ha⁻1) represents 9%. Potential pathways of N fertilizer input losses may be dissolution in runoff water, volatilization and leaching which were not accounted for in this study.

4.2. Critical slope length approach for soil loss mitigation in smallholder cropping systems in SW Kenya

4.2.1. Results

In the LR 2017, runoff and soil loss were measured on three nearby farms in Rongo on three slopes of 20, 60 and 84 m length (SL20, SL60, SL84).

4.2.1.1. Impact of slope length on runoff and soil loss

Cumulative soil loss increased with increasing slope length from 20 to 84 m, whereas the reverse was observed for runoff (Table 7). Runoff per hectare was similar at SL20 and SL60 across all farms, but was significantly lower on SL84. Overall soil loss on Farm 1 exceeded that on Farm 2 and 3.

Table 7. Effect of slope length on total runoff and soil loss for the 2017 long rainy season on three farms. Data show means and standard errors of 19 events. Treatments with different superscript letters differed among same slope lengths at p<0.05 at each farm (F1, F2, F3) and on all farms combined.

Farm	Slope length (m)	Cumulative runoff (m^3 ha^{-1})	Cumulative soil loss (kg ha^{-1})
F1	20	565±77^a	6450±3298^a
	60	477±8^a	10393±1902^a
	84	330±22^b	14284±1120^a
F2	20	576±4^a	80±38^c
	60	437±29^a	216±41^b
	84	287±38^b	1238±100^a
F3	20	654±137^a	184±73^b
	60	619±13^a	316±63^b
	84	338±5^b	1644±312^a
All farms	20	605±73^a	2238±1136^c
	60	511±16^a	3642±668^b
	84	319±22^b	5722±511^a

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Seasonal totals of runoff and soil loss showed opposite trends with regards to slope length. Therefore, we examined the event–based runoff and soil loss data more closely. Runoff peaked early in the season on all three farms (Fig. 17) and was reduced towards the middle of the season despite major rain events. Heavy rain events were recorded at the end of the season and major runoff during this period occurred particularly on F2 and F3. Regarding different slope lengths, SL60 generated the highest runoff on F1 at the beginning of the season, while runoff under SL20 was highest on F2 and F3 at the beginning of the season. In the mid-season and late season SL20 was always greater in runoff than SL60 and SL84.

Event observations for soil loss showed high soil loss at the beginning of the season on all farms. Soil loss also peaked in the mid-season in contrast to runoff, but was again low at the end of the season. Event–based soil loss was always higher on F1 than F2 and F3.

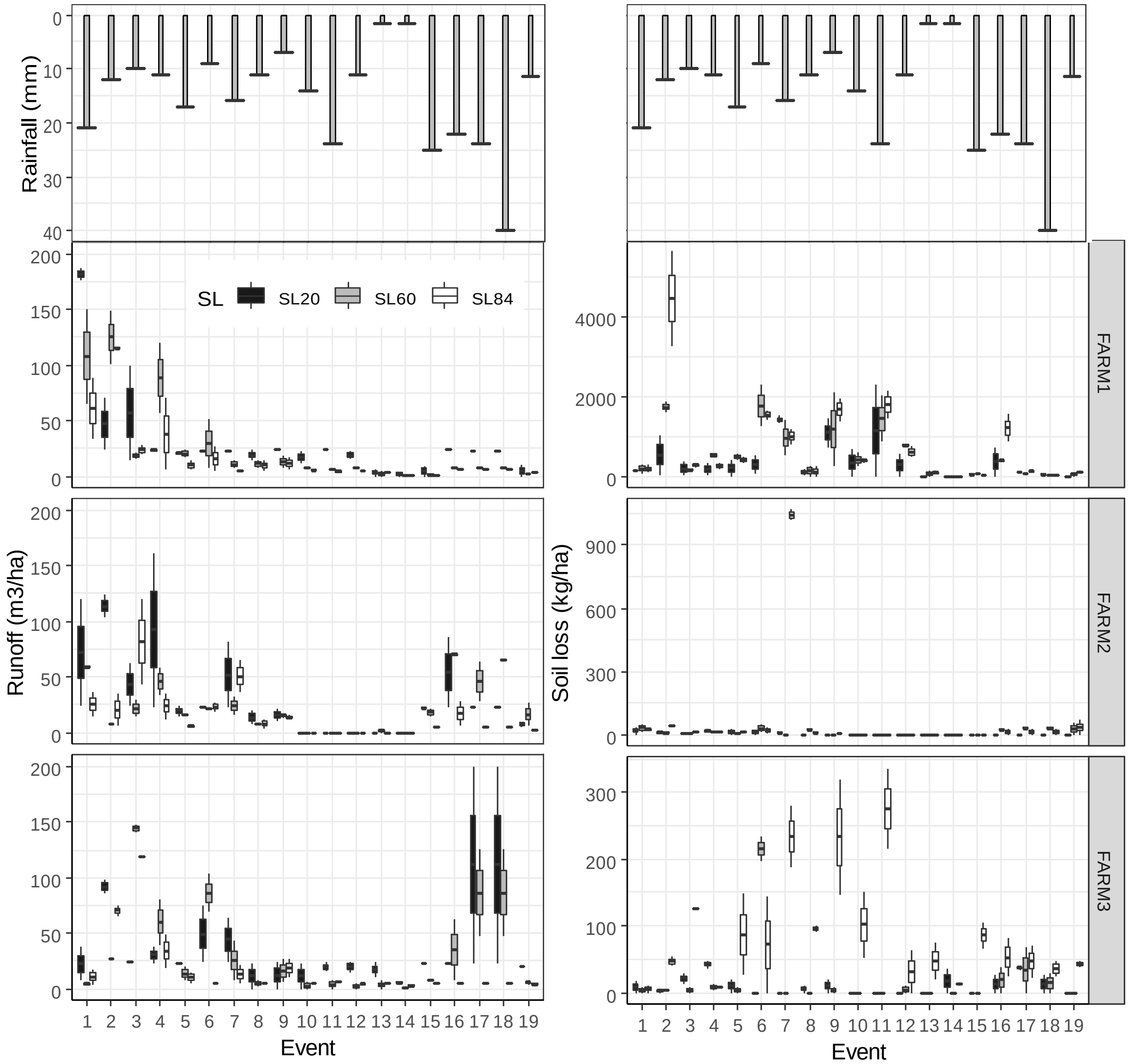

Figure 17. Event–based runoff and soil loss under different slope lengths. Note the different y-axis scales for soil loss. SL20, SL60 and SL84 are slope lengths 20, 60 and 84 m respectively.

The impact of different slope lengths on relative soil loss, runoff, sediment load and soil loss to maize grain yield ratio was evaluated for all the farms combined (Fig. 18). Runoff decreased gradually with increasing slope length, and the decrease was most pronounced at SL > 50 m. Soil loss, sediment load and soil loss to yield ratio (an index which shows the susceptibility of crops or cropping systems to accelerated soil erosion) also ascended gently with increasing slope length up to the 50 m slope length and thereafter, began to show a sharp increase. Beyond 50 m slope length, sediment load showed the highest increase on the long slopes.

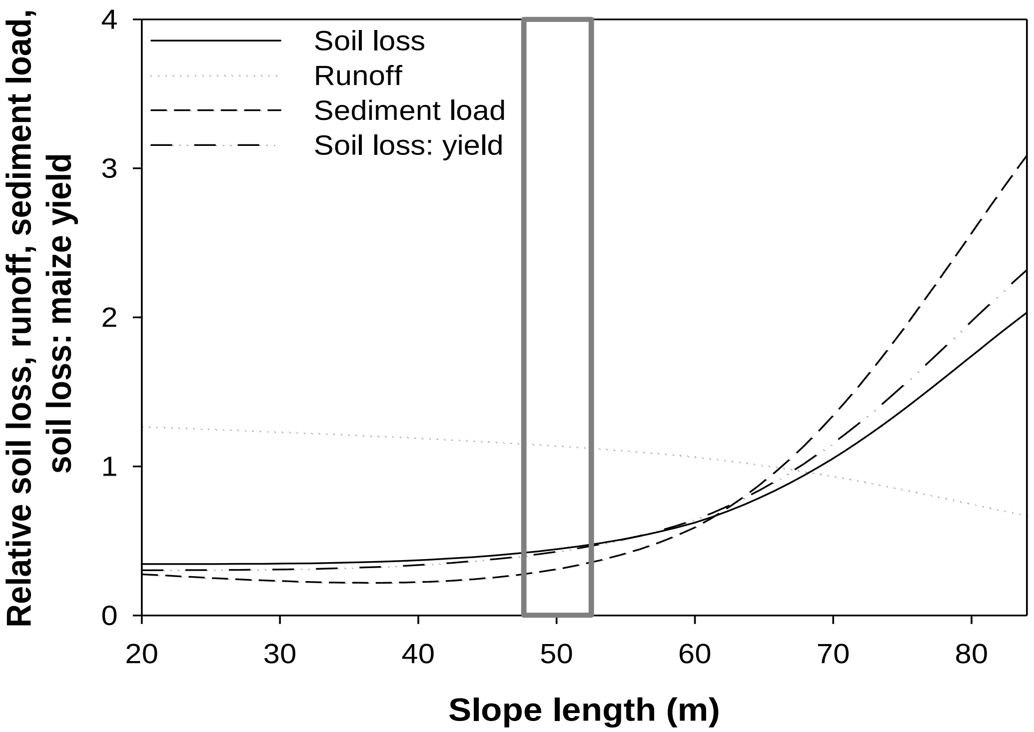

Figure 18. Relation of slope length to soil loss, runoff, sediment load and soil-loss-to-maize-yield-ratio relative to averages across all three farms. The vertical bar indicates critical slope length.

4.2.1.2. Evaluating the relative influence of predictor variables on soil loss

Slope length and profile curvature showed the strongest effect on soil loss on F1, F2 and F3 *individually* (Table 8) in the statistical mixed effect model that best predicted soil loss (selected by AIC). Soil loss at F1 and F2 was mainly dominated by slope length and at F3 by profile curvature. Slope gradient and texture were not included in the individual farm models, because they were uniform. Assessing the impact *over all farms combined* indicated that slope gradient was the strongest factor affecting soil loss, followed by slope length and profile curvature. Groundcover under MzBn did not vary widely across the farms. Rainfall was the same across all three farms, so it was not included in the combined farm analysis.

The established mixed model over all farms combined [Eq 10] based on Table 8 was used to predict soil loss for all rainfall events of the LR 2017 cropping season (Fig. A1 in Appendix). Overall, the model showed good prediction (R^2 = 0.54). Assessing soil loss prediction under the different slope lengths showed that the model performed quite well for SL84 (R^2 = 0.44) and even better for SL60 (R^2 = 0.58) and SL20 (R^2 = 0.64).

$$\log_{10}(y) = 1.75 + 0.18SL + 0.06RO + 0.48GR - 0.12PC \quad \text{……[Eq10]}$$

where y is soil loss (kg ha^{-1}), 1.75 is the intercept, SL, RU, GR and PC are the regression coefficients or estimates of slope length (m), runoff (m^3 ha^{-1}), slope gradient (%) and slope profile curvature (), respectively.

Table 8. Mixed model of explanatory variables on log transformed soil loss in LR 2017. Absolute magnitude of B-value indicates explanatory power, and sign indicates direction. Soil loss data were log transformed for analysis.

		Standardized coeff.		Confidence limit	
Dependent variable	Explanatory variable	*B–value*	Std. error	Lower	Upper
	Farm 1				
Soil loss (kg ha^{-1})	(Constant)	2.4101	0.1149	2.1706	2.6497
	Slope length(m)	0.2026	0.0581	0.0806	0.3246
	Runoff (m^3 ha^{-1})	0.1160	0.0508	0.0141	0.2179
	Groundcover (%)	-0.0738	0.1201	-0.3195	0.1717
	Rainfall (mm)	-0.1242	0.1241	-0.3845	0.1362
	Profile curvature ()	-0.1609	0.0502	-0.2669	-0.0550
	Farm 2				
	(Constant)	1.3070	0.0980	1.0922	1.5219
	Slope length	0.1492	0.0932	-0.0505	0.3490
	Runoff	0.0613	0.0393	-0.0203	0.1431
	Groundcover	0.0310	0.0925	-0.1605	0.2226
	Rainfall	0.1026	0.1082	-0.1320	0.3371
	Profile curvature	-0.1012	0.0438	-0.1931	-0.0093
	Farm 3				
	(Constant)	1.5198	0.1559	1.0542	1.9854
	Slope length	0.1468	0.2026	-0.3246	0.6181
	Runoff	0.0554	0.0613	-0.0683	0.1792
	Groundcover	0.1078	0.0937	-0.0881	0.3037
	Rainfall	0.0275	0.0729	-0.1310	0.1860
	Profile curvature	-0.1690	0.1499	-0.4942	0.1563
	All farms				
	(Constant)	1.7518	0.0676	1.6145	1.8891
	Slope length	0.1886	0.0531	0.0810	0.2962
	Runoff	0.0639	0.0296	0.0052	0.1226
	Gradient	0.4858	0.0657	0.3526	0.6191
	Profile curvature	-0.1215	0.0393	-0.2016	-0.0413

[i] Texture and gradient did not appear in the individual farm models, because only one bulked topsoil sample was analysed and only one slope gradient existed per farm.

4.2.1.3. Slope length in relation to aboveground biomass and grain yield of maize

Crop AGB and grain yields were measured in the LR 2017 and compared among slope length treatments on the three farms. Grain yield and AGB appeared to decrease with increasing slope length, but showed no statistical difference (Table 9). Harvest index showed no consistent trend with slope length ranging between 32 and 47%. There were no defined trends in the spread of AGB, grain yield and HI with regards to slope length.

Table 9. Aboveground biomass, grain yield and harvest index of maize at physiological maturity under different slope lengths on three farms in Rongo during the LR 2017 season. SL1 = 20 m, SL2 = 60 m, SL3 = 84 m.

Farm	Slope length	Above-ground biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Harvest index (%)
1	**SL1**	3443 ± 232a	1430 ± 223a	41 ± 6.4a
	SL2	3399 ± 742a	1315 ± 233a	35 ± 8.6a
	SL3	3604 ± 75a	1171 ± 34a	32 ± 0.3a
2	**SL1**	9222 ± 553a	3383 ± 350a	37 ± 1.6a
	SL2	6940 ± 1775a	3015 ± 750a	44 ± 0.3a
	SL3	6613 ± 582a	2794 ± 151a	42 ± 1.4a
3	**SL1**	7242 ± 196a	3464 ± 119a	47 ± 1.6a
	SL2	6045 ± 1558a	2400 ± 705a	39 ± 1.5a
	SL3	5632 ± 1237a	2246 ± 831a	38 ± 6.3a
All farms	**SL1**	6636 ± 2077a	2759 ± 814a	42 ± 5.6a
	SL2	5461 ± 1302a	2243 ± 609a	41 ± 2.5a
	SL3	5283 ± 1085a	2070 ± 584a	38 ± 5.1a

4.2.2. Discussion

4.2.2.1. Assessing critical slope length for erosion mitigation

Soil loss increased exponentially with the increase in slope length in accordance with our second hypothesis, with the critical length being around 50 m. While there was a gradual decrease in runoff beyond 50 m, soil loss and sediment load increased drastically. This sharp increase in soil loss may be attributed to higher flow velocity, which increases the transport capacity of sediments in runoff water. Bagio et al. (2017) also explained such an exponential rise in soil loss with increasing slope length by the greater erosive power of surface runoff, influenced primarily by the increase in volume and speed of runoff. Foster et al. (1977) attributed this kind of sharp increase in soil loss to a shift from sheet to rill erosion on long slope lengths, which was also observed on SL3 plots in Rongo. Contrarily to soil loss, runoff in our case followed a negative quadratic function against slope length, i.e. it decreased – even in absolute terms – with increasing slope length. The high runoff on SL1 may theoretically have been an overestimation on the artificially short bounded plots that were not representative for infiltration in the landscape. Likewise, Silva and de Maria (2011) attributed decreased runoff to greater potential water infiltration into the soil and evaporation on longer slopes with greater variation in slope terrain compared to shorter slopes e.g. longer slope lengths could have more small depressions than shorter slope lengths, and could promote more infiltration before the water reaches the lower end of the slope. Han et al. (2019) described the gradual decrease in runoff beyond their 30 and 40 m slope as "runoff degradation" phenomenon (a condition where runoff becomes more difficult on a longer slope (Sadeghi et al., 2013), resulting in re-infiltration (Chaplot and Bissonnais, 2000)), and concluded that the 30 and 40 m slope lengths were the runoff continuity threshold. Van de Giesen et al. (2005) in a modelling study interpreted the reduction in runoff as scaling effect due to longer time for infiltration on longer slopes, and put forward spatial variability as the main cause of the observed scale effect (Seguis et al., 2002). Thus, water has more time to travel on long slope lengths than short slopes due to a longer travel length, hence a longer time for infiltration. Decreasing runoff and at the same time increasing soil erosion with increasing slope length has also been observed by Free and Bay (1969) in a tillage and slope study. Runoff was not significant under the studied slope lengths (11, 22 and 64 m), and so no explanation was imputed. Similarly, individual effect of slope length on soil loss was not significant, but interaction of slope length and tillage treatment showed statistical significance. In a related study with settings similar to ours, Lal (1997) on an Nigerian Alfisol on 7–9% slope in a maize–cowpea rotation under slope lengths varying between 10 and 60 m – found that soil erosion and sediment loads increased exponentially with slope length, while runoff per unit area decreased slightly. Under his specific settings the degradative effects of soil erosion increased sharply beyond a critical slope length of 25 m. Lal's process–based explanation attributes the degradative effects of long slopes to high sediment load and aggravated risk of soil erosion from the decay of soil structure caused by preferential loss of soil organic matter and clay over longer times. Our farmer fields have been under maize – bean cultivation over five years, and could risk the decay of soil structure from soil erosion on long slopes. The soil loss to yield ratio which measures the susceptibility of crops or cropping systems to accelerated soil erosion (Lal, 1997) also increased drastically beyond the critical slope length due to the high soil loss rate.

The critical slope length of about 50 m obtained in this study was higher than that from Lal's and this could be attributed to differences in cropping systems, slope gradient, soil properties (particularly texture and type of clay minerals) and rainfall intensity.

The Western part of the catchment, where our study sites were located, has been classified as humic Acrisols, humic and ferralic Cambisols by Wielemaker and Boxem (1982). Our soil survey in 2016 (two transects E-W and N-S with 100 augers and 11 detailed soil profiles) showed that soil texture was similar between both and comparable to the Alfisol in Lal's study. All are characterised by clay illuviation into a Bt layer. Topsoils of Lal's Oxic Paleustalf contained in average 52 and 53% sand, Acrisols in our study 51±10%, and Cambisols 68±13%. Total topsoil carbon contents were low for both Acrisols (1.42±0.35%) and Cambisols 0.96±0.34%. Phaeozems were found in smaller parts of the upper (Eastern) Rongo watershed. They are of basaltic origin (in contrast to the granitic Acrisols and Cambisols) and would need to be discussed separately; this was beyond the scope of the study as our experiments were confined to the Western part of the watershed.

These factors do not act in isolation, but may combine and interact to influence the mechanisms involved in soil erosion, and hence the critical slope length as discussed below. Cropping or management systems influence soil erosion through their ground or canopy cover provision, which affect soil hydrological characteristics (e.g. infiltration rate, flow velocity of overland flow). Generally, as groundcover increases, the resistance to overland flow increases, which leads to lower flow velocity (Liu & Singh, 2004). Hence, under similar SL with and without soil cover, critical slope length is expected to increase with increasing soil cover provision due to lengthening of ponding time until runoff is induced. Rogers & Schumm (1991) and Morgan (1995) found that vegetation effect on soil loss is not straightforward, and that plant canopy has shown to exacerbate soil loss rates under certain experimental conditions depending on how it interacts with the erosion process. Groundcover related positively with soil loss on F2 and F3, and this may be attributed to its spatial distribution at the ground surface which can modify the drop–size distribution of rainfall (Morgan, 2005). In addition, high rainfall events during times of high ground cover (middle and end of season; see Fig. 11 and Fig. A2 in the appendix) may have overridden the effect of groundcover. Unlike mulch cover from Mul in the LGE study, which was already there in the period of high rainfall intensities and provided a continuous dense ground cover in addition to

Maize canopy protection against soil loss, the canopy protection from MzBn alone on F2 and F3 could not provide similar resistance against rainfall. Factors facilitating runoff and erosion that are usually associated with cattle grazing are soil compaction (Blake et al., 2018), crusting and removal of cover (Blanco-Canqui & Lal, 2010). We did not find evidence of these despite relatively high stocking rates, probably because of prevailing cut & carry systems.

Slope gradient affects runoff generation and hydraulic characteristics such as flow velocity of overland flow, and may thus modify the critical slope length. The preeminent importance of slope gradient, more influential than slope length, was evident in our study when comparing different farms with different slopes (Table 8).

High rainfall intensities are generally associated with high runoff and erosion risks due to the high power of detachment and transport forces. The occurrence of high intensity rains especially in periods when crop cover is not strong enough to adequately protect the soil surface may decrease the critical slope length via speeding runoff generation, and consequently aggravate soil erosion. The negative relationship between rainfall amount and soil loss observed on F1 could be due to the temporal distribution or characteristics of the rains, which determines their erosivity. Thus, an outpour of a large amount of rainfall within a short period of time may result in high intensity with high erosive power to generate high soil loss. The contrary may produce less erosive rains when large rains takes a longer time, resulting in low erosivity and less soil erosion. Rainfall intensity in 2016 reached up to > 60 mm h^{-1} and events of 20 mm h^{-1} were not uncommon (data not shown).

Among the numerous pedogenic factors that affect soil loss is high stone contents, which reduces potential water infiltration (Figueiredo 1996). In Rongo we found about 20 % vol. in the top- and up to 50 % in the subsoil during our soil survey.

4.2.2.2. Designing potential slope length strategies for effective soil conservation

Soil erosion on the studied farms in the Rongo catchment was predominantly driven by slope length, which is inevitably expected to be a key precursor of more severe soil degradation problems along the landscape, particularly, if sustainable conservation measures are not sought. There are numerous soil conservation measures that exist at the plot and landscape level to control soil erosion from agricultural land, and effective conservation measures will help to sustain main crop yield (Tuan et al., 2014). However, there are difficulties in evaluating such measures in the field, because they are labour– and area–intensive and need to be monitored over various seasons. Among the various techniques of soil conservation, preference is given to agronomic measures as they utilise the direct protective role of plant cover in reducing rain drop impact, are less expensive (Morgan, 2005) and fit into existing farming systems to increase plant population. Such approaches should not be labour intensive and should not require levels of inputs or resources to which targeted farmers have no access. Strip–cropping offers the advantage of combining row crops and protective or buffer crops in alternate strips aligned on the contour. Eroded sediments from the row crops are trapped within the buffer strip behind. The difficulty with strip–cropping in mosaic landscapes is that much cropping land will be taken up by the alternate buffer strips to protect valuable crops. Targeting specific positions of the slope, in this case the critical slope length to place the buffer strip can save a considerable amount of land that would otherwise be taken out of production by the buffer strips, and would also save labour and capital input involved in establishing and maintaining the buffer strip. In the landscape, relatively higher soil loss was generated on longer slopes compared to short slope lengths in this study. Although the critical slope length level is likely to be different under alternative settings (as discussed above), the resulting strategic recommendations given below still hold. Within the same catchment (Fig. 1, LGE plot), Muoni et al. (2019a) found that MzBn plus *Calliandra calothyrsus* hedgerows with 5 Mg ha^{-1} leaf mulch amendment (Mul) and *Mucuna pruriens* (Muc) cover crops effectively reduced runoff and soil loss followed over three rainy seasons. This effect was most pronounced at the onset of each cropping season, which was dominated by highly erosive rainfall events. We recommend implementing cash crops, e.g. common beans, maize and groundnut, at the upper end of the slope down to the critical slope length, whereas, legume forage cover crops and mulch, e.g. Muc, and Mul or hedgerows or agroforestry systems, should be implemented as buffer strips beyond the critical slope length (Fig. 19). In the backdrop of land fragmentation and limitation in this region, strip–wise mulching or using Muc as live mulch in strips at strategic landscape positions can be an effective approach to sustainably maximise land area and reduce vulnerability of crops to soil erosion. To increase the likelihood of implementation of such soil conservation measures may require some incentives such as: a) provision of input subsidies to purchase quality cover legume seeds such as *Mucuna* and legume tree seedlings; b) presence of technical support on soil conservation methods e.g. provision of technical knowledge in identifying critical slope length, and c) provision of good market conditions such as access to major markets which favour high value cash crops, and thus increases the value of soil conservation investement (Brown and Shresta, 2000). Existing studies have demonstrated the effectiveness of spatial mulch application arrangements along the slope, i.e. in strips covering only a part of the slope, as being similar to the application over the entire slope. For example, Abrantes et al.s (2018) found no significant relationship in runoff and soil loss reduction when rice straw was applied as mulch over the entire flume length of 2.7 m compared to 1/3 and 2/3 flume length strips.

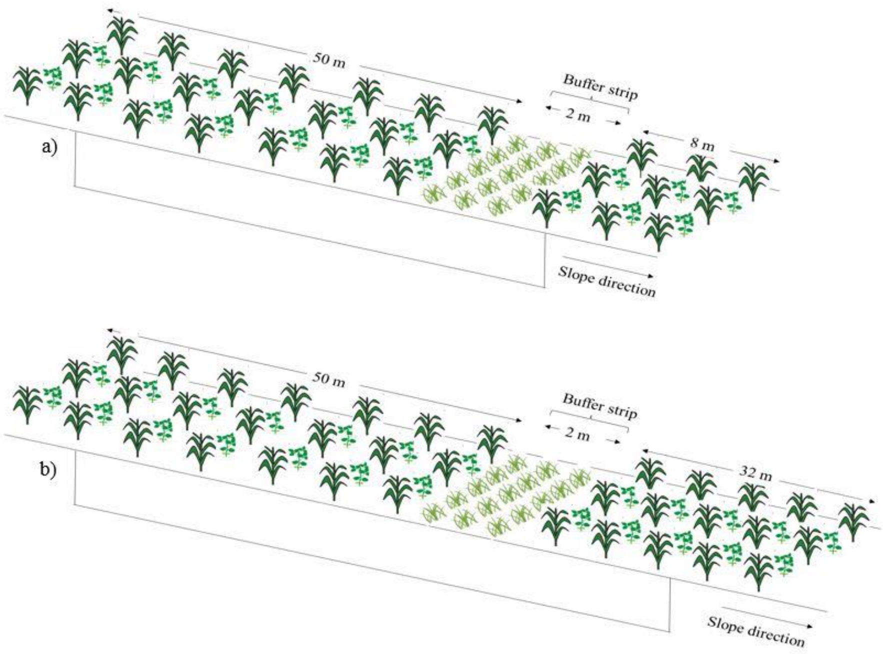

Figure 19. Schematic diagram (not to scale) showing position of buffer strips at the critical slope length (50 m) on a a) 60 and b) 84 m slope.

The width of the buffer strip may vary depending on the degree of erosion hazard, and is usually 2–4 m wide (Morgan, 2005). Lal (1997) proposed a revised formula to compute terracing width or width of buffer strip (VI) for conventional till systems as shown in Eq 11. An average plots slope of 12% gives a buffer strip width of 2 m for our recommendation settings.

$$VI = \frac{\%slope}{10} + 0.9 \ldots\ldots\ldots\ldots\ldots\ldots [Eq11]$$

4.3 Modelling agronomic water stress management strategies on crop performance and water use efficiency in SW Kenya

4.3.1 Results

4.3.1.1 Modelling strategy

While problems of excess water have been dealt with in the previous chapters, water stress is another important factor limiting crop production at our study site. We experienced drought during the 2016 long rains, which affected crop yields. We observed water stress, which could constrain plant nutrient uptake and hamper crop performance. Moreover, the crops were planted late in this experiment and critical phenological stages may have coincided with periods of low water availability. In order to gain more insights on these processes we used a dynamic crop model to determine critical factors for plant stress and possible strategies to optimise crop growth.

Thus, the first model set-up simulated the baseline (BL) conditions as practised by smallholder farmers in the study region. Crops were planted at the onset of the cropping seasons with the first rains, implying that planting date varied seasonally due to rainfall. In the alternative scenarios (late planting) PD1WL and PD3WL e.g. in section 3.4.5, crops were planted one and three weeks, respectively, after the BL planting dates. The BL, PD1WL and PD3WL scenarios were used to answer the research question in section 1.11.

The third, and fourth alternative scenario evaluated the impacts of early maturing crop varieties (SDC10 = short duration crop 10 days < than BL in physiological maturity, and SDC30 = short duration crop 30 days < than BL in physiological maturity) on grain yield and WUE. These two scenarios and in combination with PD3WL (PD3WL+SDC10 and PD3WL+SDC30) as the fifth and sixth alternative scenarios, respectively, were used to answer the research question on whether short duration crop genotypes can be planted late in the season when the first sown crop fails due to water stress or delayed rainfall or can be harvested before the end of the season to reduce the risk of crop failure or damage by drought.

The seventh scenario evaluated the impact of a dry spells during critical phenological stages (NR50–80 DAP = no rain 50 to 80 days after planting, coinciding with critical phenological stage (flowering)) on grain yield and WUE. This scenario was used to answer the research question whether crops are susceptible to drought stress at flowering in the context of ongoing climate change.

4.3.1.2. Model evaluation in predicting AGB and grain yield

The performance of LUCIA model in predicting AGB and grain yield for the different crops was assessed using EF and CD shown in Fig 20 below. The model showed reasonable acceptability for prediction since $0.36 < EF < 0.75$ (Moriasi *et al.*, 2007). With an EF of 0.69 and 0.68 for AGB and grain yield respectively in the calibration phase, the model fulfilled the performance benchmark used by Pansak et al. (2010) for WaNuLCAS and by Lippe et al. (2014) for Lucia-Erodep. The CD values were also between the 0.5 and 2 threshold that Liu et al. (2020) used for successful calibration and validation of the LUCIA model. With reasonable calibration and validation results, the calibrated model parameters were accepted for the scenario simulations. The large outliers in the validation data came from observed AGB and grain yield of MzBn during the 2017 LR. These high data points skewed the distribution of the data in their direction, reduced the performance indexes of the validation, and subsequently hampered the robustness of the model for prediction.

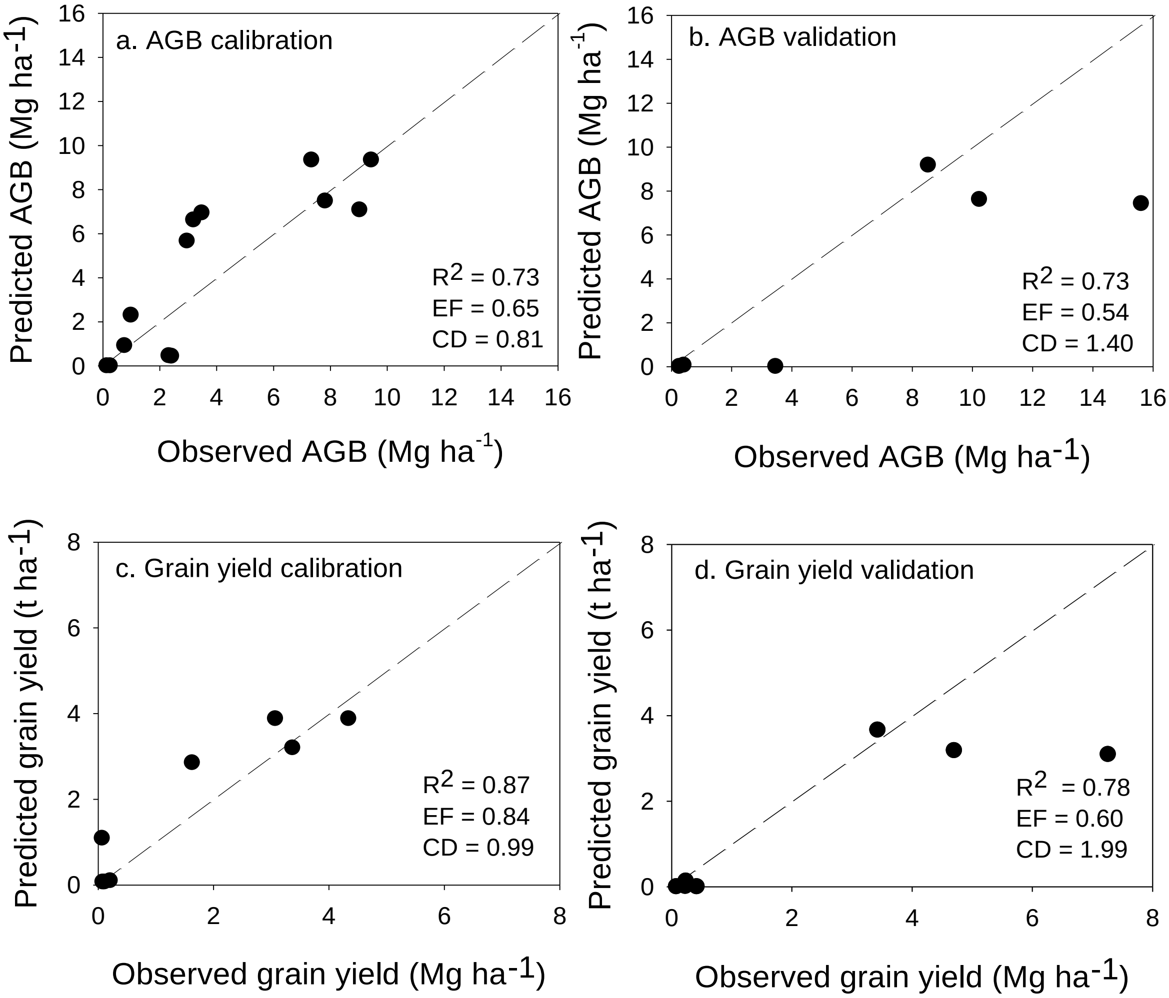

Figure 20. Model performance of different cropping systems: a) AGB (Mg ha^{-1}) in LR and SR 2016 for model calibration; b) AGB (Mg ha^{-1}) in LR 2017 for model validation; c) Grain yield (Mg ha^{-1}) in LR and SR 2016 for model calibration; d) Grain yield (Mg ha^{-1}) in LR 2017 for model validation.

4.3.1.3. Solar radiation and rainfall data under each scenario

Daily solar radiation, mean air temperature and rainfall under BL, PD1WL, PD3WL, SDC10, SDC30, PD3WL+SDC10, PD3WL+SDC30 and NR50–80DA during the 2017 LR, 2016 SR and 2017 LR are shown in Fig. 20. Daily rainfall of the two rainfall scenarios BL and NR50–80DA is also shown in Fig. 21, with the latter indicating the drought spell under each cropping season. Table 10 shows the average and total solar radiation and rainfall under each scenario during 2016 LR and SR, and LR 2017. Underlying measured weather data for the three seasons were the same for all scenarios, but the effective data for plant growth differed due to the varied vegetation periods. The highest total seasonal solar radiation occurred under BL, PD3WL and BL during LR 2016, SR 2016 and LR 2017. During both 2016 LR and SR, the lowest solar radiation occurred under SDC30, whereas, PD3WL+SDC30 showed the lowest in 2017 LR. Cumulative rainfall was higher in the 2016 SR, with lower amounts occurring in the LR 2017. Total rainfall was lowest under the drought scenario (368 and 258 mm for LR 2016 and 2017 respectively) during the two long rainy seasons (Table 10). On the other hand, the highest total rainfall during the two rainy seasons occurred under PD3WL, and this could be due to the distribution of the rainfall. The daily air temperature, solar radiation and rainfall dynamics under the BL and each scenario are shown in Figure 20.

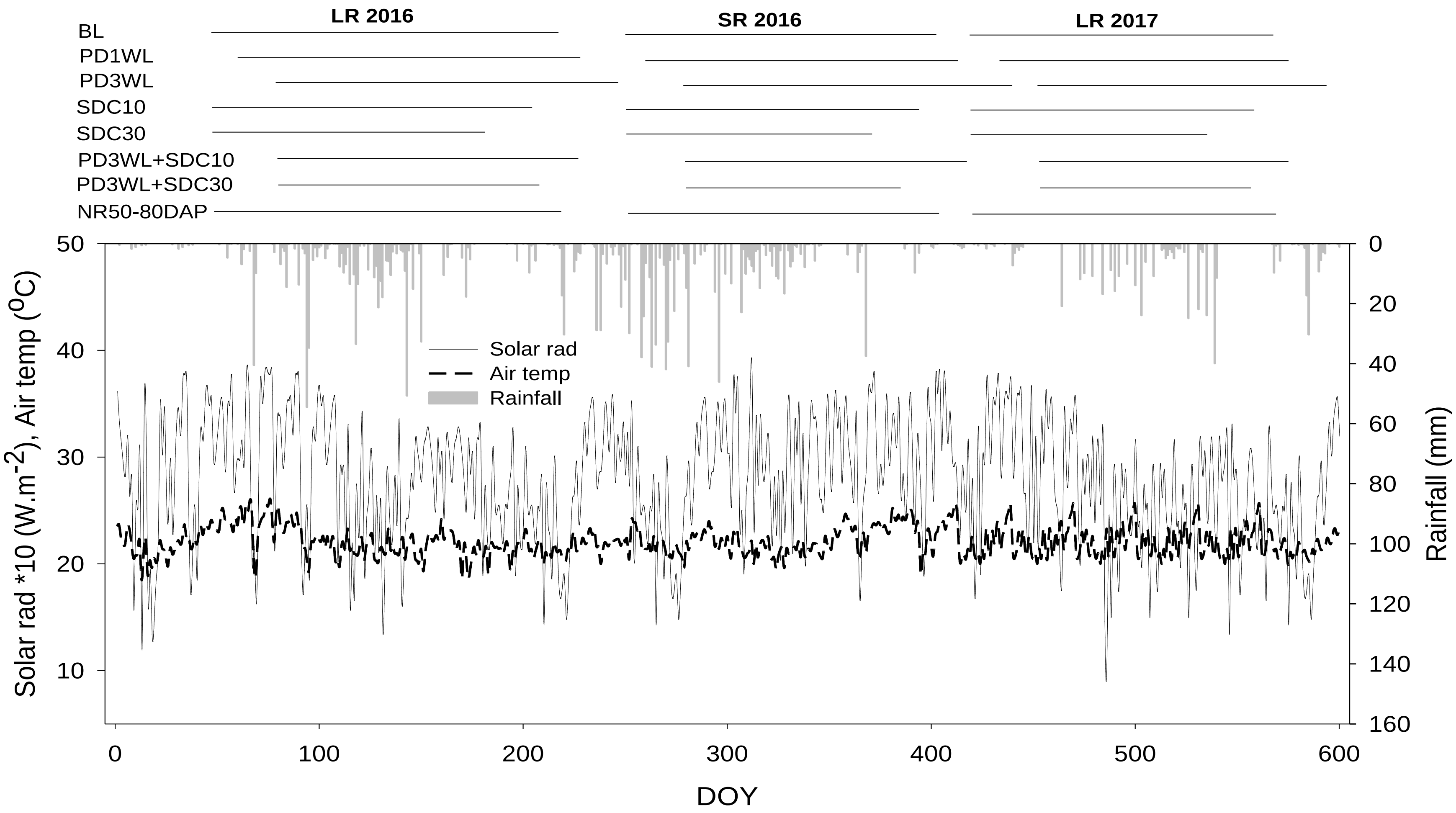

Figure 21. Daily solar radiation, mean air temperature and rainfall dynamics under each scenario during the 2017 LR, 2016 SR and 2017 LR. The horizontal lines above the graph show the crop growth duration for the various scenarios. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

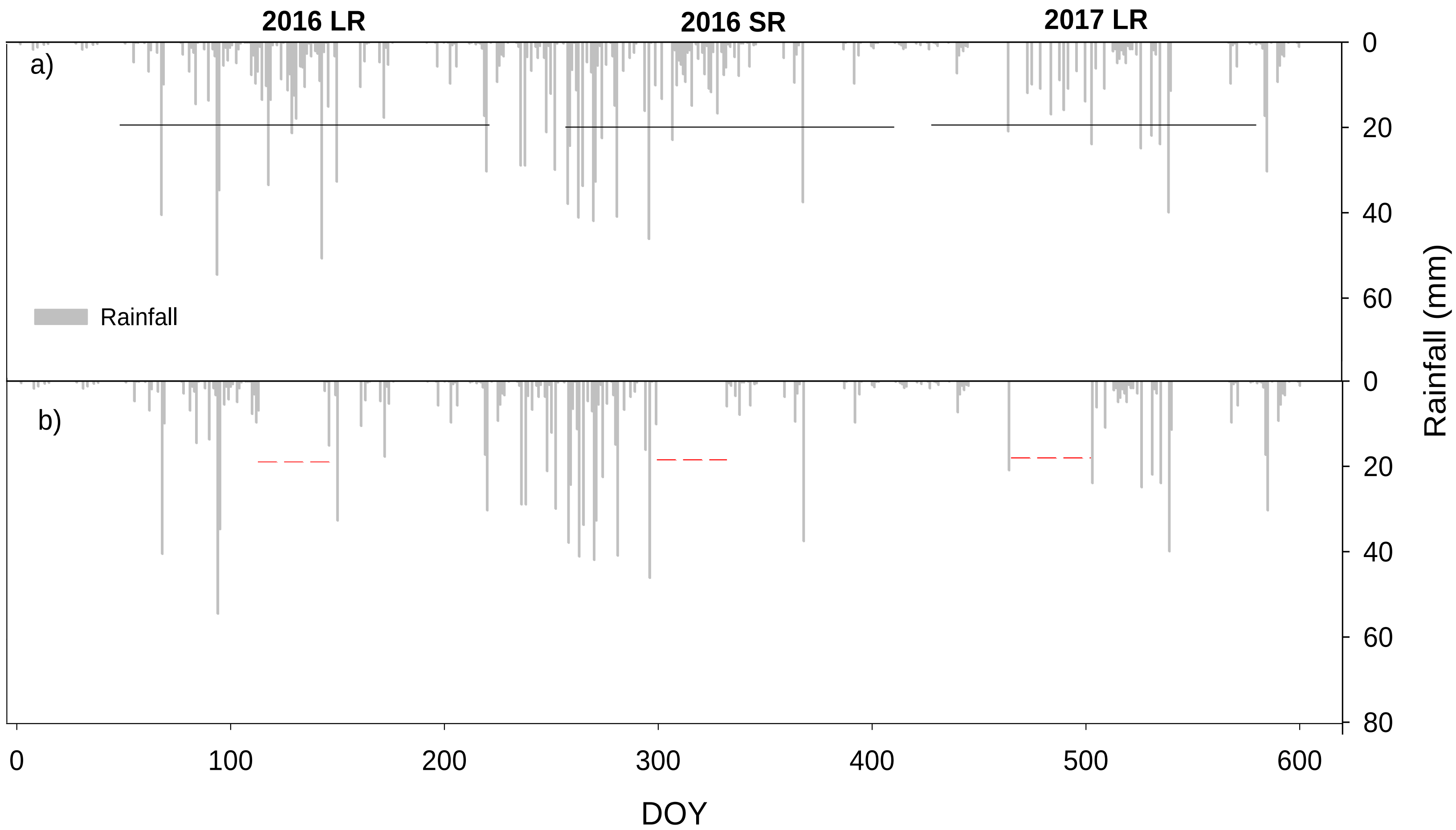

Figure 22. Daily rainfall dynamics a) baseline (BL) and b) drought scenario (NR50–80 DAP) during the 2017 LR, 2016 SR and 2017 LR. The solid horizontal line shows the seasonal growth period under BL and NR50–80 DAP, and the horizontal dotted line shows where drought was imposed for each cropping season.

Table 10. Average and total solar radiation and rainfall under all model scenarios during the 2016 LR, 2016 SR and 2017 LR (variation due to different vegetation periods). BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

	Solar radiation ($W.m^{-2}$)						Rainfall (mm)		
	2016 LR		2016 SR		2017 LR		2016 LR	2016 SR	2017 LR
Scenario	Av.	Sum	Av.	Sum	Av.	Sum	Sum	Sum	Sum
BL	278	42479	287	43334	271	40878	616	717	365
PD1WL	274	41869	291	43868	268	40393	611	649	363
PD3WL	270	41328	293	44285	257	38753	649	445	419
SDC10	280	40338	286	40388	272	38368	615	711	348
SDC30	285	34496	284	34944	275	33306	591	699	348
PD3WL+SDC10	268	39698	296	41160	257	36727	618	439	398
PD3WL+SCD30	274	34542	293	35503	261	31612	545	432	329
NR50-80DAP	278	42479	287	43334	271	40878	368	554	258

4.3.1.4. Long–term precipitation data

The rain rain gauge data and the NASA POWER data of the 2016–monitored period were correlated to assess whether NASA was comparable to the actual measured rainfall data of the rain gauge in the study region. A weak correlation (Pearson correlation coefficient, R^2 = 0.24***) was found between the two datasets (Table A10 in Appendix). However, this data was still used for the analysis of the long–term trends because the 2016 measured rainfall data included periods of long dry spells, which may have created a larger variability relative to the NASA POWER data. Apart from this, several attempts to predict seasonal rainfall in eastern Africa using predictive models have encountered several drawbacks (Nicholson, 2017). For instance, the short rains are relatively predictable, whereas the long rains are not (Dutra et al., 2013; Mwangi et al., 2014). Moreover, most of the dynamic prediction models poorly predict extreme events and under predict drought in eastern Africa (Korecha and Sorteberg, 2013; Jury, 2014). Planting dates under the long term–term rainfall data were based on the assumptions of the current BL planting dates.

Total rainfall under the three planting dates (BL, PD1WL and PD3WL) from the beginning of March and September for LR and SR respectively was analysed to reveal the trend in rainfall pattern and to assess the cumulative rainfall under each planting window (Fig. 23). Rainfall during the cropping period was less under BL planting date compared to PD1WL and PD3WL in the LR, except from 2005 to 2019, where rainfall under BL was greater than PD1WL. Planting three weeks after BL (PD3WL), showed the highest total rainfall. In the short rains, rainfall was generally highest under PD3WL, but showed the lowest amount from 1990 to 1994. In this same year, the growing period starting at farmers' traditional planting date (BL) recorded the highest rainfall amount. Thereafter, it also showed higher rainfall than PD1WL from 2000–2004, 2010–2014 and 2015–2019.

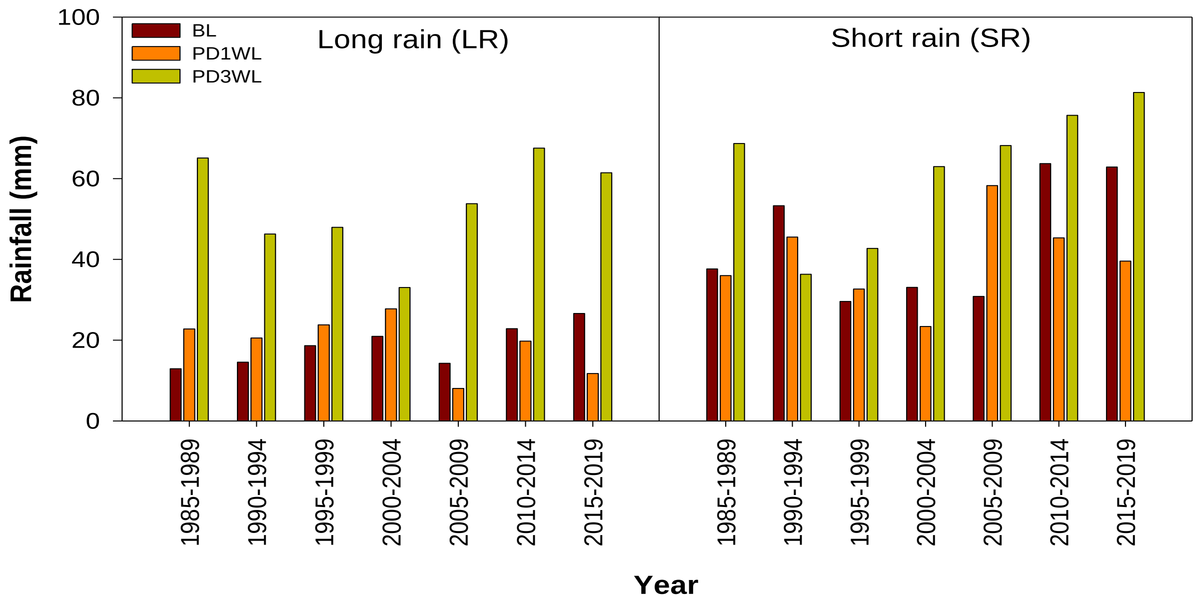

Figure 23. Trend of rainfall during the cropping period under BL (baseline), PD1WL (planting date one week late) and PD3WL (planting date three weeks late) planting dates from 1985–2019. Total rainfall was computed from the following planting windows: LR; BL (60–66), PD1WL (67–73) and PD3WL (74–87 day of year (DOY)); SR; BL (244–250), PD1WL (251–257) and PD3WL (258–271 DOY).

Deviations of the seasonal rainfall from the long–term average (1982–2019) was calculated to properly understand the nature of the rainfall overtime (Fig. 24a and b). The computed deviations were then categorised as very wet (precipitation >30% above long–term mean), moderately wet (precipitation 11–30% above long-term mean), normal (precipitation ±10% above or below the long–term mean), moderately dry (precipitation 11–30% below the long–term mean), and very dry (precipitation >30% below long-term mean).

During the long rain, very dry and very wet rainfall conditions occurred in 2000 and 2018, respectively, over the 32 years period, representing a probability of occurrence of 3% each (Fig. 24c). Normal rainfall (11–30% below the long–term mean) was dominant through the LR season, representing 45% chance of occurrence. The probability of receiving moderately wet or moderately dry rainfall ranged from 24 to 26%.

The chances of a very wet or a very dry rainfall occurring increased from 3% in the long rainy season to 16% during the short rains (Fig. 24d). The likelihood of having a normal rainfall also reduced to 26%. More of moderately dry rainfall (24%) is expected compared to moderately wet (18%) rainfall conditions.

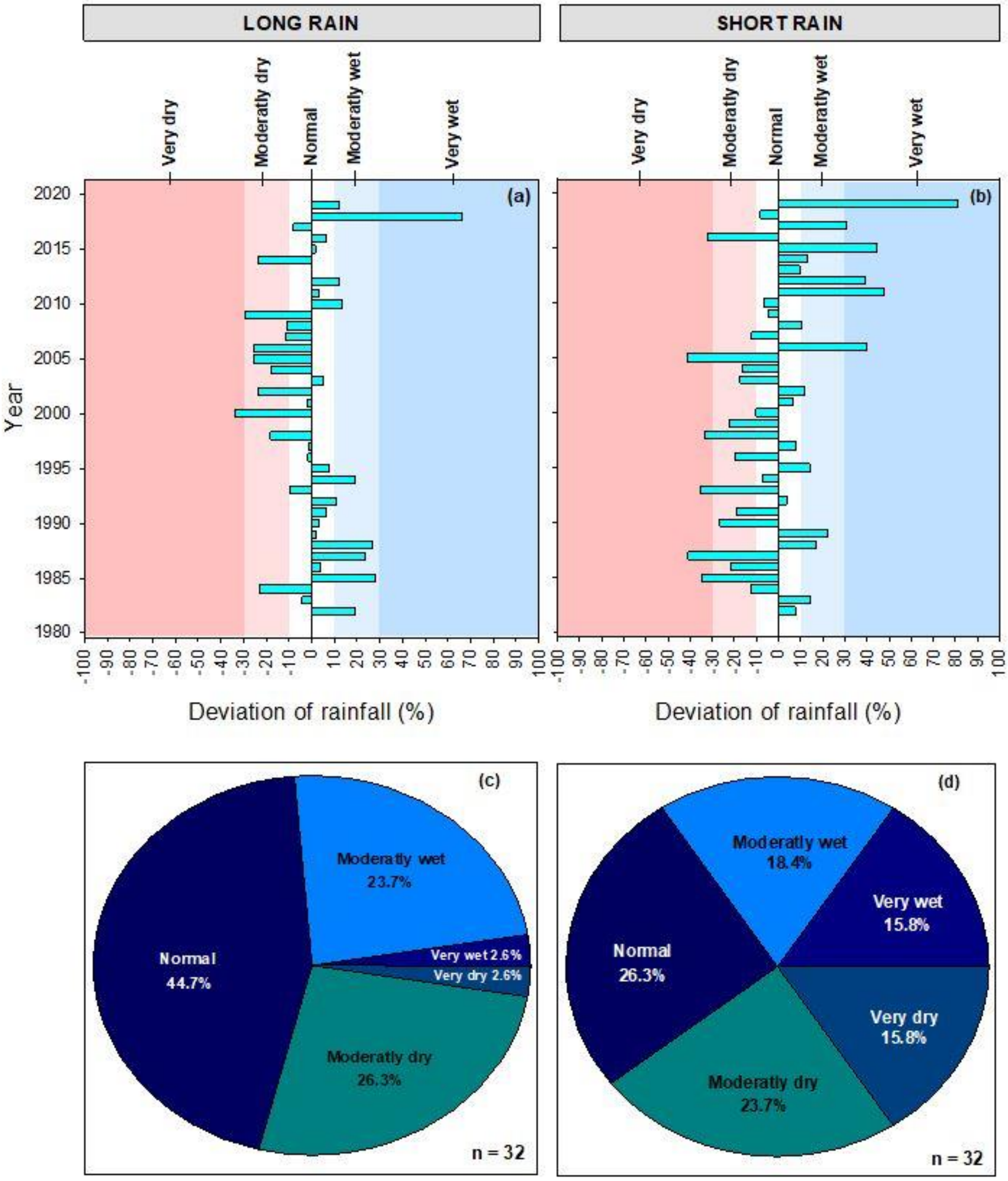

Figure 24. Deviation of seasonal rainfall from the long–term (1982–2019) rainfall mean (898 and 566 mm for LR and SR respectively) of Rongo County, Kenya (a) and probability of five rainfall categories (b): Very wet=precipitation >30% above long-term mean, Wet=precipitation 11–30% above long-term mean, Normal=precipitation ±10% above or below the long–term mean, Moderately dry=precipitation 11-30% below the long–term mean, Very dry=precipitation >30% below long-term mean. Rainfall data was accessed from NASA Prediction of Worldwide Energy Resources (POWER) for Rongo County.

4.3.1.5. Effect of delayed planting, early maturing crop and drought on crop performance

We simulated the impact of late planting (PD1WL, PD3WL), short duration crop (SDC10, SDC30), their combinations (SDC10+PD3WL, SDC30+PD3WL) and drought (NR50–80DAP) on aboveground biomass production (AGB) and grain yield.

In the 2016 LR, lower AGB was attained under the baseline condition (BL) and the other scenarios for all the crops compared to the 2016 SR and 2017 LR (Fig. 26). The BL showed higher AGB than the two SDC cultivars and NR50–80DAP during 2016 LR for Muc, Mul and MzBn. The AGB of Gnt and Lab were similar for all the scenarios during this season. In 2016 SR, the BL AGB of Muc, Mul, MzBn further exceeded PD3WL+SDC10 and PD3WL+ SDC30 in addition to the two SDC cultivars and NR50–80DAP in 2016 LR. For Gnt and Lab, AGB was higher under BL compared to the other scenarios except the two SDC cultivars during the 2016 SR. All the scenarios except climate change produced higher AGB than the BL during the 2017 LR for Muc. However, for Mul and MzBn, PD3WL, SDC10 and PW3WL+SDC10 were the only scenarios that produced higher AGB than BL. No AGB was produced under all the scenarios for Gnt and Lab during the 2017 LR.

The two SDC showed lower AGB compared to the rest of the scenarios in exception of climate change during the 2016 LR for Muc, MzBn and Mul. The AGB of Muc under SDC10 and SDC30 similar. For Mul and MzBn, the AGB of SDC10 was higher than SDC30. Relative to BL, the AGB of SDC30 showed a reduction of 75.4 and 75% for Mul and MzBn respectively (Fig. 27). A similar trend in AGB of Muc under SDC10 and SDC30 in 2016 LR was observed during the 2016 SR except NR50–80DAP, which also showed higher AGB than the two SDC cultivars. The lowest AGB of Muc, Mul and MzBn was produced under SDC30. In this same season, the AGB's of Gnt and Lab were highest under SDC10 and SDCC30. In the subsequent season (2017 LR), SDC10 showed the highest AGB for Muc, exceeding the BL by 62%, whereas, SDC30 was the third highest after PD3WL+SDC10. The

AGB of Mul and MzBn under SDC10 was third highest after PD3WL and PD3WL+SDC10, but increased over BL by 20 and 18% respectively.

Late planting of Muc, Mul and MzBn one and three weeks (PD1WL and PD3WL) during the 2016 LR and SR produced relatively higher AGB compared with BL and the other scenarios. For Gnt and Lab, AGB simulation under late planting exceeded only PD3WL+SDC10, PD3WL+SDC30 and NR50–80DAP. Among the late planting scenarios, PD3WL showed higher AGB than PD1WL. In 2017 LR, simulated AGB was highest under PD3WL for Mul (12,600) and MzBn (12,500 kg ha^{-1}) exceeding the BL by 37 and 35% respectively. The highest AGB of Muc in 2017 LR was simulated under SDC10.

Planting the short duration crops late (PD3WL+SDC10, PD3WL+SDC30) showed higher AGB of Muc, Mul and MzBn than BL during the 2016 LR. However, during the 2016 SR, a reverse trend was observed under PD3WL+SDC30 with lower AGB compared to BL. The AGB under PD3WL+SDC10 exceed the BL by 11, 18, and 15% for Muc, Mul and MzBn respectively. Late planting of SDC cultivars of Gnt and Lab decreased AGB compared to BL during the 2016 SR. The AGB of Muc under PD3WL+SDC10 and PD3WL+SDC30 was higher than the BL in the 2017 LR. But for Mul and MzBn, only PD3WL+SDC10 exceed the BL, whereas, PD3WL+SDC30 showed similar AGB to BL.

The drought scenario (NR50–80DAP) produced no AGB for all the crops during the 2016 LR. Much of the AGB under NR50–80DAP was produced in the 2017 LR for Muc, Mul and MzBn, but it was still the lowest compared to the BL and the rest of the scenarios. In 2016 SR, only SDC30 showed lower AGB compared to NR50–80DAP.

Delayed planting of the SDC cultivars (PD3WL+SDC10 and PD3WL+SDC30) gave higher AGB than planting them to the BL (SDC10 and SDC30) during the 2016 LR and SR for Muc, Mul and MzBn. The opposite trend was observed for Gnt and Lab during the 2016 SR.

Also, PD3WL+SDC10 produced higher AGB than PD3WL alone whereas, PD3WL+SDC30 showed lower AGB than PD3WL alone during 2016 LR and SR for Muc, Mul and MzBn. The AGB of Muc under PD3WL+SDC30 was higher than PD3WL during 2017 LR whereas, under Mul and MzBn, PD3WL+SDC30 showed lower AGB than PD3WL.

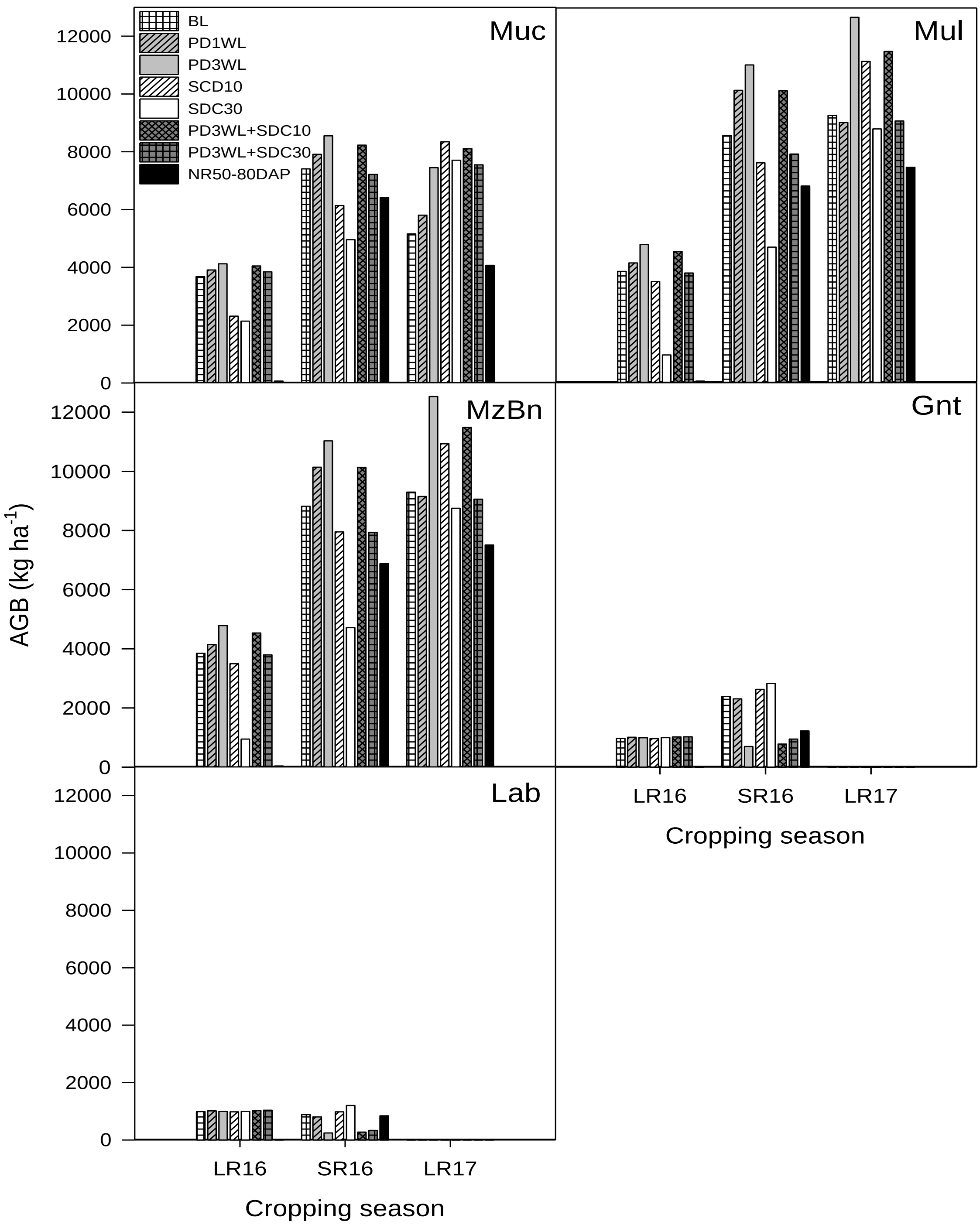

Figure 25. Effect of late planting, short duration cultivar and drought scenarios on aboveground biomass (AGB) under each cropping system (Muc: Mucuna Mul: Maize bean under mulch, Gnt: Groundnut, MzBn: maize bean intercrop and Lab: Lablab) during LR 2016, SR 2016 and LR 2017. Biomass production failed under Gnt and Lab during the 2017 LR. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

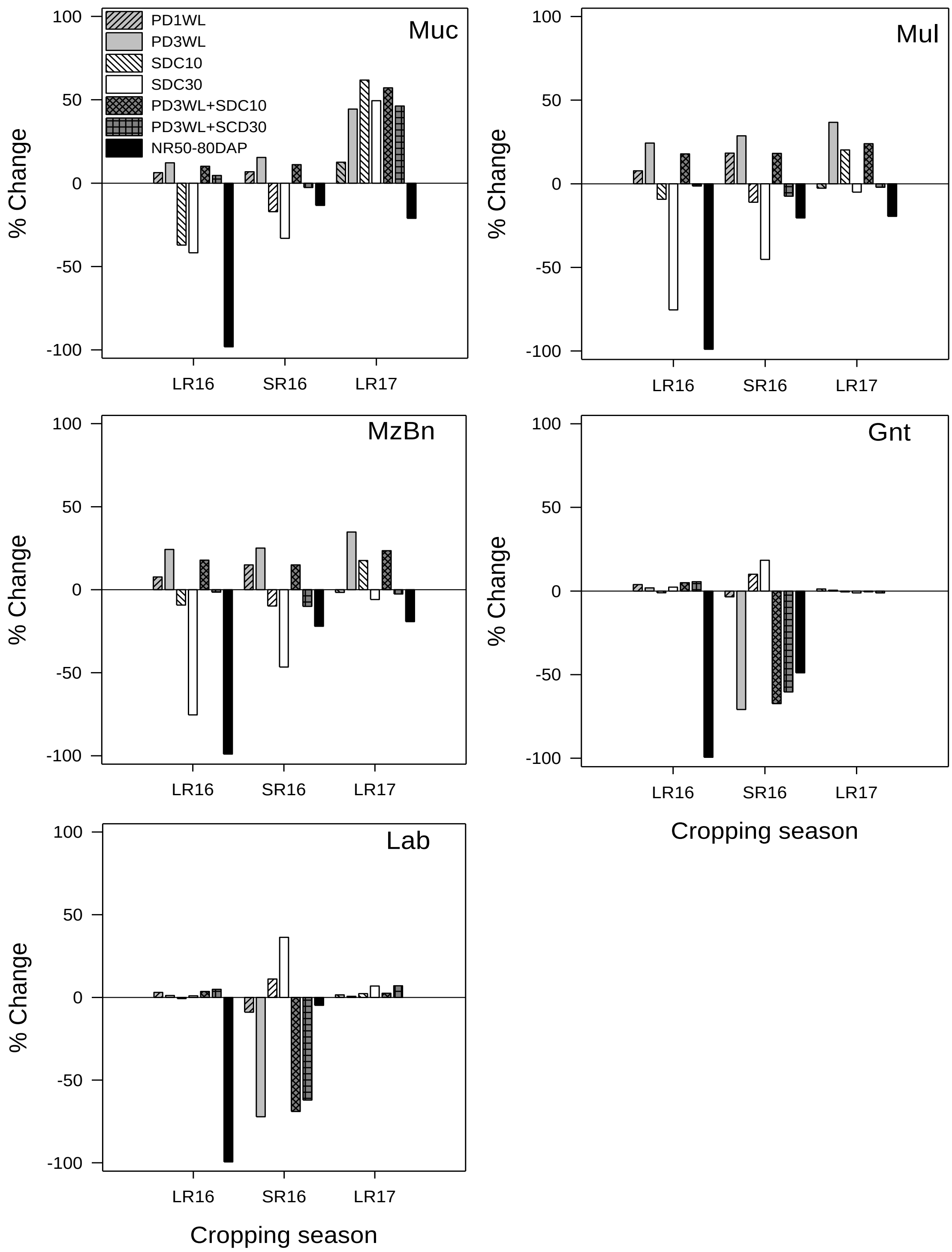

Figure 26. Percent change in AGB of the late planting, SDC genotypes and drought scenarios relative to the baseline (BL) under each cropping system (Muc: Mucuna, Mul: Maize bean under mulch, Gnt: Groundnut, MzBn: maize bean intercrop and Lab: Lablab) during LR 2016, SR 2016 and LR 2017. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

Grain yield production followed a similar dynamic as was observed for ABG for each crop under the tested scenarios per season. (Fig. 28). Grain yields of Mul and MzBn under BL during the 2016 LR and 2017 LR were relatively higher than 2016 SR. For Muc, simulated grain yield under BL was lower in the 2017 LR compared to the previous two seasons. Simulated Gnt grain yield under BL was higher in the 2016 SR than the 2016 LR. Lablab grain was almost zero under BL during the 2016 SR.

The grain yield of Muc simulated under SDC10 and SDC30 were lowest during the 2016 LR except NR50–80DAP, and lowest during the 2016 SR. For Mul and MzBn, SDC10 and SDC30 were still among the low grain yields in 2016 LR and SR. In 2016 LR, grain yield reduction under SDC30 relative to the BL was 75 and 76% for Mul and MzBn respectively (Fig. 29). In 2017 LR, simulated grain yield under SDC10 was higher than the baseline.

Delayed planting showed higher grain yield compared to the BL for Muc, Mul, MzBn during all three seasons except, PD3WL in 2016 LR for Muc. Groundnut and Lablab yields under PD1WL and PD3WL were similar to BL during the 2016 LR. In 2016 SR, Gnt yields under PD1WL were sustained but yields under PD3WL reduced 90% below the BL whereas, no grain was produced under PD1WL and PD3WL for Lab.

Grain yields of Muc, Mul and MzBn under PD3WL+SDC10 exceeded the grain in all three seasons except, Muc in 2016 LR where BL showed 9% increase over PD3WL+SDC10. On the other hand, simulated Mul and MzBn grain yield under PD3WL+SDC30 were lower compared to the baseline yields in all the three cropping seasons. Similar grain yields were observed under PD3WL+SDC10, PD3WL+SDC30 and BL for Gnt and Lab during the 2016 LR, whereas, grain yield under PD3WL+SDC10 and PD3WL+SDC30 showed 87 and 85% reduction below BL for Gnt.

Under drought spell, no grain was produced during the 2016 LR cropping season for all the crops. In the next season, grain yield produced under drought were lower than the BL for all the crops but, exceeded the simulated grain yield under SDC10, SDC30 and PD3WL+SDC30. The drought spell produced the lowest grain yield during the 2017 LR.

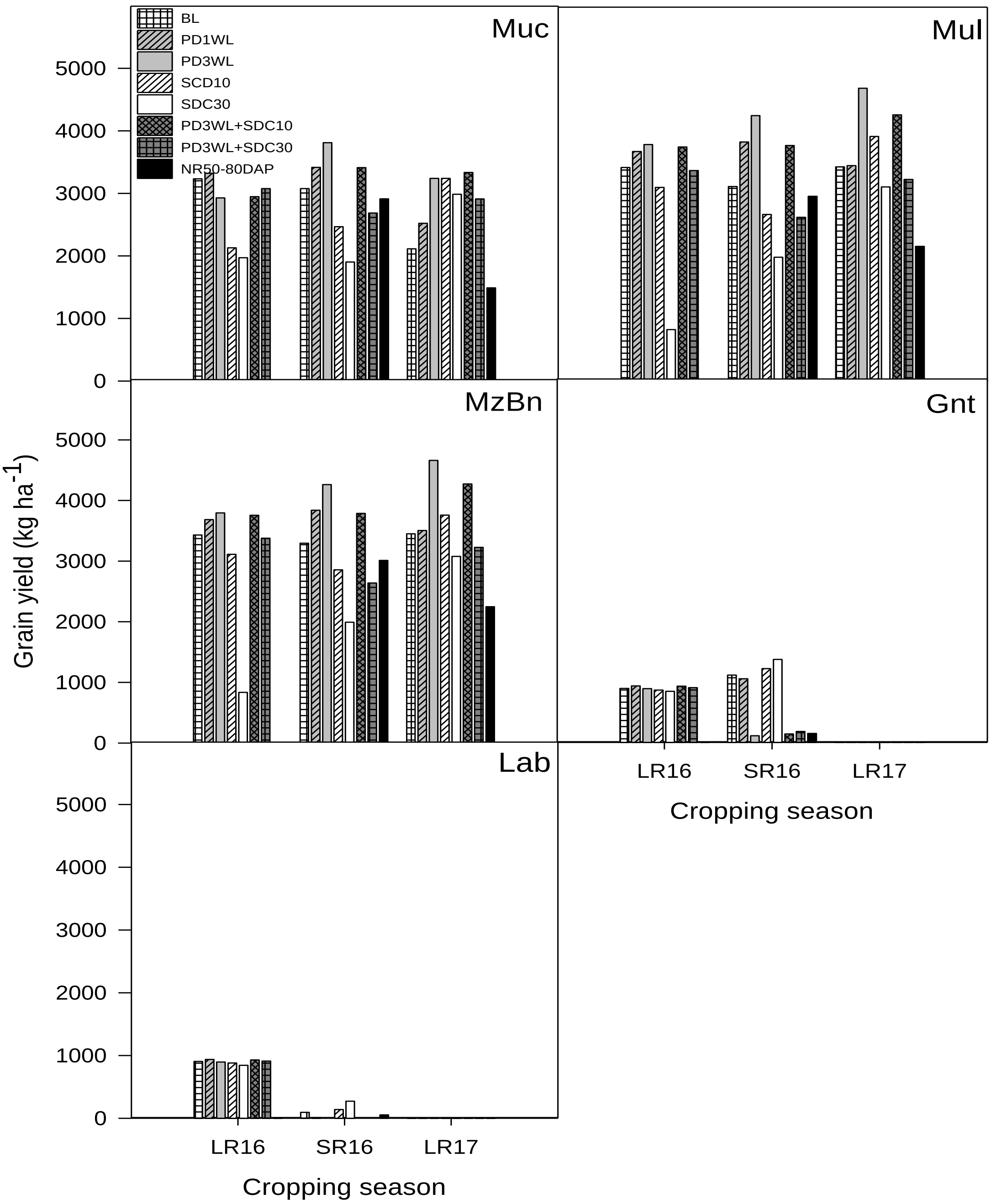

Figure 27. Effect of late planting, short duration genotype and drought scenarios on grain yield under each crop (Muc: Mucuna, Mul: Maize bean under mulch, Gnt: Groundnut, MzBn: Miaze bean intercrop and Lab: Lablab) during LR 2016, SR 2016 and LR 2017. Grain production failed under Gnt and Lab during the 2017 LR. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

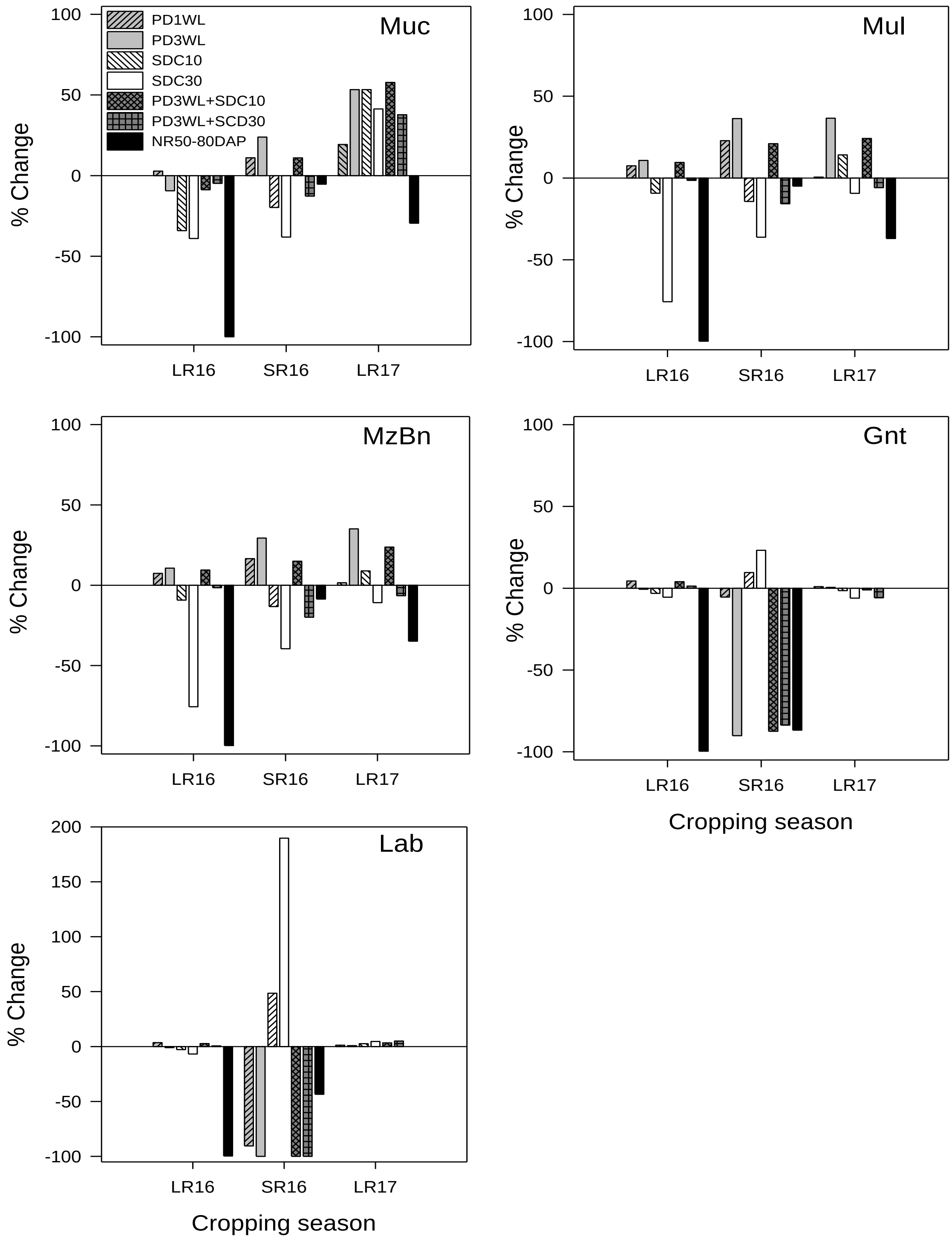

Figure 28. Percent change in grain yield of the late planting, SDC genotypes and drought scenarios relative to the baseline (BL) under each cropping system (Muc: Mucuna, Mul: Maize bean under mulch, Gnt: Groundnut, MzBn: Maize bean intercrop and Lab: Lablab) during LR 2016, SR 2016 and LR 2017. Note the different y–axis for Lab. BL: baseline, PD1WL: planting date one week late, PD3WL: Planting date three weeks late, SDC10: short duration crop 10 days < baseline, SDC30: short duration crop 30 days < baseline, SDC10+PD3WL: SDC10 planted three weeks late, SDC30+PD3WL: SDC30 planted three weeks late, and NR50-80DAP: No rainfall from 50–80th day after planting.

4.3.1.6. Assessing the impact of delayed planting, early maturing crop and drought on ET and WUE

Simulated total seasonal evapotranspiration (ET) and water use efficiency (WUE; computed as grain yield per unit water evapotranspiration) were used to evaluate the impact of the water stress management scenarios. Total seasonal ET and WUE varied under each management scenario for each cropping system (Table 11).

Under baseline simulations, the highest ET was achieved during the 2016 SR for all the crops. In this same season, WUE under BL was at its lowest compared to the other seasons for Muc, Mul and MzBn. Muc showed the highest ET among the crops during the 2016 LR and SR. For WUE, the highest occurred under Mul and MzBn followed by Muc for all three seasons.

The short duration cultivars (SDC10 and SDC30) were among the scenarios that showed the lowest ET apart from NR50-80DAP during the 2016 LR. Their corresponding WUE's were lower than the BL. Among the crops, Mul and MzBn showed the highest WUE followed by Muc. The WUE under SDC10 was mostly higher than SDC30. In 2016 SR, SDC10 and SDC30 showed lower ET and WUE than BL for Muc, Mul and MzBn. However, in 2017 LR, higher ET were simulated under SDC10 and SDC30 than BL for Muc whereas, the rest of the crops showed the lower ET than BL. The estimated WUE were however higher under SDC10 and SDC30 compared than BL for all the crops except Gnt and Lab.

Under late planting (PD1WL and PD3WL), PD3WL in particular showed the highest ET compared to the rest of the scenarios during all the three seasons. A similar trend in ET under PD3WL was not observed for the estimated WUE. However, WUE under PD3WL was higher than BL during the 2016 SR and 2017 LR for Muc, Mul and MzBn. Simulated ET under PD1WL was only higher than BL during the 2016 and 2017 long rains for Muc. The

WUE under PD1WL was similar to BL during the 2016 LR for Muc, but was higher than BL during the subsequent two seasons.

Looking at the combined late planting and short duration cultivar scenarios, PD3WL+SDC10 showed greater ET and lower WUE than the BL during the 2016 LR for Muc, Mul and MzBn. Evapotranspiration and WUE in absolute terms between PD3WL+SDC10 and BL were similar for Gnt and Lab during this season. In 2016 SR, both PD3WL+SDC10 and PD3WL+SDC30 showed lower ET compared to BL for all the crops. This corresponded to higher WUE of Muc, Mul and MzBn under PD3WL+SDC10 and PD3WL+SDC10 than BL. Simulated ET increased under PD3WL+SDC10 relative to BL in 2016 LR for Muc, Mul and MzBn, but also showed similar trend in WUE.

Generally, the drought scenario showed the lowest ET among the scenarios for all the crops throughout the three cropping seasons. Water use efficiency was low under NR50-80DAP during the 2016 LR for all the crops. In the 2016 SR cropping season, estimated WUE under NR50-80DAP was higher than BL for Muc, Mul and MzBn.

Table 11. Effect of late planting, SDC genotypes and drought on evapotranspiration (ET) and water use efficiency (WUE) under each cropping system (Muc, Mul, Gnt, MzBn and Lab) during LR 2016, SR 2016 and LR 2017. Data shows averages of simulated total seasonal ET and WUE.

	2016 LR									
	ET (mm)					**WUE (kg ha^{-1} mm^{-1})**				
Scenario	Muc	Mul	Gnt	MzBn	Lab	Muc	Mul	Gnt	MzBn	Lab
BL	240	212	195	212	195	13.45	16.20	4.57	16.21	4.64
PD1WL	251	211	192	211	193	13.24	17.50	4.85	17.50	4.88
PD3WL	306	242	196	242	196	9.57	15.67	4.52	15.67	4.57
SDC10	203	195	195	195	195	10.51	15.99	4.43	16.00	4.51
SDC30	197	171	177	171	177	10.03	4.88	4.76	4.88	4.77
PD3WL+SDC10	284	220	191	220	191	10.40	17.04	4.87	17.04	4.88
PD3WL+SCD30	232	195	180	195	180	13.26	17.37	5.01	17.37	5.05
NR50-80DAP	109	98	98	98	98	0.00	0.07	0.03	0.07	0.03

	2016 SR									
	ET (mm)					**WUE (kg ha^{-1} mm^{-1})**				
Scenario	Muc	Mul	Gnt	MzBn	Lab	Muc	Mul	Gnt	MzBn	Lab
BL	413	355	241	360	238	7.46	8.79	4.61	9.16	0.39
PD1WL	401	362	231	362	229	8.52	10.59	4.56	10.60	0.04
PD3WL	437	391	263	391	262	8.73	10.90	0.42	10.91	3.43
SDC10	371	328	241	334	238	6.64	8.16	5.06	8.56	0.59
SDC30	332	284	229	284	226	5.73	7.03	5.99	7.02	1.20
PD3WL+SDC10	349	312	181	312	179	9.79	12.13	0.77	12.15	0.00
PD3WL+SCD30	320	276	178	276	176	8.39	9.53	1.02	9.55	5.16
NR50-80DAP	302	246	158	246	156	9.64	12.08	0.93	12.25	0.34

	2017 LR									
	ET (mm)					WUE (kg ha^{-1} mm^{-1})				
Scenario	Muc	Mul	Gnt	MzBn	Lab	Muc	Mul	Gnt	MzBn	Lab
BL	228	234	118	247	118	9.28	14.70	0.02	13.98	0.02
PD1WL	244	235	117	248	117	10.35	14.70	0.03	14.11	0.03
PD3WL	297	273	125	276	125	10.93	17.22	0.02	16.90	0.02
SDC10	275	230	118	236	118	11.79	17.03	0.02	15.92	0.03
SDC30	254	163	88	169	88	11.77	19.13	0.03	18.17	0.04
PD3WL+SDC10	274	249	111	255	111	12.18	17.12	0.03	16.77	0.03
PD3WL+SCD30	238	191	111	190	111	12.23	16.95	0.03	16.94	0.03
NR50-80DAP	166	164	82	168	82	8.98	13.17	0.04	13.40	0.04

4.3.2. Discussion

4.3.2.1. Grain yield production as affected by late planting, early–maturing cultivars and drought

Variations in planting date and selection of varieties with different vegetation periods offer the opportunity to explore favourable conditions at critical growth stages for increased or high yield production. Early planting generally increases or improves grain yield through early harvesting which helps to avoid likely environmental stresses like solar radiation and unbalanced growth period interval, which reduces grain yield (Shrestha et al., 2018). However, this is only the case where water is not limiting, i.e. no pronounced dry seasons occur. In regions with uni- or bimodal rainfall, regime-planting dates are bound to rainy seasons. Under these conditions, delayed rainfall and drought conditions resulting from weather variability may additionally force farmers to plant late (either through replanting or gap filling of failed crops late in the season), a practice that increases operation cost (Benson, 1990).

Late planting reduces the length of the growing season (Nielsen et al., 2002) and, depending on the region, may expose plants to drought, less radiation availability and thermal conditions during their active vegetation stage, which leads to over vegetation development and reduces dry matter accumulation in kernel that ultimately results in decreased grain yield (Otegui and Melon, 1997). We showed in the LGE experiment that groundcover protection under Mul was decisive for the low soil erosion. On the other hand, late planting caused delayed canopy development, which led to increased soil erosion and reduction in grain yield even though this was not investigated in detail.

Our simulated grain yield from delayed planting contradicts the late planting and decreasing grain yield relationship. Maize (Mul and MzBn) and Muc planted one and three weeks later than usual showed increased grain yield, and this could be explained by delay of an unevenly distributed rainfall pattern, which could have shifted the optimal planting window ahead in favour of the late planting dates. A regionally specific understanding of the trends in the planting window are needed, especially in the context of climate change.

Planting short duration crops (SDC) to the baseline-planting window decreased their grain yield compared to the baseline full–season cultivar (BL). It has been shown that SDC may suffer yield penalty if the length of the cropping season is sufficient for late–maturing cultivars (Sorensen et al., 2000). Lauer et al. (1999) attributed this to the inability of SDC’s to fully utilize the available solar radiation for the period when temperatures are optimum for growth, so that they will not realise the full yield potential of the growing season.

Interestingly, late planting of the SDC’s increased their grain yield relative to the level of BL or more especially for PDWL3+SDC10 during all three seasons for Mul and MzBn, and during 2016 SR and 2017 LR for Muc. Gnt and Lab only showed this trend during the 2016 LR. This supports the findings of Staggenborg et al. (1999) that SDC’s could equal or outperform full–season cultivars when planted late. The different trend for Muc during the 2016 LR could be due to environmental factors such as less accumulation of solar radiation under PD3WL+SDC10, which hindered grain production, in contrast to higher AGB under PD3WL+SDC10 compared to BL (Fig. 25) in the same season. For Gnt and Lab, the less allocation of assimilates to their organs in LUCIA, coupled with the late planting in combination with lesser length of the growing season might have limited adequate use of growth resources resulting in low grain yield.

The results of the late planting and its combination with the short duration crop confirmed our third hypothesis, that grain yield production under drought will improve compared to BL. In the case of PD3WL+SDC30, where grain yields were lower than under BL, Richards

(1996) found that early planting with a full–season cultivar has greater yield potential than a late planting with an SDC only if there is sufficient water in the early season. This is because the larger length of the growing season allows for greater use of resources such as radiation, water, and nutrients by the crop (Andrade et al., 2000; Tsimba et al., 2013; Parker et al., 2016).

In most crops, the impact of drought stress (which is expected to increase due to climate change) is mostly experienced during flowering. Shaw (1997) found that maize is most vulnerable to drought stress at flowering. In our simulation study, grain yield showed decreased trends particularly in the two rainy seasons (2016 and 2017 LR) when all the crops were exposed to water stress at flowering. Exposure of crops to water deficit during flowering may delay silking, increasing the anthesis–silking interval that may result in reduced sink size through poorly pollinated ears or through abortion of kernels and ears (Bolanos and Edmeades, 1996). From a modelling perspective, this could be explained by the allocation of assimilates to the different parts of the plant before and after flowering as the LUCIA model does not include pollination and abortion of kernels.

This simulation study brings into perspective decision making regarding planting date and cultivar maturity in Rongo. The combination of planting date and cultivar maturity aimed to maximize grain yield. When planting occurs beyond the optimum planting date (first rain in March and September for LR and SR respectively), planting an SDC becomes useful, because it ensures early grain production and secures harvest before the season ends. This study also elucidated the risk associated with drought stress, especially when it coincides with the flowering period.

The cropping calendar of farmers in this region will be severely affected if drought occurs early in the season. There is a high risk of losing all investments in seeds, fertilizer, labour etc. through re–planting or seed and labour cost in the case of gap filling. Depending on the temporal extent of the drought e.g. if it becomes extensive and decreases the length of the cropping season, early–maturing cultivars must be planted and this brings additional cost to the farmer. There is hardly any window of opportunity for farmers e.g. for replanting if the drought occurs late in the season. Farmers may risk losing all their crops and investments especially, if the late drought coincides with periods of critical crop phenological development such as flowering. Thus, selection of the right crop cultivar and the optimal planting window will be key for future crop productivity, specifically in the context of climate change.

The use of planting date and different vegetation cultivar are two main strategies used for crop adaptation and mitigation to manage unfavourable growing conditions (Baum et al., 2019). These strategies are useful for grain crops such as *Maize*, *Groundnut*, *Common bean*, but may not be useful for cover crops such as *Mucuna*. Linquist et al. (2005) affirmed that planting date and vegetation maturity together with the prevailing climatic condition control the length of the growing season in which crops accumulate radiation that is positively correlated with grain yield. Cover crops are grown purposely for increased dry matter accumulation and not for their grain yields, hence decisions, such as planting windows, are critical, because they also produce less fodder, mulch and soil cover against erosion if affected by drought although this may depend on their drought adaptation, which can be better than crops.

Improving the grain yield potential of SDC would stabilize yields and increase the income of farmers. In soybean [*Glycine max* L.] (Kantolic et al., 2007) and wheat [*Triticum aestivum* L.] (Richards and Townley–Smith, 1987), a shorter vegetative growth in favour of a longer grain filling period allowed an increase in grain yield under optimal and drought–stressed conditions among cultivars of the same maturity group. However, in tropical crops e.g.

maize, Trachsel et al. (2017) argued that the relationship among time to anthesis, the grain filling duration, and crop cycle length have not been investigated. It is therefore unclear whether reducing time to anthesis is feasible without altering physiological maturity (Trachsel et al., 2017).

Furthermore, reducing time to flowering would increase grain-filling time leading to increased grain yield, hence could also be used as a breeding strategy to improve grain production in SDC's. In our SDC scenarios, we reduced time to flowering through reduction of GDD to flowering, mainly at the expense of the vegetative phase. We simulated a reduction in biomass and grain yield when GDD to flowering was reduced beyond SDC30 (data not shown). Lee and Tollenaar (2007) showed that reduction in time to flowering can lead to yield penalties related to reduce biomass accumulation, hence targeting cultivars with good early canopy and vigour or planting at high planting density could offset this effect.

Success of early, late or short duration cultivars depends on the prevailing rainfall patterns. It can be argued therefore, that the observed trends are generally valid for the tested cropping seasons. It, however, remains unclear if the observed trends could serve as a guide to farmers in the subsequent cropping seasons. A detailed analysis of the rainfall patterns of the last decades in the region revealed 16% probability of experiencing very dry conditions in the short rains, whereas, the long rainy seasons will be dominated by normal rainfall conditions. Future long–term rainfall data from IPCC scenarios of this region, if available would be needed to test the seasonal results against the averages of the future long–term to discuss the likelihood or risk associated following the recommendations.

4.3.2.2. Significance of planting date, vegetation type and climate change on WUE.

Seasonal ET and crop grain yield were combined in this study to estimate WUE, while the crop specific physiological water use efficiency coefficient, which is the genetically determined ability of the plant to make use of the available water and convert it into biomass, was not altered in the model. Grain yield showed much variability between the planting dates and vegetation type compared to their seasonal ET. Although the impacts of the management scenarios were visible on ET, much of the variability in the estimates of WUE could be primarily explained by the variation in grain yield. It was clear that scenarios that produced low grain yield exhibited the lowest WUE value.

Late planting produced higher WUE compared to the BL planting date, and this was due to the greater loss of grain yield under the latter rather than a corresponding decrease in ET. In a related study on the effect of different sowing dates on maize grain yield and WUE, Feyzbakhsh et al. (2015) established that WUE increased with a delay in sowing. The study attributed this increase to lower temperatures, which decreased evapotranspiration, causing WUE to increase. The model simulation result agrees with Feyzbakhsh's observation. Although there is no direct feedback in LUCIA model between temperature and ET, as ET is uploaded in LUCIA as a time series data. However, LUCIA calculates actual ET based on ETO (reference eveapotranspiration) from time series and corrects for plant coefficient (kc), LAI, canopy cover, soil depth, and soil water. In another study conducted on wheat in northwest Mexico, Duchemin et al. (2015) found that WUE on fields planted late in the season was one–third reduced compared to WUE on the fields planted earliest. This was due to variations in crop production since the seasonal ET was not much affected by sowing date. Duchemin et al. (2015) explained that late sowing reduced plant growth, and fields where plant development was limited exhibited the lowest WUE.

It is expected that a short duration crop would have a lower water requirement due to its shorter growth cycle but at the cost of lower biomass / grain yield, unless they differ in physiological traits. Under semi–arid conditions in eastern Kenya, a late maturing maize cultivar showed 17.6 and 16.7% increases in grain yield and WUE respectively, compared with short duration cultivar (Mo et al., 2017). This was also consistent with the results of Wang et al. (2016), who studied the genetic gains in yield and WUE of wheat and concluded that higher yielding cultivars generally showed improved WUE. Our estimate of WUE showed this trend during the 2016 LR and 2016 SR (except Gnt and Lab), where the BL performed better in WUE than the SDC. In 2017 LR, the SDC cultivars showed higher WUE than BL due to higher grain yield production than BL, particularly for Muc and with exceptions under SDC30 for Mul, MzBn and Gnt. Condon et al. (2004) and Blum (2005) also observed that genotypic variations in WUE were driven mainly by variation in water use or requirement rather than by variations in plant production.

Climate change affects WUE through plant growth (Hatfiled and Dold, 2019). Simulated impact of drought stress from day 50-80 after planting (climate change scenario) decreased grain yield production and led to reduced WUE during the 2016 and 2017 LR's. High grain yield production under more propitious rainfall in 2016 SR could be the reason for the higher calculatory WUE among the crops compared to the other cropping seasons. Guoju et al. (2013) found that in China, WUE of maize increased over the past 50 years due to an increase in temperature and a decrease in precipitation. Further evidence has shown that, in most cases, drought suppresses both ecosystem productivity and ET simultaneously (Zhao and Running, 2009; Liang et al., 2015).

Sowing date, vegetation type and drought showed a marked effect on WUE, which increased with late sowing, and with crop genotypes that showed increased grain yield production, but WUE decreased under drought spells. Over the years, there has been incessant interest in exploiting management and cropping options to optimize agricultural water use in water – scarce environments. Our results showed that focussing on the use of planting date and plant genotypes with adequate vegetation period present the opportunity to increase food production under adverse climate conditions, while at the same time preserving water resources.

Chapter 5. General discussion

5.1. Assessing the vulnerability and mitigation potential of smallholder legume cropping systems to soil degradation

One of the principal aims of this study was to identify legume cropping systems and management practices that are capable of reducing soil erosion by understanding the main impact factors. Understanding the main drivers and control on soil erosion within the study area could lead to the identification of appropriate cropping system designs for improved smallholder farming systems. It was found that groundcover was an important factor in soil erosion mitigation. Together with other significant variables such as canopy cover and rainfall intensity it was established that groundcover had the strongest explanatory power to predict soil erosion.

The underlying hypothesis to this study was that protection of the soil through high groundcover improves soil structure and enhances infiltration, hence reduces runoff and soil loss. Our understanding of groundcover development overtime shed important light on the relationship between vegetation and soil erosion control. The impact of groundcover on soil erosion differed at each stage of crop development, and groundcover for that matter. Monitoring such vegetation growth dynamics in legume cropping systems is critical for understanding the consequences of groundcover changes for soil loss in those parts of the tropics, where soil loss is potentially caused by a limited number of extreme rainfall events.

This goes to suggest that soil erosion has a temporal dimension or is concentrated in time, and thus rapid growth of dense cover offers a better protection of soils under cropland. However, not all the legumes or cropping systems were capable of developing cover in time to counter very high rainfall intensities when they occurred. This explains the differences in the amounts of soil erosion among the tested legume cropping systems in this study, which partly explains their role as sink (erosion control) and source (vulnerability to erosion). Labrière et al. (2015) working on a meta–analysis on vegetation and soil erosion relationship in humid tropics found a common underlying hypothesis, that land use (including cropping systems) has a limited influence on soil erosion provided vegetation cover is developed enough or good management practices are implemented.

Incorporation of fast growing cover legumes such as *Mucuna* in cropping systems offers greater level of soil protection, especially at the onset of the season when the plough layer is highly disturbed and exposed to highly erodible rainfall intensities. *Mucuna* among other cover legumes succumb to adoption issues based on farmers priority, which is mainly food and income centred. Although the importance of farmers needs in such a perspective is highly acknowledged, there are also large trade–offs in soil conservation that are worth exploring. In contrast, conventional legume food crop cropping systems e.g. MzBn and Gnt in this study yielded low groundcover and high soil loss even at the beginning of the cropping seasons compared to *Mucuna*, which may suggest that a co–design of soil conservation and food production systems would lead to best–fit options.

Regarding management practices, the study also contributed to the increasing recognition that good soil management practices such as mulching and intercropping with hedgerows accounted for low erosion rates in agrosystems. This legume cropping system apart from soil conservation and provision of food, feed from maize, common bean and *Calliandra* hedgerow also reduced investment cost in weed control which makes a lot of sense for labour–constrained farmers. Unlike the *Mucuna* and mulch cropping systems, twice weeding conventional management practice carried out in the other cropping systems disrupted soil aggregation, decreased soil protection by crop residues and enhanced soil crusting and surface sealing.

In the short–term, the labour requirement in collecting *Calliandra* mulch could undermine the applicability of Mul in the context of smallholder farmer practice. However, the establishment of the *Calliandra* hedgerow within this cropping system would provide long–term on-site mulch without biomass transfer in the future, which may reduce the burden of labour and increase the likelihood of implementation. The inclusion of *Calliandra* hedgerow also stresses its usfefulness as a fodder in addition to enhancing soil fertility and soil conservation. Given that livestock plays a critical role in the generation of income in this region, the inclusion of *Calliandra* hedgerows is more likely to increase adoption.

Policy makers could make use of these findings paying special attention to supporting farmers with incentives needed to establish long–term viability of these conservation practices. Thus, farmers should be supported with technical knowledge in establishing and managing these trees, as lack of experience in growing them is one of the technical reasons that hamper their inclusion in farming systems. Government subsidy on purchasing *Calliandra* seedlings and other inputs required for its establishment should be provided as a motivation for financial support.

As a preliminary step to mitigate soilerosion, this study stress the need to identify or establish impact factors for soil erosion. Since soil erosion is temporally distributed with high rates at the beginning of the cropping season coinciding with periods of low soil cover, cropping systems that guarantee early groundcover and soil protection are desirable. Although such systems e.g. cover crops come at the compromise of smallholder food production, an improved farming system strategy e.g. Mul that bundles food production and soil protection must be sought.

5.2. Critical slope length – an alternative approach to balance landscape trade–offs

Exploring the main impact factors of landscape–scale soil erosion, we examined different smallholder slope lengths for their role in runoff and soil erosion production. Using a spatial statistical model on a slope length experiment on three farms, a critical slope length under our conditions was reached at 50 m beyond which soil loss, sediment load, and the soil loss to yield ratio began to increase exponentially.

Identification of critical slope length can be an essential step towards sustainable agricultural resource management. Our slope–scale approach to the concept of critical slope length has a potential wider application across landscapes in the context of resource use efficiency and sustainable intensification of rural tropical areas. Although many of the existing landscape–level soil conservation systems are useful, their relevance and implementation are often hindered by several factors such as availability of labour, competition for cropping area, nutrient and water resource, capital input requirements, access to resources and nature of the landscape. Under such circumstances the critical slope length approach provides alternatives to balance trade–offs by targeting specific parts of the slope or landscape to apply soil conservation measures instead of the whole farm.

Labour is required in all soil conservation activities such as building and maintaining terraces, planting of vegetative buffer strip etc. It has been shown that the likelihood for any soil conservation measure being adopted depends on whether the farmer and his household could meet the increased labour demand (Stocking and Abel, 1992). More often than not, labour is prioritized particularly at times of land preparation and harvest where the work is time bound and not in soil conservation. In this context, soil conservation measures demanding increased labour can be implemented near the critical slope length instead of the whole farm to take advantage of the decreased labour requirement.

Competition for cropping area, water and nutrient resources can compromise the direct benefits of most agronomic soil conservation measures. For example, much of the land in strip–cropping in smallholder landscapes is occupied by alternate buffer strips to protect valuable crops. Additionally, the buffer strips may compete with the food crops for water and nutrient resources, which can lead to decreased crop performance. Targeting specific positions of the slope, in this case at the critical slope length to place the buffer strips can save a considerable amount of land that would otherwise be taken out of production by the buffer strips. Such an approach can also enhance the performance of the conservation measure and optimize their benefits through offering no competition among the cropping units.

Most smallholder farmers are under resource and may lack the capital strength to undertake certain soil conservation systems, which may require initial high capital input for establishment and maintenance. The cost component can arise from the need to purchase additional seeds or machinery to support the conservation farming system. Many of these poor farmers will not consider the idea of securing loans because they do not have sufficient security to do so. Alternatively, borrowing money may also appear too risky a step. Moreover, most credit agencies see smallholder farmers as unacceptable risk, and will rather release credit to wealthier large–scale farmers. Taking into consideration all these financial demands and traps, implementing soil conservation at the critical slope length demands less financial investment.

The size of a farm does not necessarily affect or influence the type of soil conservation system to employ. However, its layout, especially the degree of fragmentation as observed in most smallholder landscapes makes it unprofitable for some soil conservation systems such as terraces, as the land is held in parcels and scattered, unless the crop is sufficiently profitable to justify the investment for terraces and whether you have the materials and labour to do this. Mulching may become difficult due to the considerable distance in transporting the mulch between strips of land where they are needed. Besides, the steep slope and rugged terrain of most smallholder landscapes will not allow residue cover crops to be applied on the whole strip of land, as it is labour intensive and these materials can easily be washed downhill. Moreover, mulching with crop residues over the whole strip of land does not make sustainable and economic sense as competing use of crop residues such as fodder, fuel or construction material exist. Making use of critical slope length in these scenarios can promote the sustainable use and development of cultivated land resources in smallholder hilly landscapes.

5.3. Integrating legume cropping systems and slope length options for effective soil conservation

Based on studies of soil erosion, sediment C and N efflux and crop performance under the studied legume planting systems, and soil degradation under smallholder long slopes at three different sites on farmer plots, integrating smallholder cropping systems and slope length options can provide a pathway for effective soil conservation and food security in vulnerable smallholder production systems. It has been shown that the central motive of farmers to adopt cropping systems or soil conservation systems are based on decisions that maximise short–term income rather than preventing long–term soil degradation by erosion. For instance, grain legumes are generally preferred by smallholder farmers in the tropics above green manures and cover crops because they ensure food security, improved diet and income (Giller, 2001). Notwithstanding, benefits from *Mucuna* cover crop relating to soil loss reduction and weed growth suppression through high ground and canopy cover provision offers a potential to co–exist with food crops in a properly defined farming system. Intercropping *Calliandra* hedgerows with smallholder maize–common bean increased diversification and intensification of smallholder farming systems especially considering soil fertility improvement of smallholder lands. Contribution of *Mucuna* and *Calliandra* to the soil–N budget or economy through BNF is crucial in low–input farming systems that prevail in Rongo catchment.

Smallholder farms in south–western Kenya are decreasing in size due to rapidly growing human population (Muyanga and Jayna, 2014). Rongo County covering an area of 208.40 km^2 has a population of 100,547 people (KeNADA, 1999), giving a population density of approximately 483 people km^{-2}. There is not sufficient land in Rongo to accommodate a wide crop rotation with green manures like *Mucuna*, which is not a cash crop. Neither is there sufficient land area to support integration of fodder legumes with animals or production of plant biomass for soil fertility improvement. There is competition for plant biomass between being used as fodder for farm animals and as residue for soil fertility improvement and erosion reduction. Although cover legumes grow rapidly and retain nutrients in the soil that would otherwise be removed by erosion or leaching, their use can sometimes pose problems. Firstly, there is a high risk to attain a satisfactory cover when the main crop establishes and groundcover conditions changed from strong, open sunshine to shade (Morgan, 2005). Secondly, the cost of growing the cover crop may outweigh the benefits to the farmer because most covers do not generate income. Additionally, cover crops compete for the available moisture and, especially in dry areas, may adversely affect the growth of the main crop. Despite these challenges, many studies have shown increased crop production in smallholder systems using leguminous cover crops. Incorporation of 22 weeks old *Mucuna* increased maize grain yield of 0.4 to 1.0 t ha^{-1} over farmers practice in east Africa (Karzzi et al., 2006). Ngome et al. (2011) reported significant increases in maize grain yield of *Mucuna* and *Arachis pintoi* across sites and seasons over control treatments. Maize green manured with *Gliricidia* pruning produced significantly higher maize yield than control by 25–87% in five seasons, and similar yields were observed over seven seasons (Rao and Mathuva, 1999). Thus, there is evidence of yield increases in the long–term when cover crops are intercropped, used in rotations or incorporated as green manures in smallholder cropping systems. This evidence can support additional efforts in generating additional economic gains in their usage in soil conservation to pay off, because the adoption of soil conservation measures is not attractive to smallholders unless accompanied by short-term economic added value (Govers et al., 2017). Ojiem et al. (2006) stated that many of these grain and fodder legumes may offer such a benefit, if planted in the appropriate socio–ecological context. Similarly, soil conservation measures that reduce slope gradient and length (e.g. terraces, grass filter strips, hedgerows) are recognized for their efficacy but only implemented if providing added value or incentive is obtained. The application of soil conservation measures at specific parts of the slope rather than over the entire slope length can be an effective approach to reduce installation costs and minimise competition between crops and legumes, which increases the likelihood of implementation. Knowledge of critical slope length (here 50 m) is crucial for spatial plot design (soil conservation strips) along slopes. *Calliandra* hedgerows and mulch or *Mucuna* in maize–bean systems could serve as buffer strips to truncate long slope lengths when implemented below the critical slope length at derived buffer width using plot slope gradient for conventional systems. Planting legume cash crops (e.g. groundnut, common bean) and maize above the critical slope length will ensure provision of food and income to smallholder households. The relevance and the practicability of these strategies to smallholder farmers is obvious given that it will reduce the burden of labour requirement needed to access and apply mulch only in critical slope length defined wide spaced buffer strips compared to applications over the whole field. Moreover, such approaches are critical in the backdrop of land fragmentation in the region to sustainably maximise land area, and to produce more food per unit resource to achieve positive social outcomes without negative effects on the environment (Cassman, 1999; Hochman et al., 2011). More effort should be put in consolidating and implementing policies particularly those that can provide incentives to farmers to adopt these soil conservation practices. Thus, the provision of good quality legume tree seedlings and cover seeds, technical support in identifying critical slope length, and creation of good market conditions to sell cash crops can increase the value of soil conservation investement, and thus help to enhance its uptake and adoption.

5.4. Modelling sowing window, vegetation cultivar and drought as a decision support for water stress mitigation in smallholder cropping systems.

There is a continuous demand to improve agricultural water management strategies, especially in locations where seasonal variability in rainfall patterns has often resulted in drought and crop water stress. The use of flexible planting windows and hybrid vegetation maturity that enhance water use are recognised strategies that offer a pathway in optimizing agricultural water use (Baum et al. 2019). Simulation models can provide more conveniences in identifying the most suitable sowing date since they permit the evaluation of climatic impact on crop development and yield over longer times and varying planting dates (Teixeira et al., 2017). Dallacort et al. (2010) simulated irrigation schemes to predict effects on crop yield and hydrological components such as evapotranspiration and water requirement. In a study related to our modelling objective on sowing date and vegetation cultivars, Duchemin et al. (2015) used spatial modelling and satellite images to assess the impact of sowing date on yield and WUE in wheat fields. Similarly, Varga et al. (2014) in a greenhouse study simulated the impact of drought spells at different phenological phases of wheat and evaluated their impact on grain yield, phenological traits and WUE. Based on our modelling exercise, it can be shown that planting date and vegetation cultivar type can be used to manage unfavourable growing conditions such as drought and water stress. It can be highlighted from this exercise that: a) critical planting windows for crops should be re–examined for this region due to a changing climate. It is possible to plant later if the weather turns out to be favourable during the rest of the season. Regional climate or meteorological offices should constantly provide farmers with timely weather information to inform and shape farmer's choices about how to adapt their farming practices and operations under a changing climate. However, late planting could delay canopy development and expose the soil to erosion. It could be possible that late planting leads to increased soil erosion, which in turn reduces yields, although this was not examined in detail; b) drought will become more frequent and severe in the future (Yan et al., 2016) necessitating the understanding of the responses of plant performance, ET and WUE to drought. Adaptation measures such as the use of drought tolerant seed varieties, employing irrigation and water harvesting techniques, agriculture crop insurance, and early warning and monitoring systems can reduce the negative impact of drought (Kabubo-Mariara and Karanja, 2007). Some of these adaptation technologies such as irrigation system requires large capital investment which becomes a constraint to smallholder farmers in particular. Governmental support, incentives and policies should be provided to help farmers increase adaptations that protect the agroecosystem in the longer term; and c) the combination of late planting with short duration or vegetation crop showed a high potential to increase grain yield. Breeding strategies could further target traits that will enhance the grain-filling sink without compromising yield penalties of SDC. Such genotypes will be very useful under climate change situations to ensure crop establishment and completion of its life cycle without a reduction in yield. The engagement and incorporation of local knowledge and local stakeholder perspective can enhance the opportunity to identify locally viable implications and decision support for the choice of planting windows and crop duration genotypes. Several participatory modelling approaches are currently in use for this kind of information dissemination. The common element that runs through most of these approaches is the involvement of the local stakeholders with their knowledge of the local conditions. Examples of these approaches are companion modelling (Bousquet et al., 1999; Becu et al., 2008), the use of role–play games (Pak and Brieva, 2010), and participatory rural appraisal (Castella, 2009).

5.5. Outlook

As soil erosion fosters soil degradation and threatens crop performance in Rongo catchment, this study laid some foundation, based on which further research should be carried out. Measurement of ground and canopy cover of cropping systems provided vegetative factors that explained variations in soil loss. However, at the slope scale, the role of plant roots in reducing soil loss is crucial and must be considered as one of the major drivers of soil loss. Since farmers normally harvest all the stover from their fields to feed farm animals, and roots are the only biomass left after every cropping season, it will be interesting to know their relative contribution to runoff and soil erosion under the studied cropping systems. Plant roots have shown positive correlation with soil stable aggregate levels and their effects on soil detachment (Li et al., 1992). Hence, further research into soil conservation practices related to plant roots especially, during periods of low soil cover at the beginning of the cropping season can be explored.

The slope length study was carried out for one cropping season during the long rainy season in 2017. Although we analysed 19 rain events with a range of measured precipitation that represented different stages of groundcover during the course of the season, we recommend that this study should be repeated to cover all the cropping seasons in the study region. The implementation of the slope length studies on farmer fields revealed a knowledge gap regarding farmers' perception and understanding of slope length and how it drives soil erosion in their landscapes. At the same time we encourage approaches that assess the performance of soil conservation strategies on farmer fields, as well as those that reveal an understanding of farmers' reasons for (non–) use of innovations to guide in re–design of soil conservation practices. The outputs and recommendations discussed especially in relation to slope length should not be used to draw general conclusions regarding the whole highland regions of western Kenya, as for instance the slope lengths and cropping systems may differ from Rongo catchment. Nevertheless, it can be expected that although the critical slope length level is likely to be different under alternative settings, the resulting strategic recommendations given still hold.

Modelling agricultural systems can provide decision support in finding solutions to devastating agricultural problems. Results of the modelling study indicate that the LUCIA model could be used as a decision support to help identify optimal planting window and suitable vegetation genotypes, especially in the light of climate change where drought stress can constrain seasonal crop yields. More efforts should be made to simulate runoff and soil loss, particularly under the different slope lengths to assess which position and how conservation measures be implemented to be effective in erosion control. This will be one of the next steps to be done in continuation of this study.

Summary

Soil erosion and land fragmentation threaten agricultural production in large parts of the Western Kenyan Highlands. In Rongo watershed, maize–common bean intercropping systems, which dominate the agricultural landscape, are vulnerable to soil degradation, especially on long slope lengths where ground and canopy cover provision fail to protect the soil from the disruptive impact of raindrops. The inclusion of soil conservation measures like hedgerows, cover crops or mulch can reduce soil erosion, but compete with crops for space and labour. Knowledge of critical slope length can minimise interventions and trade–offs. Hence, we evaluated maize–common bean intercrop (MzBn) regarding runoff, erosion and crop yield in a slope length trial on 20, 60 and 84 m plot lengths, replicated twice on three farms during one rainy season in Rongo, Migori County. Additionally, we investigated systems of MzBn (farmers' practice), MzBn with 5 Mg ha^{-1} *Calliandra calothyrsus* mulch (Mul), *Arachis hypogaea* (Gnt), *Lablab purpureus* (Lab) and *Mucuna pruriens* (Muc), regarding their impact on infiltration, runoff, soil loss, soil C and N loss during three rainy seasons (long and short rains, LR and SR, 2016, and LR 2017). Measured field data on soil, crop, spatial maps and meteorology were used as input datasets to parameterize and calibrate the LUCIA model. The calibrated and validated model was then used to simulate agronomic management scenarios related to planting date (planting with first rain vs baseline) and vegetation cultivar (short duration crop) to mitigate water stress.

Based on the measurements, groundcover was most influential over rainfall intensity (EI_{30}) and plant canopy cover in predicting soil loss. Dense groundcover of Mul at the beginning of the rainy seasons was decisive to significantly ($p<0.05$) lowering overall seasonal average runoff by 88, 87 and 84% over MzBn, Lab and Gnt, respectively, whereas, soil loss under Mul was reduced by 66 and 65% over Gnt and Lab, respectively. The high proportion of large soil aggregates (> 5mm) in the topsoil under Mul at the end of SR 2016 significantly ($p<0.05$) increased infiltration rates (420 mm hr^{-1}) in LR 2017 compared to Lab (200 mm hr^{-1}) and Gnt (240 mm hr^{-1}). Average C and N concentrations in eroded sediments were significantly reduced under Mul (0.74 kg C ha^{-1}, 0.07 kg N ha^{-1}) during the LR 2016 as compared to MzBn (3.20 kg C ha^{-1}, 0.28 kg N ha^{-1}) and Gnt (2.54 kg C ha^{-1}, 0.23 kg N ha^{-1}). Likewise, in SR 2016 Mul showed significantly lowered C and N losses of 3.26 kg C ha^{-1} and 0.27 kg N ha^{-1}, respectively, over Lab (9.82 kg C ha^{-1}, 0.89 kg N ha^{-1}).

Soil loss over 84 m slope length was overall significantly higher by magnitudes of 250 and 710% than on 60 and 20 m long plots, respectively, which did not differ significantly among each other ($p<0.05$). For runoff, 84 m plot length differed significantly from 60 and 20 m, but in the opposite trend as for soil loss. Across all three farms, slope gradient and slope length were the variables with highest explanatory power to predict soil loss. At the individual farm level, under homogeneous slope and texture, slope length and profile curvature were most influential. Considering results of slope length experiments, plot lengths less than 50 m appear to be preferential considering soil loss, sediment load, and soil loss to yield ratio under the given rainfall, soil and slope conditions. Our results call for integrating slope length options and cropping systems for effective soil conservation. We recommend planting *Mucuna* and *Calliandra*–hedgerows as buffer strips below the critical slope length, and legume cash crops and maize uphill. Such approaches are critical in the backdrop of land fragmentation and labour limitation in the region to sustainably maximise land area.

In the modelling exercise, crops planted one and three weeks after the baseline planting date increased Maize and Muc grain yield over the baseline during the three cropping seasons, the three weeks treatment in particular. This could be due to more favourable weather conditions during the shifted vegetation period. Increased grain yield corresponded to high water use efficiency (WUE). The short duration crop planted three weeks after the baseline planting

date (PD3WL+SDC10) showed the highest grain yield after PD3WL (three weeks late plaing with BL variety). The use of cultivars with short growth cycle offers the flexibility of planting again where crops failed due to crop water stress or where the rains delay, ensuring completion of the growth cycle before the season ends. Given that short growth duration crops produce less grain yield compared to their counterpart full season crops, due to the length of their cycles, breeding programs must prioritize traits that can enhance the size of the grain-filling sink. At the plot level, management systems that reduce evaporation and retain soil moisture, e.g. mulching, application of farmyard manure etc., must be promoted to reduce evapotranspiration.

Zusammenfassung

Bodenerosion und Kleinteiligkeit von Betriebsflächen bedrohen die landwirtschaftliche Produktion in weiten Teilen des westkenianischen Hochlands. Im untersuchten Wassereinzugsgebiet von Rongo sind die weit verbreiteten Mais-Bohne-Mischkkultursysteme gefährdet durch Bodendegradierung. Dies ist vor allem auf langen Hängen und dort der Fall, wo der Oberboden nicht durch entsprechende Bodenbedeckung vor Schlagregen geschützt ist. Bodenschutzmaßnahmen wie Hecken, Bodendecker oder Mulch können das Ausmaß von Bodenerosion verringern, konkurrieren aber oft mit der Hauptkultur um Raum bzw. Arbeitskraft. Der gezielte Einsatz solcher Interventionen ausschliesslich in Bereichen kritischer Hangpositionen kann solcherlei Aufwand und Konkurrenzeffekte minimieren. In diesem Zusammenhang wurden in der hier vorgestellten Studie Mais-Bohne-Mischkulturen (MzBn) während einer Anbausaison auf drei unterschiedlichen Hanglängen (20, 60 und 84 m) mit jeweils zwei Wiederholungen auf drei Betrieben in Rongo, Migori County, hinsichtlich Oberflächenabfluss, Erosion und Ertrag verglichen. Zudem wurden MzBn, MzBn mit 5 Mg ha^{-1} *Calliandra calothyrsus* Mulch (Mul), *Arachis hypogaea* (Gnt), *Lablab purpureus* (Lab) und *Mucuna pruriens* (Muc) hinsichtlich Infiltration, Oberflächenabfluss, Erosion, organischem Boden-C und Gesamt-Boden-N während dreier Anbauperioden (lange und kurze Regenzeit 2016 und lange Regenzeit 2017) verglichen. Gemessene Boden- und Pflanzenparameter sowie Boden-, Landnutzungskarten und ein digitales Höhenmodell wurden nebst tagesgenauen Wetterdaten als Eingaben für das Lucia (Land Use Change Impact Assessment)-Modell verwendet. Mit dem kalibrierten und validierten Modell wurden dann Szenarien zum Wasserstressmanagement mit Fokus auf Aussaatzeitpunkten und Sortenwahl (verschiedene Vegetationsdauer) getetstet.

Die Auswertung der Feldversuche zeigte, dass der Grad der Bodenbedeckung (durch Biomasse, Mulch und Streu) stärkeren Einfluss auf Bodenabtrag hatte als Regenintensität (EI_{30}) und Bodenbedeckung des Blätterdachs allein. Die dichte Bodenbedeckung durch Calliandramulch in Mul zu Beginn der Saison war dabei entscheidend für signifikant geringeren Oberflächenabfluss (88, 87 und 84% niedriger als in MzBn, Lab und Gnt) und Bodenabtrag (66 und 65% niedriger als in Gnt und Lab). Der hohe Anteil großer Bodenaggregate > 5mm im Oberboden zum Ende der kurzen Regenzeit (SR) 2016 stand in Zusammenhang mit im Vergleich zu Lab (200 mm hr^{-1}) and Gnt (240 mm hr^{-1}) signifikant erhöhten Infiltrationsraten unter Mul (420mm h^{-1}) in der langen Regenzeit (LR) 2017.

Durchschnittliche C- und N-Konzentrationen in Sedimenten waren in der LR 2016 unter Mul (0.74 kg C ha^{-1}, 0.07 kg N ha^{-1}) signifikant niedriger als unter MzBn (3.20 kg C ha^{-1}, 0.28 kg N ha^{-1}) und Gnt (2.54 kg C ha^{-1}, 0.23 kg N ha^{-1}). Ebenso waren in der SR 2016 C- und N-Verluste deutlich geringer als unter Lab (3.26 kg C ha^{-1} und 0.27 kg N ha^{-1} im Vergleich zu 9.82 kg C ha^{-1} und 0.89 kg N ha^{-1}).

Bodenabtrag bei 84 m Hanglänge war 250 bzw. 710% höher als auf den 60 und 20 m Anlagen, wobei sich letztere statistisch ($p<0.05$) nicht unterschieden. Hinsichtlich Oberflächenabfluss unterschieden sich die Hanglängen ebenfalls statistisch, aber in entgegengesetzter Richtung. Im Vergleich der Flächen auf allen drei Betrieben waren Hangneigung und –länge die statistisch einflussreichsten Faktoren bezüglich Bodenabtrag. Auf den einzelnen Betrieben, d.h. bei gleich Hangneigung und Bodenart, waren Hanglänge und Hangform ausschlaggebend. Als Ergebnis der Hanglängenversuche erwies sich eine Länge von 50 m unter den gegebenen Wetter-, Boden- und Geländebedingungen als kritisch bzgl. Erosion, Sedimentmengen und dem Verhältnis von Erosion zu Ertrag.

Die Ergebnisse dieser Studie legen nahe, dass effektiver Bodenschutz vor allem durch die Integration von Hanglänge und Anbausystem (Pflanzenwahl) erreicht werden kann. Es wird empfohlen *Calliandra*-Hecken mit *Mucuna*-Unterpflanzung als Pufferzonen in Streifen unterhalb der kritischen Hanglänge anzulegen sowie Körnerleguminosen und Mais als cash crops oberhalb. Durch diesen Ansatz kann vor dem Hintergrund der Landfragmentierung und Knappheit an Arbeitskraft in der Untersuchungsregion die nutzbare Landfläche nachhaltig optimiert werden.

Der Modellierungsteil dieser Studie zeigte, dass Erträge bei einer und besonders bei drei Wochen späterem Aussaatzeitpunkt im Vergleich zum lokal üblichen Termin während aller drei Anbauperioden zu höheren Kornerträgen führte. Grund hierfür könnten günstigere Wetterbedingungen während der somit verschobenen Vegetationsperiode sein. Die höheren Erträge gingen einher mit effizienterer Wassernutzung der Pflanzen. Eine Sorte mit verkürzter Vegetationsperiode, drei Wochen nach dem üblichen Termin gepflanzt (PD3WL+SDC10), erzielte die höchsten Erträge.

Sorten kürzerer Vegetationsdauer bieten allgemein höhere Flexibilität in Fällen spät einsetzender Regenfälle oder von Pflanzenmortalität, da auch bei wiederholter Aussaat die Regenzeit noch hinreichend genutzt werden kann. Angesichts der niedrigereren Ertragbildung während verkürzter Vegetationsdauer sollte ein höherer Kornanteil prioritäres Zuchtziel für zukünftige Sorten sein. Auf der Seite der Landwirte bedeutet dies, dass vermehrt Anbausysteme, die Evaporation verringern und Bodenfeuchte konservieren (z.B. Mulchen, Mistgaben), zur Anwendung kommen sollten.

Appendices

Table A1. Profile curvature per replicate (R) and slope length plots (SL). Negative values indicate concave and positive indicate convex shape. Minimum and maximum values for profile curvature are -0.0092 and 0.007, respectively (Blaga, 2012).

Slope length (m)	Farm 1	Farm 2	Farm 3
SL1R1	3.87E-04	-5.00E-04	-1.00E-04
SL1R2	-7.38E-04	1.06E-04	-5.25E-04
SL2R1	-6.88E-05	2.50E-04	5.00E-05
SL2R2	2.08E-04	2.29E-05	6.04E-05
SL3R1	2.98E-05	1.04E-04	-1.49E-04
SL3R2	4.76E-05	1.64E-04	1.79E-04

Positive curvature shows convex slope and negative indicates concave slope (Perkham 2011).

Table A2. Soil characteristics of profile pit on LGE plot.

				Particle size [%]				Soil colour		
Depth [cm]	pH	C	N	Sand	Silt	Clay	BD [Mg ha^{-1}]	Hue	Value	Chroma
0-22	5.1	0.97	0.10	59	12	29	1.16	2.5YR	4	2
22-60	5.2	0.38	0.06	53	13	34	1.21	2.5YR	5	3
60-98	5.3	0.34	0.01	55	12	33	-	2.5YR	4	4
>98	5.1	0.48	0.02	58	13	28	-	2.5YR	3	3

Table A3. LUCIA model soil input parameters obtained during the model parameterization.

Parameter	Input Value	Unit	Explanation	Source of data
Thickness Top	20	[cm]	Topsoil thickness	Measured (LGE & SLE)
Thickness Sub	80	[cm]	Subsoil thickness	Measured (LGE & SLE)
Stones Top	20	[ ]	Stone contents topsoil	Measured (LGE & SLE)
Stones Sub	30	[ ]	Stone contents subsoil	Measured (LGE & SLE)
BD Top	1.6	[Mg.m-3]	Bulk density topsoil	Measured (LGE & SLE)
BD Sub	1.7	[Mg.m-3]	Bulk density subsoil	Measured (LGE & SLE)
Sand Top	63	[ ]	Sand contents topsoil	Measured (LGE & SLE)
Sand Sub	0.5	[ ]	Sand contents subsoil	Measured (LGE & SLE)
Clay Top	25	[ ]	Clay contents topsoil	Measured (LGE & SLE)
Clay Sub	31	[ ]	Clay contents subsoil	Measured (LGE & SLE)
Corg Top	1	[%]	Soil organic carbon topsoil	Measured (LGE & SLE)
Corg Sub	0.9	[%]	Soil organic carbon subsoil	Measured (LGE & SLE)
NT Top	0.1	[g.kg-1]	Total nitrogen topsoil	Measured (LGE & SLE)
NT Sub	0.1	[g.kg-1]	Total nitrogen subsoil	Measured (LGE & SLE)
Nmin Top	0.09	[g.kg-1]	Mineral nitrogen topsoil	Measured (LGE & SLE)
Nmin Sub	0.08	[g.kg-1]	Mineral nitrogen subsoil	Measured (LGE & SLE)
P Bray I Top	0.9	[mg.kg-1]	Phosphorus Bray I extract topsoil	Measured (LGE & SLE)
P Bray I Sub	0.12	[mg.kg-1]	Phosphorus Bray I extract subsoil	Measured (LGE & SLE)
Kav Top	0.061	[g.kg-1]	Plant available potassium topsoil	Measured (LGE & SLE)
Kav Sub	0.077	[g.kg-1]	Plant available potassium subsoil	Measured (LGE & SLE)
pH Top	4.8	[ ]	pH $CaCl_2$ extract topsoil	Measured (LGE & SLE)
pH Sub	4.9	[ ]	pH $CaCl_2$ extract subsoil	Measured (LGE & SLE)
Ksat parent	30	[mm.d-1]	Saturated conductivity of parent material	Default (LUCIA)
Water Top	0.2	[ ]	Topsoil water content (proportion of TPV)	Measured (LGE & SLE)
Water Sub	0.3	[ ]	Subsoil water content (proportion of TPV)	Measured (LGE & SLE)

Estimated parameters (pedotransfer functions)				
Parameter	**Input Value**	**Unit**	**Explanation**	**Source**
TPV Top	0.42	[ ]	Total pore volume (proportion of soil volume) of topsoil	calculated
TPV Sub	0.43	[ ]	Total pore volume (proportion of soil volume) of subsoil	calculated
FC Top	0.25	[ ]	Volumetric water contents at field capacity of topsoil	calculated
FC Sub	0.31	[ ]	Volumetric water contents at field capacity of subsoil	calculated
PWP Top	0.16	[ ]	Volumetric water contents at permanent wilting point of topsoil	calculated
PWP Sub	0.19	[ ]	Volumetric water contents at permanent wilting point of subsoil	calculated
Lambda Top	0.13	[ ]	Pore size distribution index of topsoil	calculated
Lambda Sub	0.13	[ ]	Pore size distribution index of subsoil	calculated
Ksat Top	480.9	[$mm.d^{-1}$]	Saturated conductivity of topsoil	calculated
Ksat Sub	209.9	[$mm.d^{-1}$]	Saturated conductivity of subsoil	calculated
PsiE Top	0.09	[$mm.d^{-1}$]	Water potential in topsoil at bubbling pressure of topsoil	calculated
PsiE Sub	1.18	[$mm.d^{-1}$]	Water potential in topsoil at bubbling pressure of subsoil	calculated

Table A4. LUCIA landcover parameters and their input values obtained during parameterization

Parameter	Unit	Range	Description	Source
LAI initial	[$m^2.m^{-2}$]	0.0075	Initial leaf area index	**Literature**
LAI critical	[[$m^2.m^{-2}$]	2 to 6	Maximum leaf area index	**Literature**
Root Max	[cm]	80	Species-specific maximum rooting depth	**Literature**
RWD fine	[$Mg.m^{-3}$]	0.006	Fine root density	**Literature**
Root shape	[ ]	0.7	Vertical extension over horizontal radius of rootstock	**Literature**
N fixation	[$kgN.ha^{-1}.d^{-1}$]	0.44 to 0.75	Biological N fixation	**Literature**
kC	[ ]	0.5	Empiric single crop coefficient for evapotranspiration	**Literature**
Drought adaptation	[ ]	2 to 5	Empirical factor from WOFOST: Ability to extract water from the soil. 1=drought sensitive, 5=drought tolerant	**Literature**
WUE	[l.kg-1]	524	Water use efficiency	**Literature**
Tbase	[°C]	10 to 11	Minimum air temperature for assimilation	**Literature**
TOptLow	[°C]	24 to 25	Upper threshold for assimilation, reduced growth beyond	**Literature**
TOpHigh	[°C]	30 to 35	Upper threshold temperature for assimilation	**Literature**
T max	[°C]	42 to 45	Upper threshold for assimilation, no growth beyond	**Literature**
Albedo plant	[ ]	0.2	Proportion of sunlight reflected by plant surface	**Literature**
Maintenance respiration stem	[$kgCO_2.ha^{-1}.d^{-1}$]	0.03 to 0.06	Daily maintenance respiration of stem and branches as a proportion of stem weight	**Literature**
Maintenance respiration leaves	[$kgCO_2.ha^{-1}.d^{-1}$]	0.04 to 0.07	Daily maintenance respiration of leaves and branches as a proportion of leave weight	**Literature**
Planting density	ha^{-1}	44,444 to 100,000	Number of individual plants per hectare under sole cropping	**Measured**

Table A5. LUCIA plant NPK, lignin and polyphenol parameters and their input values obtained during parameterization.

Parameter	Unit	Range	Explanation	Source
N leaf	[$g.g^{-1}$]	0.01 to 0.04	Target content of N in leaves	**Measured**
N root	[$g.g^{-1}$]	0.01 to 0.03	Target content of N in roots	**Measured**
N stem	[$g.g^{-1}$]	0.01 to 0.03	Target content of N in stems	**Measured**
N harvest	[$g.g^{-1}$]	0.01 to 0.03	Target content of N in harvestable parts	**Measured**
P leaf	[$g.g^{-1}$]	0.001 to 0.003	Target content of P in leaves	**Measured**
P root	[$g.g^{-1}$]	0.0001 to 0.001	Target content of P in roots	**Measured**
P stem	[$g.g^{-1}$]	0.001 to 0.002	Target content of P in stems	**Measured**
P harvest	[$g.g^{-1}$]	0.0004 to 0.004	Target content of P in harvestable parts	**Measured**
K leaf	[$g.g^{-1}$]	0.01 to 0.02	Target content of K in leaves	**Measured**
K root	[$g.g^{-1}$]	0.01 to 0.02	Target content of K in roots	**Measured**
K stem	[$g.g^{-1}$]	0.01 to 0.02	Target content of K in stems	**Measured**
K harvest	[$g.g^{-1}$]	0.003 to 0.02	Target content of K in harvestable parts	**Measured**
Lignin leaf	[%]	3.587 to 13.786	Target content of lignin in leaves	**Measured**
Lignin root	[%]	8.425 to 13.159	Target content of lignin in roots	**Measured**
Lignin stem	[%]	2.898 to 11.980	Target content of lignin in stems	**Measured**
Polyphenol leaf	[mg TA eq 100^{-mg}]	0.342 to 2.863	Target content of polyphenol in leaves	**Measured**
Polyphenol root	[mg TA eq 100^{-mg}]	0.258 to 1.716	Target content of polyphenol in roots	**Measured**
Polyphenol stem	[mg TA eq 100^{-mg}]	0.268 to 1.692	Target content of polyphenol in stems	**Measured**

Table A6. LUCIA measured weather variables and their input values obtained during parameterization.

Parameter	File	Unit	Range	Source
Rainfall	rain.tss	[mm]	0 to 60	Measured
Evapotranspiration	et0.tss	[mm]	2.2 to 6.3	Measured
Air temperature	airtemp.tss	[°C]	19 to 24	Measured
Soil temperature	soiltemp.tss	[°C]	14 to 30	Measured
Solar radiation	rad.tss	[$W.m^{-2}$]	118 to 384	Measured

Table A7. Effect of different legume cropping systems on dry aggregate size distribution, dry mean weight diameter (dMWD) and dry geometric mean diameter (dGMD) after the 2016 LR in Rongo. Treatments did not differ (p<0.05).

	Aggregate size classes [mm]						
	>5	5–4	4–2	2–1	<1		
Treatment	-------------------------------- % weight of dry aggregates --------------------------------					dMWD [mm]	dGMD [mm]
Muc	27±1.4a	8±2.0a	48±1.4a	15±2.8a	2±0.4a	3.4±0.1a	1.7±0.03a
Lab	29±5.0a	11±2.6a	35±0.8b	20±4.6a	5±2.5a	3.3±0.2a	1.6±0.06a
Gnt	33±6.3a	9±1.4a	40±3.5ab	15±3.3a	3±0.5a	3.5±0.1a	1.7±0.03a
MzBn	26±1.1a	10±0.8a	40±1.2ab	19±1.2a	4±0.9a	3.3±0.0a	1.6±0.01a
Mul	24±3.6a	6±1.3a	37±1.7ab	26±2.4a	6±0.5a	3.1±0.1a	1.6±0.03a

Table A8. Effect of different legume cropping systems on dry aggregate size distribution, dry mean weight diameter (dMWD) and dry geometric mean diameter (dGMD) after the 2017 LR in Rongo. Treatments did not differ (p<0.05).

	Aggregate size classes [mm]						
	>5	5–4	4–2	2–1	<1		
Treatment	---------------------------- % weight of dry aggregates ------------------------------					dMWD [mm]	dGMD [mm]
Muc	53±5.9a	20±2.7a	11±2.1a	5±1.7a	11±3.1a	4.0±0.16a	1.8±0.04a
Lab	45±0.9a	16±0.9a	11±0.1a	7±0.6a	21±1.2a	3.6±0.06a	1.6±0.02a
Gnt	45±4.7a	18±0.2a	11±2.0a	6±1.6a	20±2.1a	3.7±0.15a	1.6±0.04a
MzBn	45±1.4a	16±1.1a	11±0.1a	7±0.4a	20±1.6a	3.7±0.07a	1.6±0.02a
Mul	46±1.7a	19±1.6a	11±0.4a	8±0.8a	17±1.6a	3.7±0.08a	1.7±0.02a

Table A9. Wet aggregate size distribution, wet mean weight diameter (wMWD), wet geometric mean diameter (wGMD) and water stable aggregates (WSA) under different legume cropping systems after the 2017 LR in Rongo. Treatments did not differ (p<0.05).

	Aggregate size classes [mm]								
	>5	**5–4**	**4–2**	**2–1**	**1-0.15**	**<0.15**			
Treatment	**% weights of water–stable aggregates**						**wMWD [mm]**	**wGMD [mm]**	**WSA [%]**
Muc	12±4.9a	6±1.9a	8±2.3a	15±1.6a	51±3.7a	8±5.7a	1.65±0.29a	1.01±0.09a	26±6.8a
Lab	9±1.4a	6±1.2a	9±1.7a	15±0.7a	56±2.2a	5±0.7a	1.55±0.09a	1.00±0.02a	24±2.3a
Gnt	11±3.7a	4±1.2a	9±2.7a	15±0.7a	56±2.0a	5±1.3a	1.59±0.08a	1.01±0.03a	25±2.4a
MzBn	8±3.2a	7±1.8a	9±2.4a	11±2.6a	61±5.6a	4±1.2a	1.50±0.19a	0.99±0.04a	24±5.8a
Mul	12±1.2a	5±0.7a	8±1.2a	15±1.8a	56±2.0a	5±0.7a	1.60±0.04a	1.01±0.01a	25±0.7a

Table A10. Correlation of rain gauge measured rainfall and downloaded rainfall data from NASA in 2016. Pearson correlation coefficient = 0.24**.**

Variable	Rain gauge	Download (NASA)
Rain gauge	1	
Download (NASA)	0.24126	1

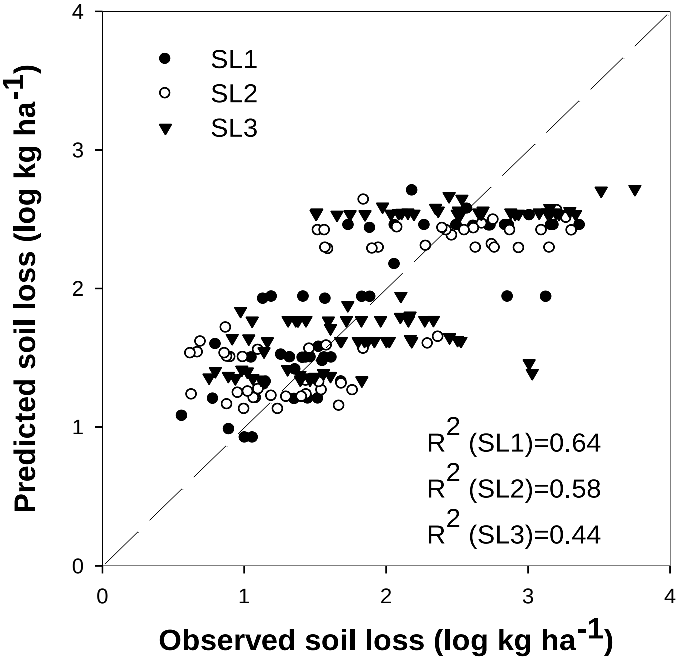

Figure A1. Observed versus predicted soil loss for the mixed model according to Table 8. Plots are shown on the log_{10} transformed scale.

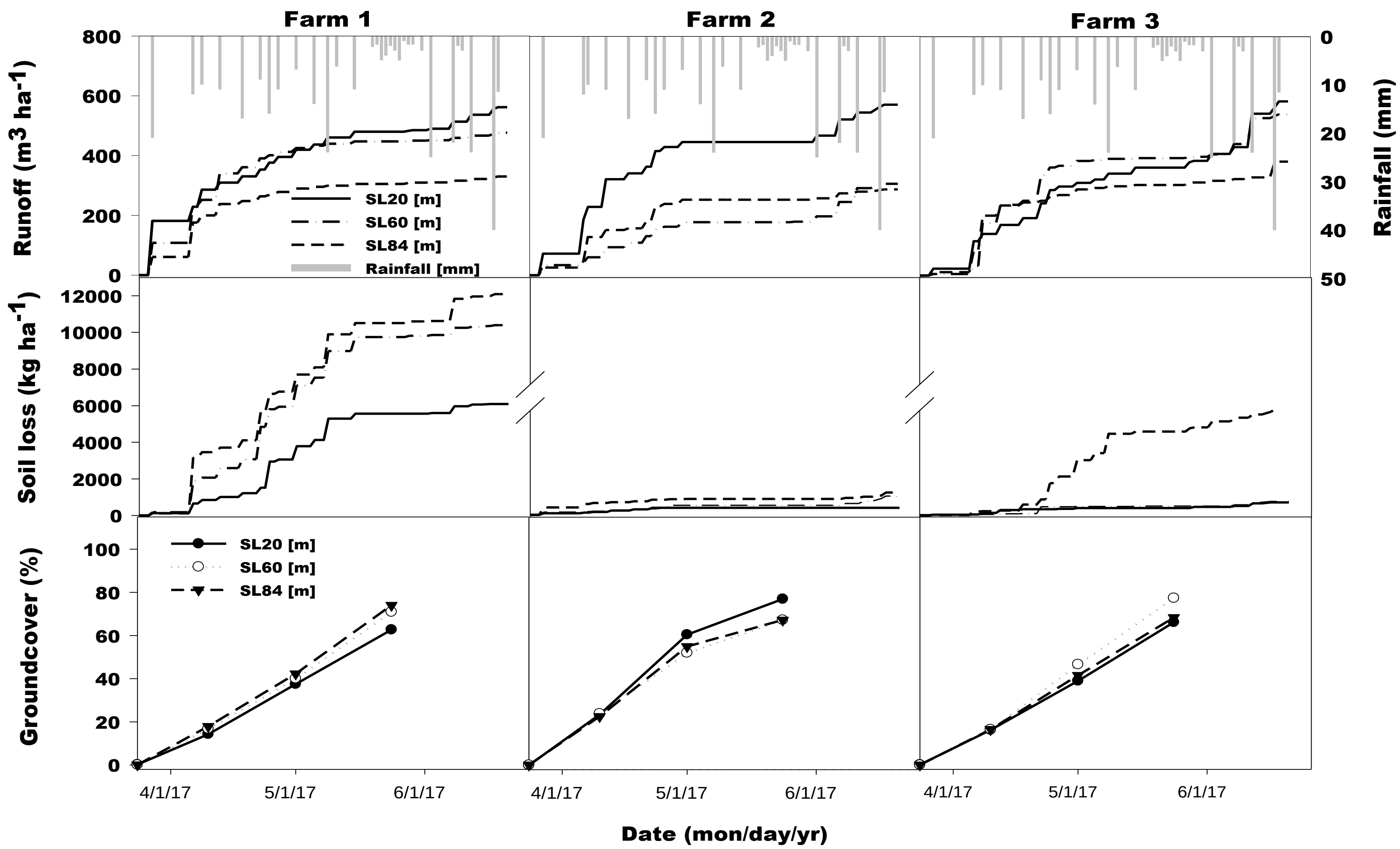

Figure A2. Daily rainfall, cumulative runoff and soil loss (n=3), and mean percent groundcover (n=3) under different slope length with time under MzBn cover for the LR 2017.

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