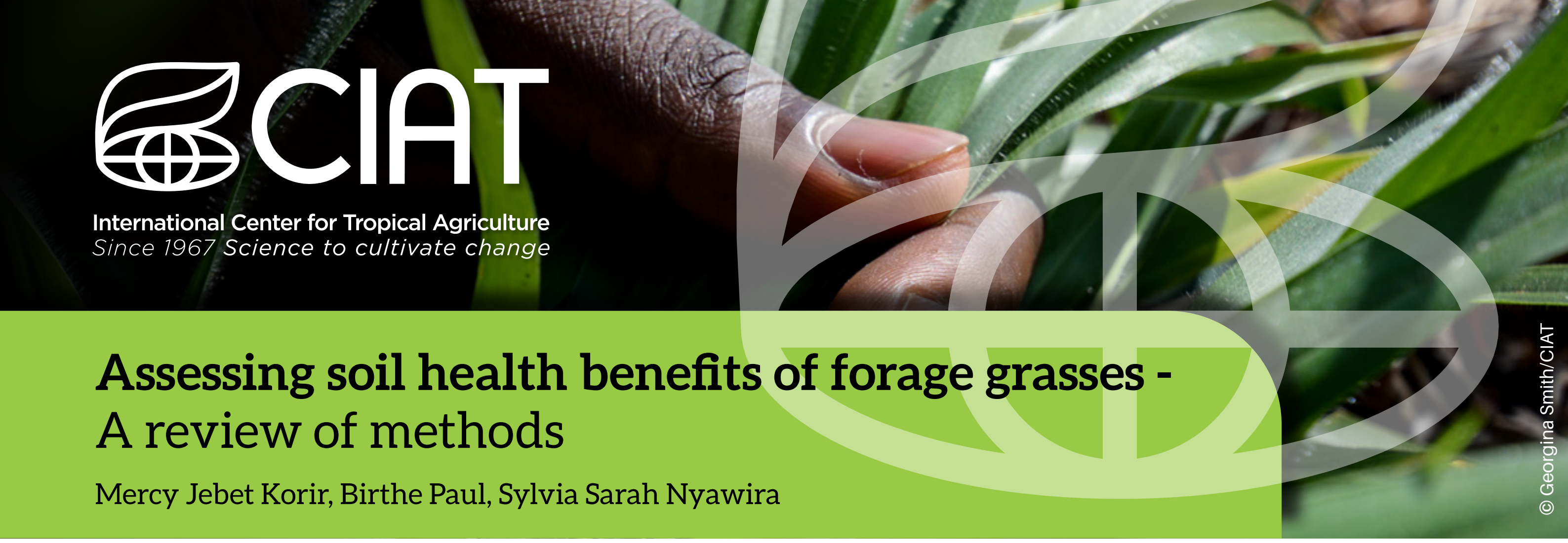

Assessing soil health benefits of forage grasses - A review of methods

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1. Introduction

Land degradation has already affected 67 percent of the land in sub-Saharan Africa (World Bank, 2010) with up to two thirds of productive land being affected (UNCCD, 2013). United Nations Environment Programme (UNEP) estimates approximated 20 percent of cropland and 20 to 25 percent of rangeland to be degraded (ELD Initiative and UNEP, 2015). The total annual costs of land degradation is estimated at US$ 65 billion which accounts for about 4% of the total gross domestic product (GDP) (Global Mechanism of the UNCCD, 2018). The major causes of degradation in sub-Saharan Africa include high population growth leading to pressure on land, conversion of grassland to cropland, deforestation, inappropriate management practices, low adoption of sustainable land management practices soil erosion, low inputs and overgrazing (Nkonya and Mirzabaev, 2016; Muchena et al., 2005). This has led to soil nutrient loss and loss of productive land resources, decreased quality and quantity of available water, salinization, acidification, crop yield losses, loss of biodiversity, increased food insecurity, hunger and malnutrition, and increased poverty (Kirui and Mirzabaev, 2014). Given the severity and the consequences on the ecosystem functioning, food security and mitigation of climate change (Demessie et al., 2015; Lal, 2012), there is an urgent need to restore degraded lands and prevent further degradation.

Land restoration can be achieved through protecting natural forests, afforestation, establishing livestock enclosures, and adopting sustainable land management practices in cropland areas. Countries in Sub-Saharan Africa have committed to restore 100 million hectares of degraded and deforested areas through the African Forest Landscape Restoration Initiative (AFR100), which will contribute to the achievement of the domestic and development commitments set in the Bonn challenge and Land Degradation Neutrality (LDN). Forage grasses have the potential to contribute to achieve the massive targets of restoration, although their potential in SSA remains unexploited (Kitonga, 2019). Forages form parts of plants that are eaten my livestock and they can be herbaceous or dual-purpose legumes, shrubs or grasses.

In this research brief, we focus on forage grasses. Soils under well managed forage grasses exhibit good soil health qualities such as large organic matter concentrations, efficient nutrient use, low susceptibility to erosion and good soil structure. However, poorly managed forage grasses can also accelerate the land degradation potential.

To assess the contribution of forage grasses in enhancing soil health and land restoration, changes in chemical, biological and physical soil properties have to be monitored. The biological indicators include microbial communities, enzyme activities, total nitrogen and organic carbon, while the physical indicators include aggregate stability, bulk density, soil moisture and porosity. Soil organic carbon (SOC) content is one of the main indicators of soil health which is affected by forage grass species (Horrocks et al., 2019). In addition, due to their deep-rooted systems forage grasses have a great effect on soil aggregation and aggregate stability (Harris et al., 1996), which contributes in soil erosion and degradation reduction (Amézketa, 2008). Over the last decades, several in-depth field approaches have been applied to monitor some of these indicators in different parts of the globe. In addition, the application of biophysical models particularly for quantifying SOC in forage grasses has gained momentum over the last decades.

The objective of this research brief is to review methods that are used to quantify the contribution of forage grasses to land restoration in order to inform future studies in East Africa. Publications were retrieved from Google Scholar by searching the following key words: land degradation, land restoration, soil health indicators, forage grass and land restoration, forage grass and soil health, soil, modelling and grass, simulation and forage grass, sub-Saharan Africa. The research brief reviews empirical methods as well as simulation methods.

2. Empirical methods to quantify soil health impact of forage grasses

Fifteen publications were reviewed and findings are summarized in Table 1. The review focuses on the location, year of the trial establishment and data collection period, objectives of the study, species of forage grass, study type, experimental design and treatments, management practices, soil parameters measured and the method used for analysis for each parameter.

Table 1: Empirical methods

KENYA, Embu (Angima et al., 2002)

YEAR OF TRIAL ESTABLISHMENT	1997
DATA COLLECTION PERIOD	1997-1999
OBJECTIVES OF THE STUDY	1. Determine erosion rates from on-farm plots with and without contour *Calliandra*–Napier grass hedges 2. Use the soil loss data to develop a support practice P-sub factor for use with the RUSLE soil erosion prediction computer model 3. Determine biomass production from the hedges 4. Determine N and P losses in eroded sediments from the runoff plots to gauge the effectiveness of the combination hedge system in retaining nutrients
SPECIES OF FORAGE GRASS	• *Pennisetum purpureum* (Napier grass)
STUDY TYPE	On-farm experimental trial
EXPERIMENTAL DESIGN	Randomized complete block design
TREATMENTS	*Calliandra*-Napier grass hedge plots compared to plots with no hedges (control)
MANAGEMENT	Inoculation of *Calliandra* with *Rhizobium spp.* to enhance nitrogen fixation
PARAMETERS MEASURED / METHOD USED	• Clay and silt / Gee and Bauder, 1986 - pipette method • Sand / Gee and Bauder, 1986 - wet sieving • pH • Organic clay complexes / Dry combustion method • Total carbon and nitrogen / Dry combustion method (CHN-600, Leco Corp., St.Joseph, MI) • Infiltration rate / Jury et al., 1991 - double-ring infiltrometer method • Runoff / Runoff plots • Total phosphorus / Olsen and Sommers,1982

KENYA, Chuka (Mutegi et al., 2008)

YEAR OF TRIAL ESTABLISHMENT	2001
DATA COLLECTION PERIOD	2003
OBJECTIVES OF THE STUDY	1. Determine the extent of top-soil loss by water erosion from a number of slope categories under continuous cultivation in farmers' field 2. Determine the effect of soil loss on maize crop production 3. Determine the effectiveness of leguminous hedges of *Calliandra calothyrsus* Meissner (*Calliandra*), *Leucaena trichandra* Zucc. Urban (*Leucaena*), *Pennisetum purpureum* Schumach (Napier grass) barriers, and a combination of either *Calliandra* or *leucaena* hedge with napier grass barrier in soil conservation, nutrient enhancement and maize crop production
SPECIES OF FORAGE GRASS	• *Pennisetum purpureum* Schumach (Napier grass)
STUDY TYPE	On-farm experimental trial
EXPERIMENTAL DESIGN	Randomized design

TREATMENTS	Plots with monospecific hedges of *Calliandra, Pennisetum purpureum* Schumach, *Leucaena* and plots with combination hedges of *Calliandra* + *Pennisetum purpureum* Schumach and *Leucaena* + *Pennisetum purpureum* Schumach were compared to plots with no hedges (equivalent to continuous cropping) as a control
MANAGEMENT	• Effective strains of *Rhizobium spp.* were inoculated into *Calliandra* and *Leucaena* to enhance nitrogen species • Hedges/barriers were pruned every two months after one year of establishment) and then resulting biomass from any one hedge/barrier was cut into fine pieces and incorporated into the test plot it served
PARAMETERS MEASURED / METHOD USED	• Soil water content / Gravimetric method • Nitrate plus nitrite / Dorich and Nelson, 1984 - cadmium reduction method • Ammonium / Anderson and Ingram, 1993 - salicylate-hypochlorite colorimetric method • Soil bulk density / Anderson and Ingram, 1993 - undisturbed core method • Soil pH / McLean, 1982 • Exchangeable calcium, magnesium and potassium / EDTA extraction method • Soil texture / Gee and Bauder, 1986 - hydrometer method • Total organic carbon / Anderson and Ingram, 1993 - colorimetric method • Soil loss / FAO, 1993 - calibrated plastic erosion pins

KENYA, Katumani (Gichangi et al., 2016)

YEAR OF TRIAL ESTABLISHMENT	2013
DATA COLLECTION PERIOD	2015
OBJECTIVES OF THE STUDY	1. Investigate the short-term (2-years) changes in aggregate size distribution and the stability of soil aggregates following cultivation of Brachiaria grasses. 2. Examined linkages between SOC, particulate organic matter (POM), microbial biomass carbon (MBC), and root biomass with aggregation by comparing Brachiaria cultivated soils verses commonly grown Napier and Rhodes fodders and not cultivated weed free soils.
SPECIES OF FORAGE GRASS	• *Brachiaria decumbens* cv. Basilisk, • *Brachiaria humidicola* cv. Llanero, • *Brachiaria brizantha* cvs. Marandu, MG4, Piatã, Xaraes, • *Chloris gayana* cv. KAT R3 (Rhodes grass), • *Pennisetum purpureum* cv. Kakamega 1 (KK1)
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Randomized complete block design in split plot arrangement
TREATMENTS	• Brachiaria species were compared to locally cultivated forage grasses with bare plot as a control. Also, the grass treatments/species were evaluated with fertilizer application (40 kg P applied at sowing and 50 kg N ha^{-1} in each wet season) and with no fertilizer applications.
MANAGEMENT	N/A
PARAMETERS MEASURED / METHOD USED	• Water stable aggregates / N/A • Soil microbial biomass carbon / Vance et al., 1987 - fumigation-extraction technique

MADAGASCAR, Vakinankaratra (Rahetlah et al., 2012)

YEAR OF TRIAL ESTABLISHMENT	2006
DATA COLLECTION PERIOD	2011
OBJECTIVES OF THE STUDY	1. Determine the effect of intercropping *Brachiaria Sp.* cv Mulato with forage perennial peanut, in single alternate row (1:1) on sustainable improvement of yield and quality of forage.
SPECIES OF FORAGE GRASS	• *Hybrid Brachiaria* (Cv Mulato)
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Randomized complete block design
TREATMENTS	Plots with pure stands of *hybrid Brachiaria* (Cv Mulato) and forage perennial peanut (*Arachis pintoi*) were compared to plots with their mixture There was no control
MANAGEMENT	• Basal fertilizer composed of 33 N, 66 P_2O_5 and 48 K_2O kg ha^{-1} in the form of NPK (11-22-16) was applied during planting • 20 tons of cattle manure ha^{-1} were evenly applied to all treatments at the planting time and at the beginning of the third and the fourth year • No fertilizer was applied to all plots at the beginning of the fifth year
PARAMETERS MEASURED / METHOD USED	• Soil carbon, nitrogen, phosphorus, potassium, exchangeable bases, CEC, pH / N/A

COLOMBIA, CIAT Palmira, Valle del Cauca (Horrocks et al., 2019)

YEAR OF TRIAL ESTABLISHMENT	2006
DATA COLLECTION PERIOD	2016-2017
OBJECTIVES OF THE STUDY	1. Compare the impact of different tropical forage cultivars on soil health 2. Assess the potential to use low-tech methods of measuring soil health in the field
SPECIES OF FORAGE GRASS	• *Brachiaria* hybrid Mulato I • *Brachiaria humidicola* (CIAT 679) • *Brachiaria humidicola* (CIAT 16888) • *Panicum maximum* (CIAT 6962)
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Randomized block design
TREATMENTS	Plots with the above species were compared to bare plots (control)
MANAGEMENT	N/A
PARAMETERS MEASURED / METHOD USED	• Total organic carbon / Elemental analyzer (Carlo Erba NA 1500 analyser) • Soil sugars / Blakeney et al., 1983; Docherty et al., 2001 • Soil n-alkanes / Nunez et al., 2018 • Total soil DNA / Bull et al., 2000 • Aggregate stability / Le Bissonais, 1996; Elliott, 1986 • Aggregate friability / Rogowski et al., 1968; Dexter, 1975

INDIA, Kondaiyampalayam (Sundaram et al., 2012)

YEAR OF TRIAL ESTABLISHMENT	2010
DATA COLLECTION PERIOD	2010-2011
OBJECTIVES OF THE STUDY	1. Quantify the impact of changing soil organic carbon (SOC) storage with farming forage crops
SPECIES OF FORAGE GRASS	• Hybrid Napier
STUDY TYPE	On-farm experimental trial
EXPERIMENTAL DESIGN	Randomized complete block design
TREATMENTS	Plots with perennial forage crops [hybrid Napier and *Desmanthus virgatus* (Hedge Lucerne)] were compared to plots with annual forage crops [*Zea mays* (fodder maize)] and *Vigna unguiculata* (fodder cowpea)
MANAGEMENT	Farmyard manure and mineral fertilizer
PARAMETERS MEASURED / METHOD USED	• Carbon content / Analytikjena multi N/C 2100S carbon analyzer • Bulk density / Dry weight of the soil was divided with the volume of the soil

CHINA, Ganqika (Molatudi et al., 2015)

YEAR OF TRIAL ESTABLISHMENT	2006, 2008 and 2009
DATA COLLECTION PERIOD	2012-2013
OBJECTIVES OF THE STUDY	1. Compare the soil moisture, mineral nitrogen and microbial biomass carbon under different switch grass plantations
SPECIES OF FORAGE GRASS	• *Panicum virgatum* (Switch grass), • *Leymus chinensis* Trin. Tzvel (Chinese leymus), • *Calamagrostis epigejos* L. Roth (Chee reedgrass), • *Deyeuxia angusitifolia* Kom. Y. L. Chang (Small reed), • *Setaria viridis* L. Beauv (Bristle grass)
STUDY TYPE	Field experimental trial
EXPERIMENTAL DESIGN	N/A
TREATMENT	Plot with *Panicum virgatum* established in 2006 (SG2006), 2008 (SG2008), and 2009 (SG2009) were compared to plot of native grasses (*Leymus chinensis* Trin. Tzvel ,*Calamagrostis epigejos* L. Roth, *Deyeuxia angusitifolia* Kom. Y. L. Chang and *Setaria viridis* L. Beauv) as a control
MANAGEMENT	• 84 kg N ha^{-1} as urea, 99 kg P_2O_5 ha^{-1} as diammonium phosphate, and 45 kg K_2O ha^{-1} as potassium sulfate were applied to each switch grass plot as topdressing before the plant regrowth in 2012 and 2013
PARAMETERS MEASURED / METHOD USED	• pH • Electrical conductivity • Nitrate nitrogen / Norman et al., 1985 - dual wavelength method • Ammonium nitrogen / Keeney and Nelson, 1982 - 2 mol /L KCl extraction indophenols blue colorimetric method • Soil microbial biomass carbon / Vance et al., 1987 - fumigation-extraction method • Organic carbon / Digestion-titration method

INDIA, Umiam (Das et al., 2016)

YEAR OF TRIAL ESTABLISHMENT	2008
DATA COLLECTION PERIOD	2008-2011
OBJECTIVES OF THE STUDY	1. Assess the impact of perennial forage grasses and organic amendments on soil properties and fodder productivity
SPECIES OF FORAGE GRASS	• *Thysanolaena maxima* (Broom grass), • *Brachiaria ruziziensis* (Congosignal grass), • *Pennisetum typhoides x Pennisetum. Purpureum* (Hybrid Napier), • *Megathyrsus maximus* (Guinea grass)
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Factorial Randomized Block Design
TREATMENT	Plots with the above species were compared to nutrient source (inherent soil fertility, organic manure and inorganic fertilizers) as a control
MANAGEMENT	• Fertilizer was applied at the rate of 80 kg ha^{-1} N, 60 kg ha^{-1} P_2O_5 and 40 kg ha^{-1} K_2O
PARAMETERS MEASURED / METHOD USED	Bulk density / Blake and Hartge, 1986 - core method Total carbon / Nelson and Sommers, 2005 - Dry combustion method pH / Potentiometric method using a pH meter Soil available nitrogen / Subbiah and Asija, 1956 - Alkaline permanganate method

FRANCE, Estrées -Mons (Ferchaud et al., 2016)

YEAR OF TRIAL ESTABLISHMENT	2006
DATA COLLECTION PERIOD	2006, 2011 and 2012
OBJECTIVES OF THE STUDY	1. Comparing changes in SOC stocks of various bioenergy cropping systems with perennial, semi-perennial, or annual crops established on arable land 2. Studying the interaction with crop management, that is nitrogen fertilization rate and harvest date of perennial crops
SPECIES OF FORAGE GRASS	• *Miscanthus x giganteus* Greef & Deuter ex Hodkinson & Renvoize (Miscanthus), • *Panicum virgatum* cv. Kanlow (Switch grass), • *Festuca arundinacea* (Fescue)
STUDY TYPE	On- station experiment
EXPERIMENTAL DESIGN	Split-block design, Split-plot design
TREATMENTS	Plots with perennial crops (*Miscanthus x giganteus* Greef & Deuter ex Hodkinson & Renvoize and *Panicum virgatum* cv. Kanlow), semi-perennial crops (*Festuca arundinacea* and *Medicago sativa* (Alfalfa)) and annual crops (*Sorghum bicolor* (L.) Moench cv. H133 (Sorghum) and *Triticosecale Wittmack* (Triticale)) were compared. Also, plots had two nitrogen treatments (N- and N+) with fertilizer-N rates depending on the crops.
MANAGEMENT	Fertilizer was either applied or not applied with different nitrogen rates depending on the crop
PARAMETERS MEASURED / METHOD USED	• Bulk density / Steel cylinder and probe • Soil organic carbon stocks on equivalent soil mass basis / Ellert and Bettany, 1995

CANADA, Prince Edward Island (Carter et al., 2003)

YEAR OF TRIAL ESTABLISHMENT	1985
DATA COLLECTION PERIOD	1985-1995
OBJECTIVES OF THE STUDY	1. Compare potato yields, and the productivity of companion forages and barley 2. Evaluate soil-borne pathogens and plant parasitic nematode populations 3. Evaluate changes in soil structure and organic matter retention
SPECIES OF FORAGE GRASS	*Festuca perennis* (Italian ryegrass)
STUDY TYPE	Field experimental trial
EXPERIMENTAL DESIGN	Split-plots arranged in randomized complete blocks
TREATMENT	Plots with *Festuca perennis* , *Hordeum vulgare* (barley) plus *Festuca perennis*), *Trifolium pratense* (red clover) and (*Hordeum vulgare* (barley) all in rotation with *Solanum tuberosum* (potato) were compared. There was no control.
MANAGEMENT	• The forage herbage and barley straw were returned and spread over the respective plots • Before seeding forages and barley, the site was fertilized with 87 kg ha^{-1} of P and 166 kg ha^{-1} of K • Ammonium nitrate was applied on ryegrass and barley at the early tillering stage at 50 kg N ha^{-1} and on red clover at 25 kg N ha^{-1} • Ammonium nitrate at 40 kg N ha^{-1} was applied again after the first and second cut for the Italian ryegrass, and after the barley harvest for the barley plus Italian ryegrass rotation • Fertilizer was broadcast at 90, 87, and 166 kg ha^{-1} of N, P and K, respectively, and incorporated into the soil prior to planting • The last three years three N rates (0, 45 and 90 kg N ha^{-1}) was applied from ammonium nitrate
PARAMETERS MEASURED | *METHOD USED*	• Soil structure, organic carbon and organic nitrogen | Carter, 1998 • Structural stability | Angers and Mehuys, 1993 - wet sieving technique • Clod size distribution | ADAS, 1982 • Soil carbohydrates | Angers et al., 1993 • Soil microbial biomass | Voroney et al., 1993 • Nematode measurement | Kimpinski, 1993; Hooper, 1986

USA (Stewart et al., 2015)

YEAR OF TRIAL ESTABLISHMENT	1998
DATA COLLECTION PERIOD	1998, 2001, 2004 and 2007
OBJECTIVES OF THE STUDY	1. Assess soil properties over 9 years for a rainfed study of N fertilizer rate (0, 60, 120, and 180 kg N ha^{-1}) and harvest management on switchgrass (harvested in August and post frost) and no tilled corn (NT-C) (with and without 50% stover removal)
SPECIES OF FORAGE GRASS	*Panicum virgatum* Trailblazer, *Panicum virgatum* Cave-in- Rock
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Randomized complete block split-split plot experimental design
TREATMENTS	Plots with two cultivars of switch grass (*Panicum virgatum* Cave-in- Rock and *Panicum virgatum* Trailblazer), nitrogen fertilizer rate (0, 60 and120 kg N ha^{-1}) and harvest management (harvested in August and post-frost) was compared to plots with no-tilled *Zea mays* (corn), nitrogen fertilizer rate (60, 120 and 180 kg N ha^{-1}) and harvest management no residue removal or 50% residue removal for). There was no control.

MANAGEMENT	No phosphorus (P) or potassium (K) fertilizer was applied
PARAMETERS MEASURED | *METHOD USED*	• Bulk density, wet aggregate stability, pH and available potassium / USDA-NRCS, 2004 - established methods • Soil microbial biomass / Jenskinson and Powlson, 1976 - incubation-fumigation method • Total carbon, total nitrogen and Isotope signature 13 carbon / Automated nitrogen carbon analyzer

USA, Minnesota, North Dakota, South Dakota (Liebig et al., 2005)

YEAR OF TRIAL ESTABLISHMENT	Years under cultivation ranged from one to more than 100
DATA COLLECTION PERIOD	2000-2001
OBJECTIVES OF THE STUDY	1. Evaluate soil carbon stocks within established switchgrass stands and nearby cultivated cropland
SPECIES OF FORAGE GRASS	*Panicum virgatum*
STUDY TYPE	On-farm experimental trial
EXPERIMENTAL DESIGN	N/A
TREATMENTS	42 on farm sites with switch grass was compared to nearby cultivated cropland
MANAGEMENT	Conventional, minimum and no tillage
PARAMETERS MEASURED / METHOD USED	• Gravimetric soil water content / Gardner, 1986 • Electrical conductivity / Whitney, 1998 • pH / Watson and Brown, 1998 • Total soil carbon / Nelson and Sommers, 1996 - dry combustion method • Inorganic carbon / Loeppert and Suarez, 1996

USA, Oregon (Chatterjee et al., 2018)

YEAR OF TRIAL ESTABLISHMENT	2008
DATA COLLECTION PERIOD	2008-2012
OBJECTIVES OF THE STUDY	1. Compare aboveground biomass C production and depth distribution of SOC content of continuous winter wheat (*Triticum aestivum L.*) and switchgrass (*Panicum virgatum L.*) 2. Determine the contribution of switchgrass to soil organic carbon 3. Characterize soil C inventories under each crop across a wide range of precipitation regimes
SPECIES OF FORAGE GRASS	*Panicum virgatum* Blackwell
STUDY TYPE	On-station experimental trial
EXPERIMENTAL DESIGN	Randomized complete block
TREATMENTS	Plot with (*Panicum virgatum* Blackwell) was compared to plot with continuous *Triticum aestivum* (winter wheat). There was no control.

MANAGEMENT	• Urea (46-00-00) fertilizer was applied to winter wheat plots at N levels of 197, 246, and 296 kg ha^{-1} • Ammonium phosphate (16-20-00) with 12% sulfur was broadcast giving 11 kg P_2O_5 ha^{-1} and 8.4 kg S ha^{-1} • Nitrogen was applied to switch grass at the rates of 45, 90, and 179 kg N ha^{-1} • Ammonium phosphate with 12% sulfur was applied at the rate of 45 kg N ha^{-1}, 56 kg PP_2O_5 ha^{-1} and 34 S ha^{-1} • No fertilizer was added in 2007 to prevent weed growth
PARAMETERS MEASURED / METHOD USED	• Gravimetric soil water content / Gardner, 1986 • Bulk density / oven dry weigh of the core was divided with its volume • pH and electrical conductivity / 1:2.5 soil/water extract • Total carbon and total nitrogen / automated dry combustion analyzer • Isotopic signature of soil carbon(13) / Garten and Wullschleger, 2000 • Zinc / Lindsay and Norvell, 1978 - DTPA-TEA extraction method • Soil dehydrogenase activity / Tabatabai, 1982; Casida et al., 1964 • Soil organic carbon stock / Lal et al., 1998

BRAZIL, Goiás and Mato Grosso do Sul (De Oliveira et al., 2004)

YEAR OF TRIAL ESTABLISHMENT	1985
DATA COLLECTION PERIOD	**Site 1:** 1989, 1992 and 1994 and **Site 2:** 1985, 1986 and 1997
OBJECTIVES OF THE STUDY	1. Examine various biological and chemical characteristics of the soil/plant systems in chronosequences of Brachiaria pastures of increasing age and decreasing productivity with a view to identify possible indicators of the degree of pasture degradation
SPECIES OF FORAGE GRASS	*Brachiaria brizantha, Brachiaria decumbens*
STUDY TYPE	Two chronosequences were investigated; private farm and cattle beef center
EXPERIMENTAL DESIGN	N/A
TREATMENTS	• **In Site 1,** Pastures with reformed (fertilised) *Brachiaria brizantha* was compared to degraded *Brachiaria decumbens* (control) • **In site 2,** pastures with reformed (fertilised) *Brachiaria brizantha* was compared to pastures with degraded *Brachiaria brizantha*
MANAGEMENT	• **Site 1:** - Fertilizer was applied as N 15 kg ha^{-1}, P 40 kg ha^{-1}, K 37 kg ha^{-1} as ammonium sulphate, single super-phosphate, and potassium chloride, respectively. - Micronutrients was applied at the rate 30 kg ha^{-1} each of fritted trace elements [FTEs] type BR12 and zinc sulphate • **Site 2:** - Fertilizer was applied at the rate of 72 kg ha^{-1} of P as single super-phosphate, 60 kg K as KCl and 46 kg ha^{-1} of N as urea in 1985 and 1995, and 2Mg ha^{-1} of lime in 1995, followed by a further 46 kg N ha^{-1} as urea in 1997. - Replanted pasture in 1997 was applied with 1.5 Mg ha^{-1} lime and fertilized with 12, 45 and 30 kg ha^{-1} of N, P and K, respectively

PARAMETERS MEASURED / METHOD USED	• Gravimetric soil water content / Gardner, 1986 • pH / 2:1 water/soil • Exchangeable potassium, magnesium and aluminium and exchangeable calcium / Embrap,1979-Mehlich I • Total nitrogen / Urquiaga et al., 1992 • Total carbon / Total carbon and nitrogen analyzer • soil microbial biomass / Vance et al., 1987-fumigation-extraction technique • soil microbial carbon / Jenkinson and Powlson, 1976-Walkey-Black • Ammonium / Alves et al., 1993 - flow injection analysis • Potentiable mineralizable nitrogen / Waring and Bremner, 1964 • Physical fractionation of soil organic matter / Meijboom et al., 1995

The review of the empirical methods shows that most of the studies were conducted outside of sub-Saharan Africa with very few studies in Africa (27 percent). The majority of the trials that were used for measurements were conducted for more than two years, with limited short-term studies. The main indicators for short-term studies were aggregate stability and microbial biomass carbon. Main species of grasses being studied were *Brachiaria* species and *Panicum virgatum* (switch grass). Most of the experiments were on on-station experimental trials instead of on-farm reserach. In sub-Saharan Africa, Napier grass was the main species studied and the main soil health indicator was soil erosion.

3. Simulation methods to study soil impacts of forage grasses

Biophysical simulation models are a specific form of models concerned with the interaction of weather, soil, and/or biological processes in agricultural production and /or environmental actions and they simulate the growth of crops to retrieve biophysical crop parameters such as crop production, biomass, water use (Kogan et al., 2013). According to Andrade et al. (2016), biophysical models have benefits compared to empirical methods since they can be used for wider region and can predict future conditions over a longer period. These models include CROPGRO, DSSAT, APSIM, ALMANAC (Andrade et al., 2016). The review highlights the simulation methods and the outline include the region, type of model, species of forage grass, data input for the model, source of data and type of study in Table 2.

Table 2: Overview of simulation methods

USA, California	(Lee et al., 2012)
TYPE OF MODEL	DAYCENT
SPECIES OF FORAGE GRASS	*Panicum virgatum* L.
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, precipitation, solar radiation, wind speed, relative humidity (CIMIS–http://wwwcimis.water. ca.gov and DAYMET–http://www.daymet. org) • **Soil data** - Soil texture class, bulk density, hydraulic properties (Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service) - Field capacity and wilting point (Calculated from soil texture) - Land use survey data (California Department of Water Resources (http:// www.water.ca.gov) • **Management data:** Tillage, fertilization, planting (Experimental data)
TYPE OF STUDY	**Model validation study**—Biomass yield was assessed across different ecoregions

BRAZIL, Sao Paulo (Pedreira et al., 2011)

TYPE OF MODEL	CROPGRO-Perennial Forage Model (DSSAT soil plant atmosphere module version 3.5)
SPECIES OF FORAGE GRASS	*Brachiaria brizantha* (Palisade grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station within the experimental site) • **Soil data:** Clay, silt, organic carbon (Experimental data) • **Crop data**: Crop establishment, planting age, transplanting weight, leaf fraction in the stubble, base temperature, optimum temperature, plant part composition, critical N concentration for photosynthesis (Experimental and reported literature data) • **Management data** - Date of harvest, amount of stubble remaining after harvest (Experimental data) - Location (Experimental data)
TYPE OF STUDY	**Model evaluation and validation study**—The model was used to asses the growth and composition.

BRAZIL, Piracicaba (Lara et al., 2012)

TYPE OF MODEL	CROPGRO-Perennial Forage Model (DSSAT soil plant atmosphere module version 3.5)
SPECIES OF FORAGE GRASS	*Panicum maximum* (Guinea grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station within the experimental site) • **Soil data:** Clay, silt, organic carbon (Experimental data) • **Crop data**: Crop establishment, planting age, transplanting weight, leaf fraction in the stubble, base temperature, optimum temperature, plant part composition, critical N concentration for photosynthesis (Experimental and reported literature data) • **Management data** - Date of harvest, amount of stubble remaining after harvest (Experimental data) - Location (Experimental data)
TYPE OF STUDY	**Model evaluation and validation study**—The model was used to asses the growth and composition.

BRAZIL, Sao Paulo (Pequeno et al., 2014)

TYPE OF MODEL	CROPGRO-Perennial Forage Model (DSSAT soil plant atmosphere module version 3.5)
SPECIES OF FORAGE GRASS	*Panicum maximum* (Guinea grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station within the experimental site) • **Soil data:** Clay, silt, organic carbon (Experimental data) • **Crop data**: Crop establishment, planting age, transplanting weight, leaf fraction in the stubble, base temperature, optimum temperature, plant part composition, critical N concentration for photosynthesis (Experimental and reported literature data) • **Management data** - Date of harvest, amount of stubble remaining after harvest (Experimental data) - Location (Experimental data)
TYPE OF STUDY	**Model evaluation and validation study**—The model was used to assess growth under irrigated and rainfed conditions

USA, Texas (Kiniry et al., 2005)

TYPE OF MODEL	ALMANAC model
SPECIES OF FORAGE GRASS	*Panicum virgatum*
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station) • **Soil data** - Runoff curve number (Natural Resource Conservation Service) - Rooting depth, texture, amount of rocks by layer, saturation, drained upper limit and lower limit, soil organic matter (Experimental data) • **Crop data**: Potential leaf area index (LAI), development curve for LAI over the growing season, the light extinction coefficient for Beer's law (k), the radiation use efficiency (RUE), duration of the season in degree day, harvest index for seeds (HI), nitrogen and phosphorus concentrations (Experimental and reported literature data) • **Management data**: Tillage (Experimental data)
TYPE OF STUDY	**Model validation study**—The model was used to assess biomass yields across different sites and years

USA, Texas (Kiniry et al., 2013)

TYPE OF MODEL	ALMANAC model
SPECIES OF FORAGE GRASS	*Pennisetum ciliare* (Buffel grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station) • **Soil data** - Runoff curve number (Natural Resource Conservation Service) - Rooting depth, texture, amount of rocks by layer, saturation, drained upper limit and lower limit, soil organic matter (Experimental data) • **Crop data**: Potential leaf area index (LAI), development curve for LAI over the growing season, the light extinction coefficient for Beer's law (k), the radiation use efficiency (RUE), duration of the season in degree day, harvest index for seeds (HI), nitrogen and phosphorus concentrations (Experimental and reported literature data) • **Management data**: Tillage (Experimental data)
TYPE OF STUDY	**Model validation study**—The model was used to assess the growth under different soil type and weather conditions

USA (Kiniry et al., 2017)

TYPE OF MODEL	ALMANAC model
SPECIES OF FORAGE GRASS	*Festuca arundinacea* Kentucky 31 and *Festuca arundinacea* BarOptima (Tall fescue grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data:** Daily maximum temperature, minimum temperature, rainfall, solar radiation (Weather station) • **Soil data** - Runoff curve number (Natural Resource Conservation Service) - Rooting depth, texture, amount of rocks by layer, saturation, drained upper limit and lower limit, soil organic matter (Experimental data) • **Crop data**: Potential leaf area index (LAI), development curve for LAI over the growing season, the light extinction coefficient for Beer's law (k), the radiation use efficiency (RUE), duration of the season in degree day, harvest index for seeds (HI), nitrogen and phosphorus concentrations (Experimental and reported literature data) • **Management data**: Tillage (Experimental data)
TYPE OF STUDY	Model validation study

THAILAND (Norsuwan et al., 2015)

TYPE OF MODEL	CSM-CanegroSugarcane model in DSSAT version 4.6 Beta
SPECIES OF FORAGE GRASS	*Pennisetum purpureum* × *Pennisetum americanum* (Napier grass)
DATA INPUT FOR THE MODEL & (SOURCE OF DATA)	• **Weather data** - Daily maximum temperature, minimum temperature, average wind speed, relative humidity (Weather station) - Solar radiation (Calculated from air temperature) - Evapotranspiration (Calculated using Penman-Monteith equation on a daily time step) • **Soil data:** Saturated water conductivity, saturated water capacity, root distribution weight, albedo, runoff curve number, lower limit, drained upper limit (Dataset of Land Development Department of Thailand) • **Crop data**: Dry leaf and leaf sheath weight, total dry matter yield, tiller number, dry stem weight) (Experimental data) • **Management data**: Irrigation and fertilizer application, row spacing, years, cultivar, harvest, treatments (Experimental data)
TYPE OF STUDY	Model validation study

The review of the simulation methods indicates that all the studies were carried out outside of Sub-saharan Africa and CROPGRO is the most commonly used model. The study also showed that the main sources of data were experimental trials.

4. Conclusion

The objective of this research brief was to review methods that are used to quantify the contribution of forage grasses to land restoration to inform future studies in East Africa. Major findings from the empirical studies indicate only 15 studies in total were found showing that forage grasses are not well studied for their potential of land restoration, with most studies focusing outside Africa. Further, methods to study short-term impacts are rare with most methods relying on multi-year experiments, which might be expensive to run. The major parameters studied include soil organic carbon and aggregate stability with Brachiaria grass as the main species. In simulation studies, the centers of expertise were in USA and Brazil with CROPGRO as the main model, which was well adapted. The main sources of data were from experimental trials thus need to set-up trials. However, since models can project long-term simulations, they can be substituted with multi-year experiments. Further, since CROPGRO was the main model, it can be calibrated and adapted in Africa. This review highlights the scarcity of experimental studies that focus on the impact of forage grasses on soil health in Africa, hence the need to explore and quantify their potential to contribute to restoration of degraded landscapes.

References

Allen, V. G., Batello, C., Berretta, E. J., Hodgson, J., Kothmann, M., Li, X., McIvor, J., Milne, J., Morris, C., Peeters, A., Sanderson, M. (2011). An international terminology for grazing lands and grazing animals. *Grass and Forage Science*, *66*(1), 2–28.

Amézketa, E. (2008). Soil Aggregate Stability: A Review. *Journal of Sustainable Agriculture*, *14*(2–3), 83–151.

An, S., Mentler, A., Mayer, H., Blum, W. E. H. (2010). Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. *Catena*, *81*(3), 226–233.

Andrade, A. S., Santos, P. M., Pezzopane, J. R. M., de Araujo, L. C., Pedreira, B. C., Pedreira, C. G. S., Marin, F. R., Lara, M. A. S. (2016). Simulating tropical forage growth and biomass accumulation: An overview of model development and application. *Grass and Forage Science*, *71*(1), 54–65.

Angima, S. D., Stott, D. E., O'Neill, M. K., Ong, C. K., Weesies, G. A. (2002). Use of calliandra-Napier grass contour hedges to control erosion in central Kenya. *Agriculture, Ecosystems and Environment*, *91*(1–3), 15–23.

Barral, M. P., Rey Benayas, J. M., Meli, P., Maceira, N. O. (2015). Quantifying the impacts of ecological restoration on biodiversity and ecosystem services in agroecosystems: A global meta-analysis. *Agriculture, Ecosystems and Environment*, *202*, 223–231.

Carter, M. R., Kunelius, H. T., Sanderson, J. B., Kimpinski, J., Platt, H. W., Bolinder, M. A. (2003). Productivity parameters and soil health dynamics under long-term 2-year potato rotations in Atlantic Canada. *Soil and Tillage Research*, *72*(2), 153–168.

Chatterjee, A., Long, D. S., Pierce, F. J. (2018). Change in Soil Organic Carbon after Five Years of Continuous Winter Wheat or Switchgrass. *Soil Biology & Biochemistry Change*, *82*(2), 332–342.

Cluzeau, D., Guernion, M., Chaussod, R., Martin-Laurent, F., Villenave, C., Cortet, J., Ruiz-Camacho, N., Pernin, C., Mateille, T., Philippot, L., Bellido, A., Rougé, L., Arrouays, D., Bispo, A., Pérès, G. (2012). Integration of biodiversity in soil quality monitoring: Baselines for microbial and soil fauna parameters for different land-use types. *European Journal of Soil Biology*, *49*, 63–72.

Das, A., Patel, D. P., Lal, R., Kumar, M., G.I., R., Layek, J., Buragohain, J., Ngachan, S. V., Ghosh, P. K., Choudhury, B. U., Mohapatra, K. P., Shivakumar, B. G. (2016). Impact of fodder grasses and organic amendments on productivity and soil and crop quality in a subtropical region of eastern Himalayas, India. *Agriculture, Ecosystems and Environment*, *216*, 274–282.

De Oliveira, O. C., De Oliveira, I. P., Alves, B. J. R., Urquiaga, S., Boddey, R. M. (2004). Chemical and biological indicators of decline/degradation of Brachiaria pastures in the Brazilian Cerrado. *Agriculture, Ecosystems and Environment*, *103*(2), 289–300.

Demessie, A., Singh, B. R., Lal, R. (2015). Land Degradation and Soil Carbon Pool in Different Land Uses and Their Implication for Food Security in Southern Ethiopia. In *Sustainable Intensification to Advance Food Security and Enhance Climate Resilience in Africa* (pp. 45-62). Springer, Cham.

Doran, J. W., Zeiss, M. R. (2000). Soil health and sustainability: Managing the biotic component of soil quality. *Applied Soil Ecology*, *15*(1), 3–11. 6

ELD Initiative and UNEP. (2015). The Economics of Land Degradation in Africa. Benefits of Action Outweigh the Costs. www.eld-initiative.org

Ferchaud, F., Vitte, G., Mary, B. (2016). Changes in soil carbon stocks under perennial and annual bioenergy crops. *GCB Bioenergy*, *8*(2), 290–306.

Gichangi, E. M., Njarui, D. M. G., Ghimire, S. R., Gatheru, M., Magiroi, K. W. N. (2016). Effects of cultivated Brachiaria grasses on soil aggregation and stability in the semi-arid tropics of Kenya. *Tropical and Subtropical Agroecosystems*, *19*(2), 205–217.

Global Mechanism of the UNCCD. (2018). Country Profile of Zimbabwe. Investing in Land Degradation Neutrality: Making the Case. An Overview of Indicators and Assessments. Bonn, Germany.

Gurtner, M., Liniger, H., Studer, R. M., Hauert, C. (2011). Sustainable land management in practice: Guidelines and best practices for Sub-Saharan Africa. TerrAfrica, World Overview of Conservation Approaches and Technologies (WOCAT) and Food and Agriculture Organization of the United Nations (FAO).

Harris, R. F., Chesters, G., Allen, O. N. (1966). Dynamics of Soil Aggregation. *Advances in Agronomy*, *18*, 107–169.

Horrocks, C. A., Arango, J., Arevalo, A., Nuñez, J., Cardoso, J. A., Dungait, J. A. J. (2019). Smart forage selection could significantly improve soil health in the tropics. *Science of the Total Environment*, *688*, 609–621.

Jiru, B. E., Wari, N. B. (2019). Review: Role of Vetiver Grass (Vetiver zizanioides L) for Soil and Water Conservation in Ethiopia. *International Journal of Agricultural Economics*, *4*(3), 87-93.

Kibblewhite, M. G., Ritz, K., Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 685–701.

Kiniry, J. (2013). Novel Application of ALMANAC: Modelling a Functional Group, Exotic Warm-season Perennial Grasses. *American Journal of Experimental Agriculture*, *3*(3), 631–650.

Kiniry, J., Muscha, J., Petersen, M., Kilian, R., Metz, L. (2017). Short Duration, Perennial Grasses in Low Rainfall Sites in Montana: Deriving Growth Parameters and Simulating with a Process-Based Model. *Journal of Experimental Agriculture International*, *15*(6), 1–13.

Kiniry, J. R., Cassida, K. A., Hussey, M. A., Muir, J. P., Ocumpaugh, W. R., Read, J. C., Reed, R. L., Sanderson, M. A., Venuto, B. C., Williams, J. R. (2005). Switchgrass simulation by the ALMANAC model at diverse sites in the southern US. *Biomass and Bioenergy*, *29*(6), 419–425.

Kirui, O., Mirzabaev, A. (2014). *Economics of Land Degradation in Eastern Africa* (No. 128). ZEF Working Paper Series.

Kitonga, K. (2019). The role of forage genetic diversity in stimulating Africa's agricultural transformation. *6th African Conference of Agricultural Economists*.

Kogan, F., Kussul, N., Adamenko, T., Skakun, S., Kravchenko, O., Kryvobok, O., Shelestov, A., Kolotii, A., Kussul, O., Lavrenyuk, A. (2013). Winter wheat yield forecasting in Ukraine based on Earth observation, meteorologicaldata and biophysical models. *International Journal of Applied Earth Observation and Geoinformation*, *23*, 192–203.

Lal, R. (2012). Climate Change and Soil Degradation Mitigation by Sustainable Management of Soils and Other Natural Resources. *Agricultural Research*, *1*(3), 199–212.

Lara, M. A. S., Pedreira, C. G. S., Boote, K. J., Pedreira, B. C., Moreno, L. S. B., Alderman, P. D. (2012). Predicting growth of Panicum maximum: An adaptation of the CROPGRO-Perennial Forage model. *Agronomy Journal*, *104*(3), 600–611.

Lee, J., Pedroso, G., Linquist, B. A., Putnam, D., van Kessel, C., Six, J. (2012). Simulating switchgrass biomass production across ecoregions using the DAYCENT model. *GCB Bioenergy*, *4*(5), 521–533.

Liebig, M. A., Johnson, H. A., Hanson, J. D., Frank, A. B. (2005). Soil carbon under switchgrass stands and cultivated cropland. *Biomass and Bioenergy*, *28*(4), 347–354.

Mandal, D., Srivastava, P., Giri, N., Kaushal, R., Cerda, A., Meherul Alam, N. (2017). Reversing land degradation through grasses: A systematic meta-analysis in the Indian tropics. *Solid Earth*, *8*(1), 217–233.

Milne, R. M., Haynes, R. J. (2004). Soil organic matter, microbial properties, and aggregate stability under annual and perennial pastures. *Biology and Fertility of Soils*, *39*(3), 172–178.

Molatudi, R. L., Steinberger, Y., Xie, G. H. (2015). Effect of switchgrass plantation on soil moisture and nitrogen availability and microbial biomass carbon in a semi-arid ecosystem Effect of switchgrass plantation on soil moisture and nitrogen availability and microbial biomass carbon in a semi-arid ecosy. *International Journal of Agronomy and Agricultural Research*, *7*(2), 130–141.

Muchena, F. N., Onduru, D. D., Gachini, G. N., de Jager, A. (2005). Turning the tides of soil degradation in Africa: Capturing the reality and exploring opportunities. *Land Use Policy*, *22*(1), 23–31.

Mutegi, J. K., Mugendi, D. N., Verchot, L. V., Kung'u, J. B. (2008). Combining napier grass with leguminous shrubs in contour hedgerows controls soil erosion without competing with crops. *Agroforestry Systems*, *74*(1), 37–49.

Nkonya, E., Mirzabaev, A., Von Braun, J. (2015). Institutional framework of (in) action against land degradation. In *Economics of Land Degradation and Improvement - A Global Assessment for Sustainable Development* (pp. 33–54).

Norsuwan, T., Attachai, J., Carsten, M. (2015). Adapting the CSM-Canegro-Sugarcane model to Simulate Napier Grass in Adapting the CSM-Canegro-Sugarcane model to Simulate Napier Grass in Chiang Mai Province , Thailand. *2nd International Symposium on Agricultural Technology*, (pp. 1-5).

Pandit, R., Parrota, J., Anker, Y., Coudel, E., Diaz Morejón, C. F., Harris, J., Karlen, D. L., Kertész, Á., Mariño De Posada, J. L., Ntshotsho Simelane, P., Tamin, N. M., Vieira, D. L. M. (2018). Responses to halt land degradation and to restore degraded land. *Assessment Report on Land Degradation and Restoration*, (pp. 435–528).

Pedreira, B. C., Pedreira, C. G. S., Boote, K. J., Lara, M. A. S., Alderman, P. D. (2011). Adapting the CROPGRO perennial forage model to predict growth of Brachiaria brizantha. *Field Crops Research*, *120*(3), 370–379.

Pequeno, D. N. L., Pedreira, C. G. S., Boote, K. J. (2014). Simulating forage production of Marandu palisade grass (Brachiaria brizantha) with the CROPGRO-Perennial Forage model. *Crop and Pasture Science*, *65*(12), 1335–1348.

Rahetlah, V. B., Randrianaivoarivony, J. M., Andrianarisoa, B., Razafimpamoa, L. H., Ramalanjaona, V. L. (2012). Yield and quality of brachiaria Sp.cv Mulato-forage perennial peanut (Arachis pintoi) mixture in the Highlands of Madagascar. *Livestock Research for Rural Development*, *24*(10), 6–11.

Stavi, I., Lal, R. (2015). Achieving Zero Net Land Degradation: Challenges and opportunities. *Journal of Arid Environments*, *112*, 44–51.

Stewart, C. E., Follett, R. F., Pruessner, E. G., Varvel, G. E., Vogel, K. P., Mitchell, R. B. (2015). Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: Implications for soil quality. *GCB Bioenergy*, *7*(2), 288–301.

Sundaram, S. M., Sivakumar, T., Sankaran, V. M., Rajkumar, J. S. I., Nishanth, B. (2012). Distribution of soil organic carbon (SOC) in agricultural lands by farming forage crops for mitigating climate change. *International Journal of Environmental Biology*, 2(3), 165–168.

UNCCD. (2013). Background Document: The Economics of Desertification, Land Degradation and Drought: Methodologies and Analysis for Decision-Making. In *2nd Scientific Conference. Economic assessment of desertification, sustainable land management and resilience of arid, semi-arid and dry sub-humid areas.*

World Bank. (2010). Sub-Saharan Africa Managing Land in a Changing Climate: An Operational Perspective for Sub-Saharan Africa Sustainable Development Department Africa Region.

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