Model-Based Assessment of Grazing Impact on Soil Organic Carbon Stocks and Dynamics of a Kenyan Rangeland

M.Sc. in Sustainable International Agriculture

Specialization in Tropical Agriculture

Faculty of Agricultural Sciences

Institute of Grassland Science

M.Sc. Thesis
Submitted by Kate Kuntu-Blankson
Matriculation number: 21568791

Supervisors:

Prof. Dr. Johannes Isselstein

&

Dr. Ronald Franz Kühne

Supervisor at CIAT: Dr Rolf Sommer

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Georg-August-Universität- Göttingen, Germany
January 18th, 2019

DECLARATION

I hereby declare that the research on the topic “Model-Based Assessment of Grazing Impact on Soil Organic Carbon Stocks and Dynamics of a Kenyan Rangeland” submitted as a thesis in partial fulfilment of the requirements for the degree of Master of Science in Sustainable International Agriculture (SIA) with specialization in “Tropical Agriculture” has been carried out by myself. Taking into account the “Guidelines on Good Scientific Practice” issued by the University of Göttingen thus work by other authors has explicitly been indicated.

Name of Student: ……………………………

Matriculation Number: ……………………

Signature: …………………………………...

Place/ Date: …………………………………

"Success is brewed in the pot of determination"

Anonymous

Dedicated to Dela-Dem Doe Fiankor and George Blankson. Thank you for giving me the opportunity to pursue my dreams of a higher education.

ABSTRACT

As the largest terrestrial ecosystem carbon (C) sink, soils store about 2500 Pg C in the top 1 m depth. Rangelands make up around 40 % of global land surface and contain about 30 % of global terrestrial soil organic carbon (SOC). Grazing is the most important use of rangelands worldwide which when managed properly, can make rangelands potential sequesters of significant amounts of previously lost C. This will not only offset anthropogenic C emissions and contribute to climate change (CC) mitigation but also improve soil quality and productivity to ensure food security in the worlds' poorest regions. Rangelands in East Africa cover 75 % of the total land area, but despite the importance outlined, little scientific studies have been carried out to quantify the effects of grazing management on SOC sequestration potentials and there exists a knowledge gap. The heterogeneous nature of rangelands worldwide makes it impossible to generalize grazing management recommendations across different regions as same studies have produced different results in comparable places.

We aimed to investigate the long-term effect (30 years) of four grazing regimes on three selected sites under mid-future CC scenarios of the Representative Concentration Pathways (RCPs) 4.5 and 8.5 on SOC stocks of a rangeland in Southern Kenya. Heavy (HG) lead to SOC losses in all sites with the most loss of 206 kg C ha^{-1} observed on one sandy site "sand_light". Moderate grazing (MG) increased SOC stocks in all three sites, the highest of 141 kg C ha^{-1} occurred at our clay site "clay_heavy". RG (yearly rotation) and ALT (monthly rotation) caused SOC to increase only for the clay_heavy site. We observed small reductions in SOC stocks from the baseline scenario with a more negative impact of RCP4.5 than RCP8.5 but the observed differences were not dramatically different. The possible reasons for higher SOC stocks under RCP8.5 could be attributed to higher primary productivity of the C_4 grassland under elevated CO_2 and also more production of lignified plant materials that are less decomposable. We conclude that grazing management and soil texture will be the major factors controlling SOC stocks dynamics in the future as major differences was observed under those than under the CC scenarios.

Keywords: Climate Change, Grazing management, Rangeland SOC sequestration, East Africa.

ACKNOWLEDGEMENTS

This work was funded as part of a project under the CGIAR Research Program on Livestock with the International Centre for Tropical Agriculture (CIAT) and International Livestock Research Institute (ILRI) both in Nairobi-Kenya as the main collaborators. Many thanks the organization “STUBE” for providing me with financial support during my stay in Kenya.

My sincere gratitude goes to ***Dr. Rolf Sommer***, my supervisor at CIAT for picking me as his student for this research. Thank you for the warm reception you gave me during my stay in Kenya and the extreme patience you have had for me during the course of this work. I never could have finished this work without your guidance, critics and encouragements. I am most grateful to **Dr. Sylvia Nyawira** also of CIAT who played a very big role in this research by introducing me to the use of the DayCent model and was always eager and ready to offer her assistance on any topic whenever I needed. I am grateful to Dr. Melanie Hartman of Colorado State University for the technical support with the DayCent model.

Thank you to ***Dr. An Notenbaert*** and all the staff of CIAT who made my stay in Kenya a memorable one. Special thanks goes to the scientists at ILRI who provided me with necessary information needed for this work especially the manager of Kapiti Ranch ***Dr. Ilona Gluecks*** and her assistant ***Simon Kibiru***. My respect goes to the labourers who stepped in to help when the field tasks got tough, their physical strength contributed to making the research possible.

I wish to thank ***Joshua Mutua*** and ***Peter Bolo*** (CIAT) for the help they offered to me during the ground-truthing phase of the research. Even though the soil sampling task at Kapiti was very demanding, you made it fun and I always looked forward to going to the field.

My gratitude to my examiner ***Dr Ronald Kühne*** for your support and encouragements. Your door was always opened to me to listen to me and giving recommendations even beyond the topic of my research. Same goes for ***Prof. Dr. Johannes Isselstein*** for his support. Finally, thank you to ***Christophe*** and ***Christina Tute*** my German family. A part of me will always remain in Germany because of you and to ***Dela-Dem Doe Fiankor***, thanks for believing in me.

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List of Abbreviations

AGB	Above Ground Biomass
ANOVA	Analysis of Variance
ANPP	Aboveground Net Primary Production
AR5	Fifth Assessment Report
AWC	Available Water Capacity
BD	Bulk Density
BGB	Below Ground Biomass
BMPs	Best Management Practices
C	Carbon
$CaCO_3$	Calcium Carbonate
CC	Climate Change
CDM	Clean Development Mechanism
CEC	Cation Exchange Capacity
CIAT	International Centre for Tropical Agriculture
CMIP	Coupled Model Intercomparison Project
CO_2	Carbon Dioxide
COP	Conference of the Parties
DNDC	Denitrification Decomposition
DW	Dry Weight
E	Evaporation
EC	Electrical Conductivity
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FC	Field Capacity
Flgrem	Fraction of Live Shoots Removed by a Grazing Event Over One-month
GCM	Global Climate Model
GHG	Green House Gas
ILRI	International Livestock Research Institute
IPCC	Intergovernmental Pannel on Climate Change
Ksat	Saturated Hydraulic Conductivity
LUC	Land Use Change
MPI-ESM	Max-Planck-Institute Earth System Model
Mt	Megatons

N	Nitrogen
NASA	National Aeronautics and Space Administration
N_2O	Nitrous Oxide
NPP	Net Primary Productivity
OM	Organic Matter
P	Precipitation
PAR	Photosynthetic Active Radiation
PC	Principal Component
PCA	Principal Component Analysis
PET	Potential Evapotranspiration
Pg	Petagram
POM	Particulate Organic Matter
ppm	Part Per Million
PRDX	Coefficient of Radiation Use Efficiency
PTFs	PedoTransfer Functions
PWP	Permanent Wilting Point
RCM	Reginal Climate Model
RCP	Representative Concentration Pathways
RH	Relative Humidity
RMPs	Recommended Management Practices
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRAD	Solar Radiation
SWC	Soil Water Content
T	Transpiration
USA	United States of America
USD	United States Dollar
U	Wind Speed
USDA	United States Department of Agriculture
WUE	Water Use Efficiency

Chapter 1

1.1 Background

Increase in atmospheric concentrations of carbon dioxide (CO_2) and other major greenhouse gasses (GHG) is considered to be the main cause of climate change (CC) (Lal, 2004b; Meinshausen et al., 2017). Atmospheric CO_2 was estimated to have increased by 31 % between 1750 and 2010 (Houghton et al., 2001). The main drivers of this increase are fossil fuel burning and land use change (LUC), especially the conversion of forest lands to agriculture and pasture lands (Houghton et al., 2001). Fossil fuel burning accounts for 65 % of total anthropogenic emissions while LUC accounts for 11 % (IPCC, 2014). A large amount of emitted carbon (C) is taken up by oceans (dilution of CO_2 in water as carbonic acid) and in biomass (photosynthesis), but about 3.3 Pg C[1] emitted every year remains in the atmosphere (Prentice et al., 2001).

The impact of CC is most evident: the earth's average surface temperature is expected to increase by 1.5-5.8 ℃ at the end of the 21st century, and we have also observed rising sea-levels and major ecosystems shifts (Houghton et al., 2001; Westerling et al., 2006; Greene & Pershing, 2007). The devastating effects of CC and the long residence time of CO_2 in the atmosphere raises concerns for immediate action to reduce its emissions (Girard & Girard, 2013). A proposed strategy is to reduce the use of fossil fuels. But, even the most drastic reductions will not be enough to reverse CC anytime soon (Amundson & Biardeau, 2018). There is the need to create new C sinks and enhance accumulation in already existing terrestrial sinks (Oelbermann et al., 2004).

Global agroecosystems comprising of cropland, grazing and grasslands are important terrestrial C sinks. They provide the most practical and economically feasible option to mitigate CC (Lal, 2011). Their technical/biophysical potential to sink and accumulate C has been estimated to range between 30 to 60 Pg C over 50 years; an amount that could off-set about one-third of the 3.3 Pg C added to the atmosphere on an annual basis (Lal, 2004b; McDermot & Elavarthi, 2014).

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[1] 1 Peta gram (Pg) = 10^{15} g = 1 Giga ton (Gt)

As the third largest C sink after oceans and geological reserves, the soil's potential in mitigating CC lies in its key role in the global C cycle (Herzog, 2001; Lal, 2007). Globally, soil stores twice the amount of C in the atmosphere and three times that in vegetation. The upper 1 m of soils is estimated to store an approximate 1550 Pg of soil organic carbon (SOC) and an additional 750 Pg C in the form of soil inorganic carbon (SIC). This amount is at least 230 folds more than emission from anthropogenic sources in 2009 (Sommer & Bossio, 2014).

Over the past decade, a range of (global) soil C sequestration studies have given estimates of the soil's technical capacity to sequester C, and various strategies have been proposed in order to achieve this. The most prominent one these days, the 4 per 1000 Initiative (www.4p1000.org) launched in 2015 at the 21st Conference of the Parties (COP21) climate summit aims to increase SOC in the top 30-40 cm depth of all soils by 0.4 % each year (Minasny et al., 2017). Lal (2004b) estimates that soils have a global technical capacity to recover 50 to 60 % of historic C losses since 1885 which is estimated to be between 41 and 79 Pg C. Zomer et al. (2017) estimated a technical potential between 18 to 37 Pg C of all agricultural soil (with a few exceptions) in the next 20 years if best management practices are fully adopted on agricultural soils.

Many soil C sequestration policies and strategies describe a "win-win" and "no-regret" situation where not only CC is mitigated but increase in food security and improvement in environmental quality are achieved (Lal, 2004b). Nevertheless, the actual effectiveness of recommended strategies faces some major – economic, social, logistical – challenge, and many scientists argue especially about its economic feasibility (Smith, 2005, 2008). For example, for the 4 per 1000 initiative to be successful, it would require – among many other assumptions – that agricultural soils worldwide immediately be put under best management practices (BMPs) without change for 20 years (Amundson & Biardeau, 2018). Some scientists have argued that this is in fact not a rational assumption altogether, as such adoption processes take time (Sommer & Bossio, 2014). Most recently, Amundson and Biardeau (2018) outlined policy and economic challenges that prevent farmers in the USA from adopting soil C sequestration strategies. Huge capital investments and lack of technical assistance to farmers were some of the challenges mentioned for the rich developed country. This speaks volume as to what challenges are faced by smallholders in developing regions. Adopting BMPs for many resource poor farmers in developing regions especially in Africa is almost impossible. For instance, smallholder farmers in Africa have alternative use for crop residue as livestock feed (Giller et al., 2011). Soil C sequestration requires a constant supply of soil organic matter (SOM) to the SOC pool the maintenance of which depends on enormous amounts of nitrogen (N). High fertilizer costs and limited availability in some places makes it not very practical for some farmers to adopt this option (Van Groenigen et al., 2017). Some BMPs (crop residue return) are already widely practiced across the temperate regions of Europe and North America. Greater adoption of BMPs gives little scope for increasing SOC accumulation as these soils are near saturation with C (Poulton et al., 2018).

Based on the physical barriers mentioned, some researchers argue that estimates of technical potentials of SOC sequestration are too optimistic. Poulton et al. (2018) argue that the magnitude of the 4 per 1000 initiative is far smaller than claimed and will not be a major contributor to CC mitigation. Another study by Lewandrowski et al. (2004) in the USA predicted that soil C sequestration options are economically feasible only at significantly higher C prices. Their model predicted farmers were unlikely to convert croplands to grasslands even at a C price of 125 USD in the absence of additional incentives. They concluded that the estimated economic feasibility to sequester C in agricultural soils is far less than the technical estimates.

Nevertheless, despite all the challenges put forward, rangelands globally have been excluded from the debate to a large extent, even though they cover vast areas and hence could contribute significantly to C sequestration – the exact technical potential, however, remaining largely unknown. This study intends to shed light on the C sequestration potentials and dynamics of semi(arid) grassland ecosystems in Kenya as impacted by grazing.

1.2 Introduction

Rangelands are uncultivated lands that are mostly left for wildlife and/or livestock grazing and managed as natural ecosystems. They are distinguished by their native vegetation of grasses, grasslike plants, forbs and shrubs communities. They include savannas, prairies, grasslands, desserts and shrublands and are widely distributed throughout the earth (Booker et al., 2013). They are estimated to cover about 30 % of the ice-free global land surface mostly in (semi) arid regions of the earth (McDermot & Elavarthi, 2014). Rangelands store about 20 % of global SOC and hold more than 36 % of the above and below ground terrestrial vegetation biomass.

For this reason, a slight change in their ecosystem's soil C reserve with respect to management can have massive implications on the global C cycle and CC (Derner & Schuman, 2007).

In general, tropical rangelands are considered as degraded with respect to C because net C inputs are constrained not only by limited water and favourable temperatures for C mineralization but by continuous C depletion as a result of livestock overstocking (De Deyn et al., 2008; Harris, 2010; Kemp et al., 2013). Temperate rangelands on the other hand are highly productive because of the presence of optimal conditions. An advantage that allows them to have higher SOC contents which Amundson (2001) reported to exceed the SOC amounts under temperate forests. These rangelands may offer little potential as C sinks as they are healthy and already in a near equilibrium state. For degraded rangelands however, restoration will significantly enhance their ability to capture back previously lost C which can help mitigate global CC (Izaurralde et al., 2001; IPCC, 2007). However, effective C sequestration potential of degraded rangelands – as is the case for any agro-ecosystem – is a question of the balance between losses and gains (Yigini & Panagos, 2016).

The single most important use of rangelands worldwide is livestock grazing (Derner, Boutton & Briske, 2006). It is an important recurrent "disturbance", and a major determining factor that controls ecosystem functioning and nutrient cycling (Hafner et al., 2012). Jobbágy and Jackson (2000) found that rangelands can store more than 100 ton[2] C ha^{-1} SOC in the upper 1 m depth and is highly influenced by grazing management. According to Powlson et al. (2011) intensive livestock production and overgrazing are gradually causing decrease in rangelands SOC stocks, turning them into sources instead of net sinks of GHG. Negative impacts of overgrazing include reduced productivity and vegetation cover which exposes the soil to erosion. Continued removal of palatable species suppress their growth and give way to encroachment by less desirable invasive species; usually woody shrubs (Wang et al., 2016). Light to moderate grazing, on the other hand, stimulates biomass regrowth. A study by Chen et al. (2015) showed moderate grazing in grasslands increased belowground biomass (BGB) production. Kimble et al. (2000) reported that US rangelands under proper management have the capacity to accumulate an estimated 6 Pg C over a 30-year period until a new (higher) equilibrium is reached. This will be equal to an off-set of 3.3 % fossil fuel associated CO_2 emissions in the

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[2] Ton= metric ton=1000 kilograms

U.S. Such changes would not only mitigate rises in global temperature but also increase soil resilience and food security, especially in poorer regions of the earth.

Due to the heterogeneous nature of (i) rangeland soils and vegetation composition and (ii) the spatial/temporal variations and complexity of factors affecting productivity among sites, all rangelands do not respond the same to grazing management. Thus, general recommendations cannot be given on sustainable grazing management. Regional and plot scale studies are necessary to quantify and understand the effects of grazing intensities on SOC dynamics, as same studies have produced varying or even contradictory results in comparable places (Abdalla et al., 2018). Our study therefore, only focuses on a grass dominated rangeland in Southern Kenya. In some cases, grazing stimulated compensational plant growth in some tropical ecosystems (Conant & Paustian, 2002), while decreases in productivity were reported by others (Wilsey et al., 2002). In temperate rangeland ecosystems, Frank and McNaughton (1993) observed positive effects on SOC while Singer and Schoenecker (2003) detected negative effects of grazing on productivity and SOC. However, continuous and heavy grazing intensities are generally accepted to have negative effects on SOC. By direct removal of aboveground biomass (AGB), photosynthetic primary production and plant growth capacity are reduced, which in turn decrease inputs to the SOM pool (Piñeiro et al., 2010).

In grassland ecosystems, grass species in adapting to the dry conditions in semi(arid) regions allocate more growth to roots, a mechanism which enables them to better extract water and nutrients from deeper layers. The deep rooting system allows for C to be sequestered at lower soil depths and is less affected by climate and physical disturbances that enhance rapid turnover (Kane, 2015). Furthermore, The roots increase the formation of soil aggregates and recalcitrant organic compounds which are less prone to rapid decomposition and associated C losses (Balesdent & Balabane 1996; Jackson et al., 1996; Silver et al., 2010). Grassland species are usually slow growing because of the limited resources available for growth. This causes them to produce poor quality litter that cannot be easily decomposed hence slowing down C cycling while enhancing SOC build-up (De Deyn et al., 2008).

Grasslands in East Africa covers 75 % of the total land area. Estimates from Conant and Paustian (2002) show that a greater percentage of these grasslands are overgrazed. Pressure from rapid human population growth together with significant herbivore wildlife numbers present a challenge on how rangelands can be managed in the region (Kariuki, Willcock &

Marchant, 2018). Kenya's rangelands include savannas and grasslands and cover approximately 464,296 km^2 out of the total land area of 582,644 km^2 (Mwagore, 2003). In part as a result of notably data scarcity, only a few studies aimed at quantifying grazing impacts on the quantity and direction of change in SOC stocks in the region have been conducted. Aynekulu et al. (2017) found there was no significant difference in SOC between grazed and ungrazed exclosures in a long-term trial in an Ethiopian rangeland. A study by Ritchie (2014) in Northern Kenya suggested that prolonged continuous heavy grazing resulted in SOC reductions. But found that low grazing intensities in degraded rangelands could potentially recover lost SOC at rates between 0.3-0.5 ton C ha^{-1} across varying soil types. Rotich (2018) conducted a study in Southern Kenya, she found that a continuously grazed site converted to rotational grazing for 11 years had higher SOC stocks than adjacent sites left to continuous grazing. Conant and Paustian (2002) suggested a sequestration rate of 0.21 C ha^{-1} yr^{-1} although this estimated was directed to African rangelands as a whole. A knowledge gap exists in the East African region which limits scientific understanding of the global C cycle and also makes it challenging to provide recommendations on grazing management strategies for rangeland policy planning, as well as to triangulate the importance that improved rangeland management could play in the global CC mitigation debate.

1.2.1 Aims, Objectives and Hypothesis

The aim of this study was to investigate the long-term effects of grazing management on SOC stock dynamics under climate change in a grassland ecosystem. Our study site is the International Livestock Research Institute's (ILRI) experimental livestock station.

The objectives are to:

- Quantify current SOC stocks of selected plots under varying soil textural types and grazing intensities;
- Simulate long-term SOC dynamics under different grazing intensities, and thus pinpoint entry points for improved grazing management;
- Compare the impacts of two climate change scenarios, namely RCP4.5 and RCP8.5 on SOC.

We hypothesised that:

- Light to moderate grazing stimulates biomass production thus positively influencing the SOC stocks, while heavy grazing triggers the opposite;

- Clay content impacts SOC contents positively, by providing increased protection of organic matter against rapid microbial breakdown;
- Climate change will affect SOC stocks negatively, potentially fully overriding SOC gains to be made by improved grazing management.

Chapter 2

Literature Review

2.1 The Carbon Cycle and Climate Change

In recent times, the global C cycle is increasingly receiving attention due to the inter-relatedness with CC. The C cycle is a biogeochemical process which describes the biosphere's exchange of C between the major reservoirs – ocean, atmosphere, terrestrial ecosystems and geosphere. Any shift in the cycle that moves C between sinks at a faster rate than expected, causes a disequilibrium which results in excess C being pushed into the atmosphere (Lenton, 2003). Anthropogenic activities have resulted in an annual purge of excess atmospheric CO_2 more than the cycle can process and this has resulted in increased levels of atmospheric CO_2, and in consequence CC (Grace, 2004).

Plants take up CO_2 from the atmosphere through photosynthesis. Such accrued plant material when decaying, through microbial decomposition, is converted into SOM. The C in SOM is released back into the atmosphere as CO_2 through microbial respiration (Grace, 2001). Temperature is a major regulator of SOM decay. It is therefore anticipated that, as global temperature increases, the rate of C exchange from the soil to the atmosphere will accelerate. This could potentially be at a faster rate than plants can assimilate C back into the soil (Kirschbaum, 2000; Heimann & Reichstein, 2008). This is a major concern, as the soil contains twice as much C as the atmosphere and a slight loss in its C pool will mean an even faster increase in the atmospheric CO_2 concentration than by increased emissions of fossil fuel-based CO_2.

2.2 SOM and Soil Quality

SOM comprises of soil living organisms and their remains and plant litter at various stages of decomposition. Addition of SOM to the soil is followed by an initial breakdown into particulate organic matter (POM) by the actions of macro-and-micro-organisms. Resistance of POM to the activities of decomposers vary with respect to the quality. Metabolic compounds in SOM are made of substances such as simple sugars and organic acids derived directly from plants or from exudations and excretion of microbes (Dungait et al., 2012). They are rich in energy and are easily accessible to microbes and as a result, are easily decomposed (Dungait et al., 2012). Some SOM is resistant to decomposition because they have an inherent or attained biochemical resistance to decay. Complex plant structural components like lignin and cellulose/hemicellulose polysaccharides are examples that have inherent biochemical properties that inhibit microbial and enzymatic breakdown (Six et al., 2002). Other substances through the processes of condensation and complexation during decomposition attain a biochemical stabilization. SOM decomposition by pyrolysis results in the formation of charcoal which is very recalcitrant to further decomposition (Dungait et al., 2012).

Furthermore, SOM is preserved from decomposition by physical and or chemical stabilization mechanisms in the soil. Chemical stabilization comes about as a result of chemical or physicochemical binding of SOM to mineral surfaces-especially clay and or other organic molecules. Adsorption of SOM to clay particles form organo-mineral complexes that reduce activities of microbes and enzymes that cause decomposition (Six et al., 2002). A wide range of SOM from simple acids to complex bio-macromolecules can be absorbed onto clay particles for protection against mineralization (Rabbi et al., 2010).

The formation of macro-and-micro-aggregates in soils gives physical protection to SOM by occlusion into aggregates during formation. It is argued by some scientists that the size and arrangements of pore networks in these aggregates are inaccessible to microbes and enzymes which are responsible for decomposition. The micro-and-macroaggregates form compartments with microbes abundant on the outer parts and SOM safely locked in the insides. (Sollins et al., 1996; Rabbi et al., 2010). Other scientists are of the view that the pore sizes of the aggregates are accessible to bacteria but decomposition might not be profitable to the microbes because of the complex architecture of the pore networks which prevents oxygen supply into the network (Six et al., 2002; Mayer et al., 2004; McCarthy et al., 2008).

SOM contains about 45-55 % (organic) C as the major building block (Wilke, 2005). Scientists started distinguishing SOC pools by – admittedly rather arbitrarily set – turnover rates that are dependent on a combination of biochemical and physical properties (Dungait et al., 2012). These pools have no real analogue in nature but were rather broadly associated to some functional SOM fraction, such as a rather small (1-3 % of total SOM) labile fraction, i.e. microbial biomass and their by-product represent; an intermediate fraction made up of resistant plant structural components like lignin and-a rather stable fraction made up of recalcitrant humic substances and condensed substances such as charcoal. This fraction has the largest pool and takes anywhere between a century to thousands of years to stabilize making it the least sensitive to management (Paustian et al., 1992; Davison & Janssens 2006.).

Interest in increasing and maintaining SOC is not only limited to reducing atmospheric CO_2 levels. Its key role in ecosystem processes and functions has been known for decades. SOC is particularly a strong indicator of soil quality; its presence reduces bulk density (BD) which allows for root and water percolation and forming stable aggregates. It is also critical to soil health, improvement and resilience to degradation by providing a buffer to pH and temperature (Lal, 2004a; Shukla et al., 2006). It has been suggested that a minimum of 2 % of SOM is needed in order for soil function not to be impaired (Lal 2004; Dungait et al., 2012).

2.3 Factors Influencing Turnover of SOC

SOC is regulated by the balance between biotic processes of photosynthetic litter inputs on the one hand and outputs through decomposition with the turnover rate dependent on the litter quality on the other hand (Nyawira et al., 2017). It is of crucial importance to understand the major contributing factors to SOC gains and losses given its importance in ecosystem services and the feedback loop of this reserve to the atmosphere and CC.

Climate is a dominant abiotic factor controlling the major biotic processes; rainfall and temperature have positive effects on plant production which supplies organic matter (OM) to the SOC pool. However, studies in humid climates show that rises in temperature accelerate decomposition at a relatively higher rate than it stimulates plant growth (Amundson, 2001; Mulder et al., 2015). In Western Australia, Hoyle et al. (2006) found that a 10 ℃ increase in temperature – from 10 to 40 °C - doubled decomposition rates.

While recalcitrance preserves SOM from decomposition, Dungait et al. (2012) reported that turnover is more dependent on accessibility to microbial and enzymatic attack. It has been observed that the physical protection of SOM in soil aggregates increase with increasing clay contents (Six et al., 2002). Texture, therefore, plays a role in SOC storage, soils with high clay and silt contents provide labile SOM with physical and chemical protection against decomposition. Needless to mention, SOM in sandy textured soils will not have such protection from microbial attack, and therefore gets exposed to rapid decomposition (Paustian et al., 1997). Management practice is the most important anthropogenic activity that influences SOC. High removal rates of plant materials without retaining residue result in reduced inputs of OM to the

SOC pool. Indiscriminate soil disturbance destroys aggregate stability and exposes previously protected SOC to microbial attack and fast(er) breakdown (Lal, 2011).

2.4 Rangeland SOC Dynamics Under Climate Change

Climate change studies predict warming and climate variabilities for the coming future as a result of increased atmospheric GHG concentrations (Polly et al., 2017). Current CC estimates predict a 0.2 ℃ increase in global mean surface temperature per decade (IPCC, 2007). The Fifth Assessment Report (AR5) of the IPCC adopted new climate change scenarios— the representative concentration pathways (RCPs) comprising RCP2.6, RCP4.5, RCP6.0 and RCP8.5. A set of GHG concentration and emissions pathways designed to support research on future climate change (IPCC, 2013). The pathways are influenced by climate and socio-economic conditions, their names are from assumptions made from their radioactive forcing levels in the year 2100 against preindustrial levels (Moss et al., 2010). The most commonly used ones in studies on CC impact on the environment are RCP4.5 and RCP8.5, the former represents a moderate RCP level of 4.5 Wm^{-2} with CO_2 emissions stabilizing from 2150 and RCP8.5 which represents a high RCP level of 8.5 Wm^{-2} proposes that CO_2 levels will continue to rise after 2100 (Di Vittorio et al., 2014; Meinshausen et al., 2011). Both scenarios describe temperature increases accompanied a by decrease or increase in rainfall depending on the geographical location.

Many studies suggest that the increasing temperatures will be accompanied by a decline in rainfall in semi(arid) parts of the world, especially under the RCP8.5 pathway. What does that mean for rangeland C stocks? Due to the variability in factors affecting soil processes under rangeland in different geographic locations, it is not possible to give a generalized answer. It is, however, clear that climate has impacts on important soil properties and processes as well as rangeland species composition. While rangelands have potentials to recover historical C losses, the effect of increasing temperatures and prolonged drought periods may pose challenges to how much C can be sequestered (IPCC, 2007).

Changes in species composition and vegetation shifts from grassland to woody plant species due to the interaction between grazing and climate have been observed in rangelands (Wigley et al., 2010; Yusuf et al., 2015). Woody plant encroachment is common in rangelands where there is absence of fire to control their growth. Kapiti (study area) as an example has some parts of it invaded by non-native acacia shrub species since the last 10 years. Mortality of perennial grasses may occur under prolonged drought stress and can result in a shift from the once predominant perennial grass species composition to rangelands dominated by annual species (Polley et al., 2017). The rising temperatures accompanied by low rainfall amounts will also cause drought stress in plants which will directly affect the quality and quantity of litter produced (Hoffman & Vogel, 2008).

Adequate nutrient levels are required for plant growth and productivity. Nitrogen (N) supply in rangelands are mostly from organic sources and are only available to plants after mineralization into inorganic forms (Polley et al., 2017). Major processes and pathways of the soil N cycle are dependent on soil water and temperature so will be affected by CC. N plays an important role in plant growth and reproduction thus impacts on SOM supply to the soil (Polley et al., 2017). Changes in temperature and soil moisture regimes due to CC will affect activities and composition of soil microbial communities. Increased temperature is expected to impact positively on microbial biomass and respiration in the soil which implies rapid C mineralization. Previous studies across different ecosystems suggest that evaporation is enhanced under high(er) temperatures and causes a reduction in net primary productivity (NPP). This reduces SOM supply to soil but increases microbial respiration and ultimately depleting SOC stocks (Holland et al., 2000; Dalias et., 2001; Sanderman et al., 2003).

A good understanding of how rangeland management interacts with the C cycle is needed to implement effective CC mitigation strategies. Grazing management regimes that will be within the carrying capacity of the changing ecosystem will be necessary to keep C fluxes under check and increase rangeland resilience to CC.

2.5 Socio-Economic Importance of Rangeland Degradation

Rangelands are a dominant land use type in semi(arid) regions of developing countries where majority of the world’s poor live and rely on livestock production for their livelihood. In addition, they provide valuable ecosystem services that are needed for everyday life activities (FAO, 2008). In semi(arid) regions of Kenya, 90 % of employment activities are livestock related and provide 95 % of household incomes (Opiyo et al., 2015). Despite the obvious importance, overgrazing and excessive cultivation in response to rapid population growth pressure coupled with climate change are putting rangelands in developing regions under the constant threat of degradation. It is estimated that about 20 % of rangelands worldwide are degraded and an additional 12 million ha gets degraded annually (Reynolds et al., 2007).

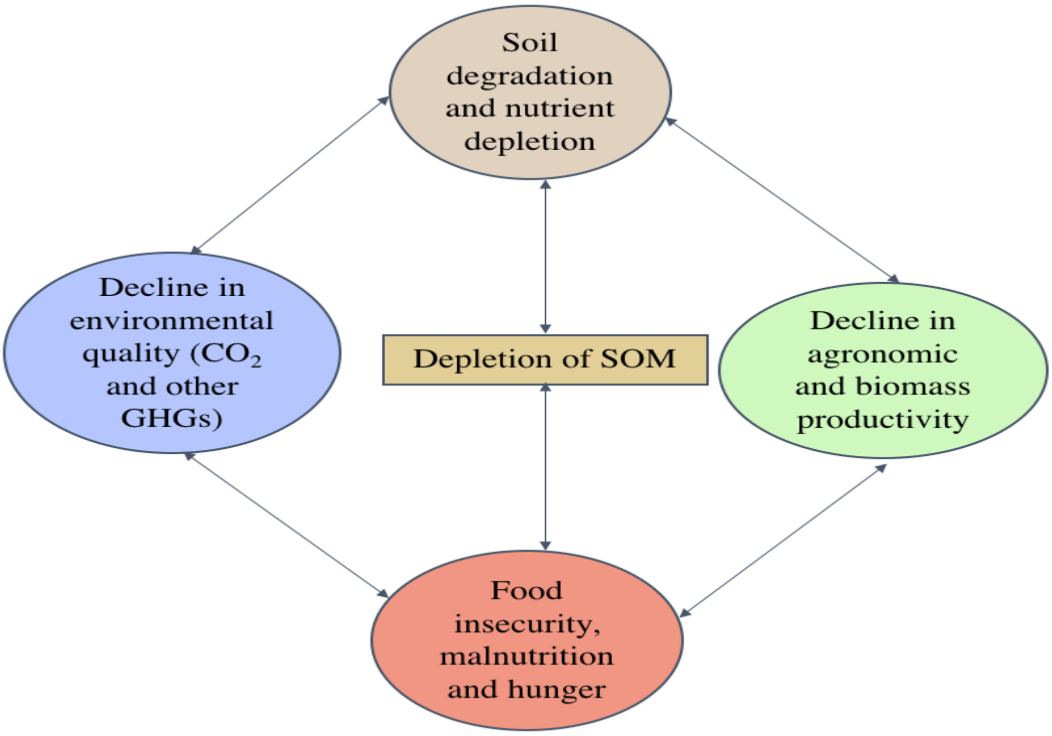

Figure 1. Link between SOM decline-food insecurity- soil and environmental degradation as illustrated by Lal, (2004a).

Lal (2004a) describes a strong linkage between climate change, rangeland degradation and food insecurity (Figure 1). Serious consequences will arise if no intervention is made to halt and reverse degradation in affected areas. About 65 % of pastoral communities in the semiarid rural parts of Kenya already live below the poverty line (Mwangi & Ostrom, 2009). There will be further food-insecurity and malnutrition related issues in pastoral and rural populations who rely entirely on rangeland for their survival (Bedunah & Angerer, 2012). This situation usually ends up in poverty and hinders development. This, in turn, gives rise to tribal conflicts over the little resources remaining and threatens political stability (Tefera et al., 2007). By improving soil quality, food security can be attained through SOC sequestration. Adaptive management strategies must be employed by policy makers to test grazing regimes options that fit within the carrying capacity of rangelands (Bedunah & Angerer, 2012). Previous studies have shown that improved grazing management can lead to more efficient use of rangeland resources and rehabilitate degraded lands (Conant & Paustian, 2002).

2.6 East African Rangelands (Kenya) — Opportunities and Challenges for Carbon Sequestration

In comparison to the developed world, little knowledge exists for rangeland SOC sequestration potentials in East Africa and other developing nations. However, the few studies available show that C sequestration in degraded lands offers additional opportunities (Lal & Kimble, 2000). Grassland Recommended Management Practices (RMP) that enhance SOC were mostly developed to address issues other than reducing atmospheric C concentrations, so there are alternate benefits if they are implemented.

Even the most aggressive CC policies implemented will do little to slow down the process of global warming anytime soon. Therefore, adaptation of semi(arid) rangeland ecosystems to longer drought spells is necessary (IPCC, 2007a). Rangeland resilience to CC is increased when soil health and quality are improved through SOC sequestration. Productivity of rangelands and ecosystem services are increased when soil quality is improved and this, in turn, brings higher economic returns to the owners (Pan et al., 2006; Lal et al., 2009b). Policies and programs that enhance C sequestration may be developed and implemented to provide incentives or direct payments to communities and individuals willing to adopt RMP on their lands. East Africa is presently Africa's biggest hotspot for C market (Jindal, 2006). Economic benefits for pastoralists could, for instance, be developed through the Clean Development Mechanism (CDM) which allows countries to trade in C offset credits (Perez et al., 2007).

Although there are promising adaptation and mitigation potentials for C sequestration in rangelands, there are challenges to scaling up. The process of SOC sequestration is reversible and so previously stored SOC is readily vulnerable to future losses when the soil in question is subjected to even small management disturbances (Page et al., 2002).

Sometimes, RMP policies that are intended to enhance SOC sequestration do not necessarily lead to good practices (Conant, 2010). Fertilizer application aims at making nutrients available for plant growth and increases SOM supply. However, the net C sequestration from inorganic fertilizer addition may become negative because the production process emits significant amounts of CO_2. Inappropriate and excessive use of fertilizers increases emissions of N_2O which is also a GHG so the overall purpose of this RMP may be defied in some instances (Schlesinger, 2000).

It is generally difficult to develop and implement appropriate policies and incentives in part, due to lack of and or poor institutional capacity (Jindal, 2006). In Kenya, a policy that was meant to permanently settle pastoral groups led to continuous heavy grazing when pastoral movements were restricted to one place (Ritchie, 2014). In other cases, pastoralists are marginalized during policy making and there are few incentives for them to adopt sustainable management options. Government policies in the region must provide higher net economic benefits than the previous management if sustainable RMP projects are to be adopted (Tennigkeit & Wilkes, 2008).

Property right issues is also a discouraging factor for policy adoption in places where target groups do not have land tenure rights (Grieg-Gran et al., 2005). It is crucial that communities that are the target for C sequestration projects have clear land tenure rights but unfortunately, this is not the case in most parts of Kenya and East Africa (Lund, 2000; Swallow et al., 2002; Woodhouse, 2003). Traditional lands for pastoralism are not under any defined tenure rights, which makes it difficult to exclude others from using the lands (Perez et al., 2007). This makes it not only difficult to implement C sequestration projects but can cause a situation where more powerful users gain all the economic benefits from the projects. Marginalized and poor land users also risk losing access to the use of lands in such situations (Kerr et al., 2006).

Good governance and economic stability create the ideal environment to attract international C investments due to the long-term gestation period of most C sequestration projects. However, political instability and unpredictable governance in some countries in East Africa make it unlikely to attract and benefit from such investments (Jindal, 2006).

2.7 Proposed Management Options for Enhancing Rangeland Sequestration

A number of specified agro-ecological management land use options have been suggested for improving productivity and C sequestration in rangeland soils of semi(arid) areas. However, effectiveness varies according to local climate and ecological conditions. In most semi(arid) rangelands, limited water availability and lack of nutrients are a drawback to biomass productivity.

Re-growth of vegetation in degraded lands by the introduction of improved species or native species that are more productive and well adapted to the local climate conditions is one option. Selected species must have the advantage of being drought resistant and be able to withstand high grazing intensities (Conant, 2010). Some introduced species that have the added benefit of nitrogen fixation may help enhance soil fertility (Perez et al., 2007). Re-seeding has been successful to an extent in rehabilitating degraded rangelands in East Africa but are not commonly adopted in pastoral systems because of the high capital investments involved

(Musimba et al., 2004; Opiyo et al., 2011). Tebaje et al. (2014) conducted a study in South-East Ethiopia that showed it is possible to restore degraded rangelands by a combination of reseeding with Rhodes grass (*Chloris gayana Kunth)* and a simple tillage and manure addition.

Supplementary irrigation, OM addition and fertilization improve productivity of rangelands. According to a review by (Derner & Schuman, 2007), fertilizers, particularly those that supply sufficient nitrogen help increase plant production and water use efficiency (WUE) thereby increasing C inputs and potentially SOC sequestration. In Oklahoma State, USA, a study showed that SOC under a pasture increased significantly after nitrogen fertilizer was applied annually for five years (McDermot & Elavarthi, 2014). However, these three practices are expensive, and, in some cases, fertilizers may not be readily available to some communities. Efforts to provide irrigation water, fertilizers and OM require energy and the benefits of C sequestration might be offset by fossil fuel consumption (and release of CO_2) required for providing such services and inputs and also by increased N_2O fluxes (McDermot & Elavarthi, 2014).

Fire is a common phenomenon in East African rangelands. It is an important factor in controlling encroachment of invasive woody shrub species (Abdulahi et al., 2016). Although the long-term effect of fires on rangeland SOC stocks is little studied, the benefits of fires include removal of old and dead vegetation biomass giving way for young regrowth of forbs and grasses. Studies also have shown that fire results in a higher aboveground nutrient concentration in rangelands as compared to unburned areas (Frank et al., 2003). However, others such as Bremer and Ham (2010) report a moderate loss in SOC when a tallgrass prairie was subjected to annual burning.

This study focuses on the importance of grazing on SOC trends and accumulation. Improved grazing management that regulates grazing frequency and intensity is proven to impact positively on plant productivity. Stocking rangelands with the right livestock herd number within the carrying capacity of the land and excluding grazing at sensitive plant growth stages and critical seasons facilitate the rehabilitation process of degraded lands and increases biomass production and inputs to the SOM pool.

2.8 Process-Based Model for Predicting SOC Dynamics

Process-based ecosystem models are useful tools for quantifying and understanding C cycling in soils as well as for making predictions of the effects of environmental and climate changes on SOC dynamics. They are developed based on an understanding of the most relevant ecological processes and the key factors controlling them (Fynn et al., 2010). Their use in simulating ecosystem processes of C and nutrient flows between agroecosystems and the atmosphere are well documented (Parton et al., 1993, Keating et al., 2003).

SOC changes on regional and plot scale resulting from management practices are mostly predicted with process-based models – among others DNDC, *ecosys* and EPIC. The most frequently used ones are CENTURY and RothC (Viaud et al., 2010). In process-based models, SOM is usually represented by multiple conceptual pools depending on the complexity of C flows. Decomposition of OM is described by first-order kinetics (Stockmann et al., 2013). CENTURY as an example divides SOM into an active pool having about five years turnover rate, the slow pool having 10 to 50 years turnover rate and the passive pool which takes anywhere from 500-1000 years to turnover, temperature and soil moisture allowing (Parton et al., 1998).

Performance and confidence in models are improved by parameterization with site specific input datasets. The availability of the required input data influences choice of model for a study (Post et al., 2001), simple models like RothC require basic input information (Coleman & Jenkinson, 1996) whereas complex models like CENTURY require more input data. Despite their tremendous capabilities to predict SOC dynamics, most models are limited in accurately simulating some management options such as intensively managed pasture systems and intercropping systems. There is still room for model improvement in this regard to properly estimate the capacity of soils as potential C sinks (Kane, 2015).

2.9 DayCent Model Description

DayCent is the daily time-step of CENTURY developed to simulate soil C in the top 20 cm soil depth as well as nutrient dynamics and trace gas fluxes on a finer time scale. It was initially developed and calibrated for grasslands in semi-arid areas. DayCent has been tested extensively across a range of other ecosystems and land use types and is proven to simulate SOC dynamics under given climate and management conditions as well (Del Grosso et al., 2008). Decomposition in the SOM sub-model (see appendix 1) is a function of temperature, moisture and texture. In the plant production sub-model, NPP is a function of soil temperature and water. It is divided into various plant parts depending on vegetation type, nutrient availability and vegetation radiation use efficiency (Metherell et al., 1993).

To make simulations in DayCent, the user requires information specific to the site of study (Table 1). Although DayCent requires many input parameters, usually those aside from very site-specific data are mostly left to default values unless robust calibration is done (Parton et al., 1993). Site specific event options can be created and scheduled in the various input files.

Table 1. Required site-specific input parameters for running the DayCent model.

Input	Required Information
Climate data	Daily maximum/minimum temperatures and precipitation, in addition, solar radiation, wind speed, relative humidity may be included.
Site specification	Coordinates and weather statistics.
Soil data	Soil depth, texture (clay, sand and silt percentages), bulk density, pH, root distribution, field capacity, wilting point and saturated hydraulic conductivity.
Plant	Coefficient of radiation use efficiency (PRDX) and plant genetic information.
Management	Historical and current land use history and agronomic practices

The literature reviewed draws attention to the importance of sequestering C under rangeland soils given its potential to (i) contribute to CC mitigation and (ii) enhance adaptation to CC keeping in mind that majority of the world's already poor populations depend on rangelands for their livelihoods and survival. Grazing is the single most important use of rangelands worldwide and its management has implications for how fast the soil's C is recycled back into the atmosphere. It is therefore crucial to give rangelands attention by studying how varying grazing intensities impact the SOC pool and what strategies can be employed to enhance capture and storage of C. The predicted extreme effects of CC require immediate actions to be taken in order to adapt. Although limited to a certain degree, predictive ecosystem models rely on an understanding of the underlying mechanisms that influence SOM changes. They are reliable tools to give us future insights on how an adopted grazing management will influence SOC stocks well into the future.

The East-African region is 75 % grassland. Few studies have been conducted in the region on the impacts of grazing intensities and CC scenarios despite the outlined importance of this ecosystem type. The purpose of this study within the scope of a master thesis is to use the ecosystem model DayCent to predict grazing impacts on rate of accumulation of SOC stocks and its dynamics under CC in a Southern Kenyan rangeland

Chapter 3

Materials and Methods

3.1 Study Area

The site for the study is the International Livestock Research Institute's (ILRI) 'Kapiti Plains'. The 13,000-hectare rangeland is located in Southern Kenya (-1.6 S, 37.1 E) at an elevation range between 1620-1900 m above sea level. Climate is semi-arid with minimum and maximum temperatures averaging at 20 °C and 26 °C, respectively. Characterised by a bimodal rain pattern, the long rain season is from March to May and the short from late October to December. Mean annual rainfall is about 550 mm. Soils are predominantly black cotton (classified under Vertisols) in the plains and red cotton (Ferrosols) in the ridges. Vegetation comprises perennial C_4 savanna grasses—Themeda (kangaroo grass); Panicum (switchgrass); Chloris (windmill grass); Pennisetum (fountain grass); Cenchrus (African foxtail grass); an invasive acacia shrub species (whistling thorns) and balanites trees sparsely distributed throughout the plains.

3.1.1 Land Use History

Kapiti was formerly a livestock ranch for beef and milk production from 1939 until purchased by ILRI in 1989. Fodder used to be grown in fenced paddocks to supplement milk cattle production. After purchase by ILRI, encroachers removed and stole existing paddock fences and water supply equipment and as a result the grazing pattern changed because some areas had water for the livestock during grazing while some areas lacked water. ILRI manages Kapiti as an extensive grazing manner, where livestock herds are taken care of by herders and sent out for rotational grazing. In reality however, shortage of water sources has resulted in an all year-round grazing in areas with water, and little to no grazing in other areas. Presently, the ranch has livestock (cattle, sheep and goats) numbering about 4,000 in total. As a result of infrastructural development in the region, it has become home also to herbivorous wildlife who graze unmonitored throughout the ranch.

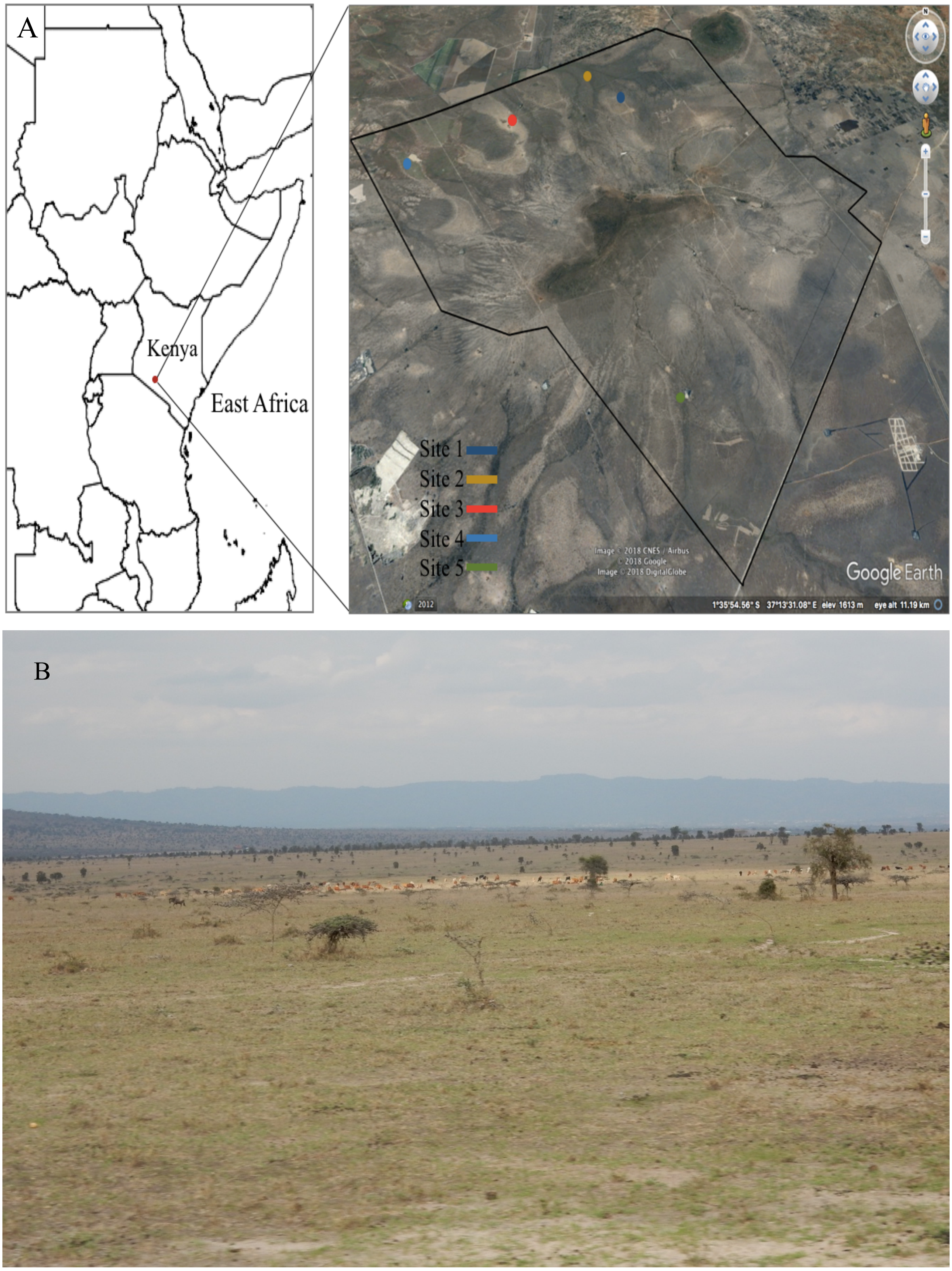

Figure 2. Study Site map (A) and (B) photo of Kapiti taken in October 2017 at the onset of the short rain season.

Taking advantage of this obviously unbalanced grazing regime, as well as expected variations in soil texture, five sites of interest out of the entire plain are singled out for the study (Table 2). Required site-specific inputs and validation datasets were collected between September and December 2017. Unavailable data were generated from online platforms or were estimated from literature.

Table 2. Characteristics of the selected sites.

Site	Soil Type	Vegetation	Management	Latitude	Longitude	Altitude (m.a.sl)
1	Sandy	Grass	Long-term continuous heavy cattle grazing	-1.59	37.13	1750
2	Black Cotton	Grass/Acacia shrubs	Long-term continuous heavy cattle grazing	-1.58	37.12	1626
3	Sandy	Grass	Long-term continuous heavy sheep grazing	-1.61	37.10	1651
4	Sandy	Grass	Recent heavy sheep grazing	-1.62	37.07	1628
5	Sandy	Grass/Balanite trees	Recent light grazing by cattle	-1.68	37.14	1654

3.2 Soil Parameters

3.2.1 Soil Sampling

Each of the five sites were sub-divided into four replicates from which soil samples were taken in October 2017 (70 samples in total, 14 representing a site). In three replicates of all five sites, we sampled at three depth intervals (0-10, 10-25 and 25-50 cm) and in case of the remaining one replicate down to one meter (50-75 and 75-100 cm), assuming that variation of soil properties at these depths was considerably lower, allowing for reduced reps (and faster, less-costly sampling). In all sites, for each depth in every replicate, five soil samples were collected in a 200 m transect using an auger. Samples were thoroughly mixed to form a composite sample. Spots of land within a site that from visual assessment seemed different as compared to the whole area were not sampled, valleys and dried water ways were also avoided to ensure that only homogenized areas were captured to represent the site in question.

3.2.2 Soil Sample Preparation

The samples were air-dried at 48 °C for one week until they reached constant weight, with occasional stirring to ensure uniform drying. Dried samples were sieved to remove debris and particle sizes larger than 2 mm, grinding was done when necessary to breakdown larger aggregates. About 100 g of each sample was subsampled into paper bags for delivery to the soil laboratory for analysis.

3.2.3 Soil Texture and Total C/N Analysis

Standard laboratory procedures were followed at the ILRI/CIAT Mazingera laboratory for soil texture and total C and N analysis. Soil texture analysis was performed using the Bouyoucos Hydrometer method (Bouyoucos, 1936). Sand, silt and clay contents are given in percentages following the United States Department of Agriculture (USDA) soil particle size classification and textural triangle.

A C/N elemental analyser (MacroCube, Elementar GmbH, Germany) was used to determine total carbon (C_{total}) and total nitrogen (N_{total}) amounts in the samples. The elemental analyser works by means of high temperature (900 °C) dry combustion of samples. Resulting C- and N-containing gases are then further oxidized, reduced and water vapour removed, to leave only N_2 and CO_2. These two gases are then analysed, one after the other, by means of a flow-through thermal conductivity detector (TCD) which produces an electrical signal proportional to the concentration of each gas.

3.2.4 Soil Chemical Analysis

Soil samples were taken to a commercial testing laboratory “Crop Nutrition Laboratory Services Ltd.” for standard wet chemistry analysis of pH, EC (salts), soil available Phosphorus (Olsen et al., 1954), exchangeable Potassium, Calcium, Magnesium, Sodium and CEC as well as exchangeable micronutrients Iron, Boron, Zinc, Copper, Manganese and Sulphur using the Mehlich 3 extraction procedure (Mehlich, 1984).

Results from the wet soil chemistry analysis showed high pH (6.80-8.61) and calcium (1120-11100 ppm[3]) contents in all sites, this led us to do further analysis of Walkley-Black organic C analysis (Walkley & Black, 1934) due to the possibility of the presence of inorganic C in the form of calcium carbonates ($CaCO_3$) which the total C and N analyser does not differentiate.

3.2.5 Bulk Density

Samples for bulk density (BD) estimation were taken two days after a rainfall event, a 5m by 5m soil corer of volume $98.13cm^3$ was used to carefully take core samples making sure not to disturb soil aggregation. All necessary sampling protocols were followed to ensure accurate BD estimation, samples were taken from three replicates at each site by depths (0-10 cm, 10-25 cm, 25-50 cm). Samples were oven dried at 105 °C for 48 hours after which dry weight was measured. BD in g cm^{-3} was calculated from the formula:

$$BD = Dry\ weight\ of\ soil(g) \div Volume\ of\ soil\ core(cm^3)$$

Figure 3. Bulk density sampling.

3.2.6 SOC Stock Estimation

In estimating SOC stocks for the five sites, the equation which uses the relationship between BD (g cm^{-3}), OC percentage (%) and soil layer thickness (cm) was used:

$$SOC_{stock} = OC\ \% \times BD\ \left(\frac{g}{cm^3}\right) \times layer\ thickness(cm)$$

Where SOC_{stock} is the SOC stock, OC % is the soil organic carbon content, BD bulk density.

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[3] ppm= part per million

3.2.7 Soil Hydraulic Properties

It is important that the user has information on soil hydraulic properties in running DayCent because these critical soil properties affect key processes that control plant growth and decomposition. Many techniques have been developed for direct field measurements of soil hydraulic but most of them are expensive, laborious and time consuming (Hu et al., 2009; Santra & Das, 2008). Bouma (1989) first introduced PedoTransfer Functions (PTFs) and since then it has been the focus of many studies to develop and improve PTFs (McBratney et al., 2011). They are equations or models that are developed for the indirect estimates of hydraulic properties easy to measure properties such as bulk density (Wösten et al., 2001). We used the equations developed by Minasny et al. (1999) to estimate the soil hydraulic properties for our soils. The equations estimate field capacity (FC), permanent wilting point (PWP), available water capacity (AWC) and saturated hydraulic conductivity (Ksat) from soil BD and texture.

3.3 Vegetation Parameters

3.3.1 Aboveground Biomass Estimation

Figure 4. Enclosure for biomass sampling

One 3 m^2 enclosure was set up on each of the five sites to measure undisturbed vegetation growth. Therefore, on 20-10-17, the remaining (old) vegetation was trimmed to about 2 mm height marking the start of biomass production for the short rain season. Two months after undisturbed vegetation growth, vegetation above the soil surface was collected with shears to about 2 mm height on a $50\ cm^2$ quadrant randomly allocated within the 3 m^2 enclosures.

Samples were placed in labelled bags, oven dried at 70 °C for 48 hours and sample dry weight (DW) measured. C content of vegetation is estimated to be 40-50 % of the oven dry weight (Schlesinger & Bernhardt, 2013) thus:

$$C_{vegetation} = 0.475 \times DW$$

Where $C_{vegetation}$ is the C content of vegetation, DW is the dry weight of the biomass.

Total annual NPP for grasslands in DayCent is measured as peak standing biomass. We used estimates from literature since we did not have measured values for this to validate our model output.

3.3.2 Root Distribution

A vertical cross-section was cut through the soil to 1m depth near surrounding grasses and the roots distribution throughout the profile estimated was by visual assessment rather than physical measure because of the limited time period within which the field work was conducted.

3.4 Climate Data

We ran the model with the extra weather drivers option enabled (mentioned in model description) which requires solar radiation, relative humidity and wind speed data to calculate potential evapotranspiration (PET) based on the Penman-Monteith equation. Thus, we made use of a combination of available observed data and online platforms.

3.4.1 Observed Historical Data

Observed daily weather data was obtained from ILRI, this included daily, manually collected precipitation data from 1993 to 2017. Wind-speed (U), photosynthetic active radiation (PAR), air relative humidity (RH) and temperature were recorded with an automatic, onsite weather station from November 2015 to August 2016. The station's quarter-hourly recordings were aggregated to give daily values for all parameters. Since DayCent requires solar radiation (SRAD) in Watt per square meters, daily PAR measured in µmoles m^{-2} sec^{-1} was multiplied by a standard conversion factor of 0.219. PAR is only about 50 % of the total SRAD (Monteith, 1972), therefore, the resulting SRAD value was additionally multiplied by a factor 2.

3.4.2 Satellite Generated Historical Data

Long-term low-resolution climate data were downloaded for Kapiti from the NASA-PowerLarc satellite-based online weather database (https://go.nasa.gov/2E8za4q) for a period of 36 years, from 1981 to 2017, i.e. the maximum period for which NASA provides such data. NASA data for solar radiation (SRAD; Wm^{-2}), relative humidity (RH; %), daily minimum and maximum temperatures ($Tmax, Tmin$; °C), daily precipitation (P; mm) and wind speed (U, ms^{-1}) at 10 m above earth surface are available at a resolution of 0.5° x 0.5°. This grid-cell which includes Kapiti is provided for an altitude of 1332 m a.s.l, while in reality Kapiti lies at about 1750 m. Therefore, daily maximum and minimum NASA temperatures were bias-corrected for the right altitude, assuming that air temperature drops by an approximate 0.6 ℃ for every 100 meters in altitude:

$$Temp_{corrected} = Temp_{NASA} - \left(\frac{Altitude_{Kapiti} - Altitude_{NASA}}{100\ meters} \times 0.6\ ℃\right)$$

Where $Temp_{corrected}$ is corrected temperature, $Temp_{NASA}$ is satellite generated temperature, $Altitude_{Kapiti}$ is actual altitude of Kapiti and $Altitude_{NASA}$ is the altitude of satellite generated temperature.

For precipitation also, average monthly deviation (Δ) of the low-resolution precipitation data from that of the observed was calculated from the formula:

$$\Delta P_M\% = \frac{{}^{1}/_{N}\, \Sigma P_{M(Kapiti)} - {}^{1}/_{N}\, \Sigma P_{M(NASA)}}{{}^{1}/_{N}\, \Sigma P_{M\,(Kapiti)}}$$

Where P is precipitation, the subscript M is the month of the year and N is the total number of years (19 for the first 10 months of the year and 18 for the last two). A cubic spline function was then used to interpolate the resulting monthly deviations to daily precipitation values.

After bias correction and cubic spline interpolation of daily precipitation values, the NASA-lowRes-dataset was put into the GlimGen model (Osborn et al., 2016) to generate missing U and SRAD values. At the end of the day we produced a historical climate dataset of 34 years from 1983-2016 which will be used in the spinup and historical land use simulation phase.

3.4.3 Future, Climate Change Impacted Weather Data

The Long Ashton Research Station Weather generator (LARS-WG) version 6.0 (Semenov, 2008) is a stochastic generator for simulating weather data using current and future conditions.

It works by downscaling local climate scenarios based on global or regional climate models for climate change impact assessments. LARS requires daily observed ("historic") weather data, based on which the WG produces daily time series for the three climatic variables; precipitation (mm), temperature ($Tmax, Tmin$; ℃) and SRAD (MJ m^{-2}day^{-1}). The version 6.0 incorporates climate projections from the CMIP5 ensemble used in the IPCC Fifth Assessment Report. We used the WG to generate climate data for mid-future period (2040-60) under RCP4.5 and RCP8.5 scenarios from the Max-Planck-Institute Earth System Model (MPI-ESM). The LARS-WG doesn't produce RH and U so we fed the three generated climate variables into the ClimGen-WG model so we could generate RH and U.

3.5 Simulations in DayCent

DayCent's environment consists of several input files (Figure 5) and the first step in using the model is to parameterize it with site specific parameters. General information on sites and crop species for parameterization are put into files with the .100 extension. The soils.in file contains the most important soil properties (soil hydraulics, pH, BD, texture and root fraction) by predefined soil layer boundaries, these influence water and nutrient flows and decomposition. Daily weather information is created in a (.wth file) with or without the extra parameters (SRAD, RH and U) for calculation PET. Model users have to choose the extra weather option in the sitepar.in file if desired. In the same sitepar.100 file is additional site information like cloud cover and duration of rainfall event.

The site.100 file is where the initial SOM and nutrient values are specified, other specific parameters such as water drainage control and monthly weather statistics which are computed from the (.wth file). Management (grazing, fertilization, burning, harvest, cultivation) of choice are first updated or created in the respective .100 file and then specified in the (.sch) file to occur at the desired time. Daily, monthly or annual management events over any period of time can be scheduled in the. sch file as a series of one or more event blocks. The ecosystem type (grassland, savanna and forest) that is being simulated can also be specified in the (.sch) file but DayCent cannot simulate multiple grass species. One tree species and one grass species each can be selected for the savanna and forest systems. Also, in the same (.sch) file different (.wth) files can be chosen for the different event blocks. Parameters in the fix.100 file are fixed parameters that control OM decomposition and are usually not changed unless the model is being calibrated.

DayCent produces many different outputs for the various sub-models which slows down model execution and takes up disk space. The outfiles.in file has options that allow the user to specify which output file they are interested in depending on which of the sub-models they are working with, the output files are produced in a .csv and several .out files which are text files. A binary file (.bin) is produced after each simulation is executed. It is not a user readable file but stores all of the output variables that the model produces so that subsequent simulations can be run as extensions from them.

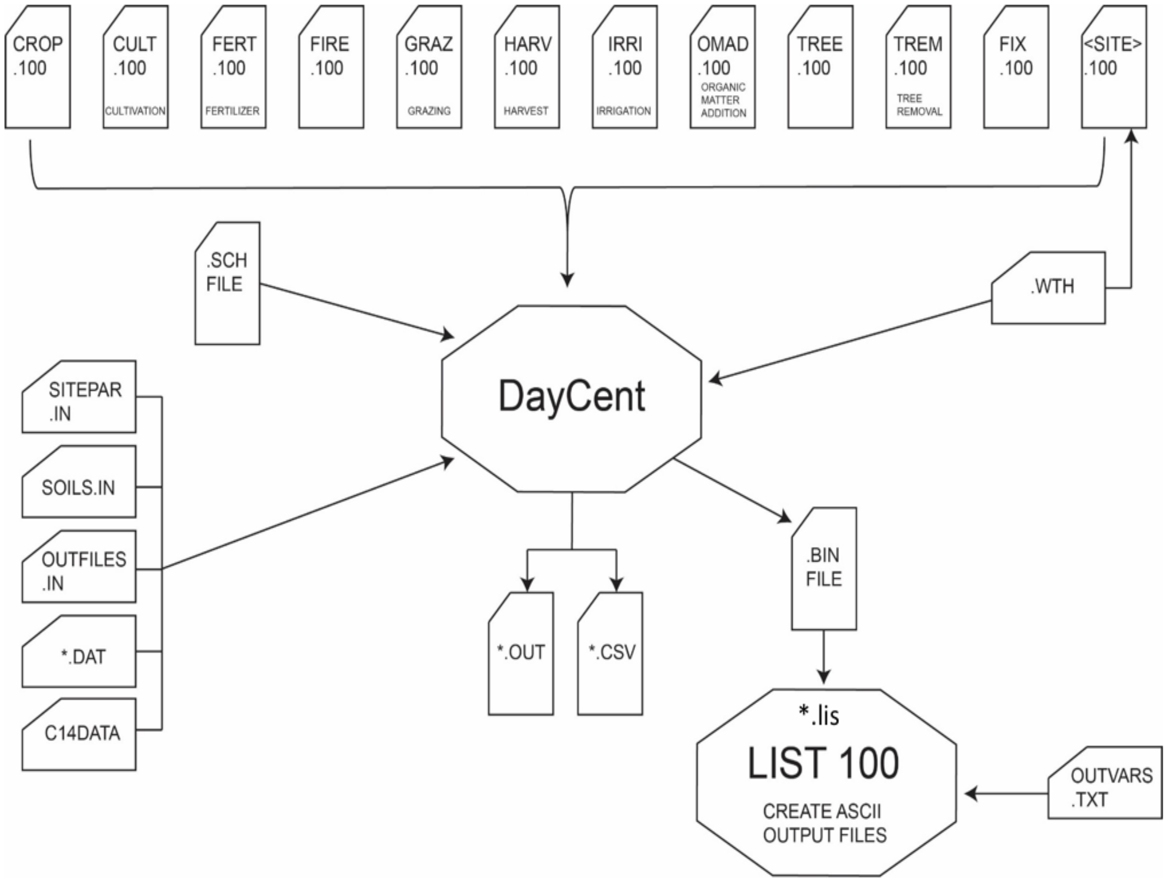

Figure 5. Daycent input and output files ((Del Grosso et al., 2008)).

3.5.1 Model Parameterization

We used the stand-alone DayCent version “DDcent_Dec2016” for all simulations. We parameterized the model by feeding in our measured site-specific parameter values into the various input files (see appendix 2 for soil.in files for each site). The vegetation in Kapiti comprises mainly C_4 perennial grass species so we selected a perennial C_4 crop type in the crop.100 file and parameterized it to suit Kapiti. PRDX (coefficient of radiation use efficiency) a coefficient determining AGB production based on genetic potential of plants was adjusted until simulated AGB and NPP were within the range of observed values because these parameters influence simulated SOC quantity. We conduct an initial run, and examine and evaluate outputs after parameterizing the model. It is recommended that the soil water content (SWC) be the first output to evaluate because it is the primary control on the key processes in the model (Del Grosso et. al., 2011). After SWC, we also evaluate plant growth and SOC quantities.

3.5.2 Sensitivity Analysis

The importance of a parameter in the model is determined by its impact on the modelled output. The model is considered sensitive to a parameter when a slight change in the parameter's value changes the modelled output. Responses of simulated output to important input parameters (pH, bulk density and texture) were determined by sensitivity analysis. In doing this, we kept all other parameters constant while the value of a single parameter of interest was increased or decreased several times and the output compared to a baseline simulation.

We tested the sensitivity of other parameters namely; DRAIN (the fraction of excess water lost by drainage) in site.100 file, hours_rain (duration of each rain event) in sitepar.in file, crop type (C_4 or C_3) and PRDX in crop.100 and flgrem (fraction of live shoots removed by a grazing event over one-month) in graz.100.

3.5.3 Effect of Grazing on Production

The model has six grazing options (see appendix 3) for controlling biomass production, we selected GRZEFF 2 which has a quadratic impact on root to shoot ratio and AGB. In this option, AGB increases as grazing intensity increases until 40 % flgrem removal and then decreases. Light/moderate grazing also drive a higher belowground biomass (BGB) allocation until 25 % flgrem after which the root: shoot ratio decreases. These two parameters have quadratic impacts on the simulated SOC quantities. Thus, satisfying our assumptions that moderate grazing induces compensational regrowth in plants while a heavy grazing event will take out more generative parts of the plant preventing/not giving plants enough time to regenerate new biomass so results in low SOM accumulation.

3.5.4 Spin-up Simulation

It is common practice, in order to stabilize the initial percentages of the three SOM pools, to carry out long-term simulations of native vegetation using best-guess initial SOM pool percentages. Such pre- or spin-up runs are usually done for some several hundred years, until

SOM pools reach steady states. The initial values fed to the model are not required to be very accurate but should be set at reasonable amounts, so as to reduce the time taken for equilibrium to be reached. Spin-up runs can also be done iteratively, feeding back final SOM pool percentages as initial values into the subsequent spin-up, until observed pools have sufficiently well equilibrated and annual changes in SOM percentages are negligible.

In our case, we fed in guessed initial SOM values and simulated years of native vegetation under a light wildlife grazing intensity that removed 15 % flgrem (fraction of live shoots removed by a grazing event over a one-month period) for each site. We verified the equilibrium of all three pools after the simulations but paid more attention to the passive pool since it is the one that takes longer to stabilize. Total SOC in the last 100 years of simulated output was compared with measured values. We went back to reduce or increase the initial SOM contents in the case of too much or too little SOC being produced after the spinup run. It is only after this has been done that our historical and present-day management simulations were executed as extension runs from the spinup binary file (.bin).

3.5.5 Historical to Present-day Simulations

After initialization, a (.sch) file of historical management events for each site between 1939 and 1989 was created and extended runs were made from the spin-up .bin file. A block of historical grazing of 45 % flgrem practiced continuous for 4 years and a six-month resting phase in the fifth year was scheduled for all the sites. A schedule block that represents the present-day management from 1990 to 2017 was specified. Current grazing events happening on the sites are as follows;

Site 1 — 45 % flgrem removed year-round.
Site 2 — 45 % flgrem removed year-round.
Site 3 — 45 % flgrem removed year-round.
Site 4 — 45 % flgrem removed year-round.
Site 5 — 15 % flgrem removed year-round.

3.5.6 Evaluation of Modelled Output

We compared the Simulated SOC output for the present-day with our measured SOC stocks for the upper 20 cm soil depth. Average annual NPP produced by the model for the last 10 years of present-day period was compared with NPP estimates measured by Kinyamario and Evenson (1992) at the Nairobi National park. A harvest event was put in the final year of the present-day simulation, so we could compare simulated AGB with that collected between 20-10-17 and 7-12-17 at the study sites.

3.5.7 Future Climate Change Scenarios Simulation

We made future projections for each site from 2018 - where the present-day conditions ended - to 30 years into the future for the effects of two mid-future climate change scenarios (RCP 4.5 and 8.5) and four grazing regimes;
Moderate (MG)— 20 % flgrem removed
Heavy (HG)— 45 % flgrem removal per month.
Rotational (RG)— one year of HG followed by one year of no grazing.
Alternating (ALT) — one month HG followed by one month of MG

3.5.8 Statistical Analysis

All statistical analysis was performed using R version 3.4.4. Normal distribution assumptions for the soil properties were evaluated using Kolmogorov-Smirnov test. Levene-test was used to test the homogeneity of variance. Some of the properties had extreme outliers and did not meet the normality assumptions. We $\log_{10}$ transformed all our soil properties prior to correlation analysis except for pH which is already a logarithmic measure. Using Principal Component Analysis (PCA), we determine soil properties that accounted for the most variation within the selected sites for each sampled depth, and the correlation amongst soil properties at each sampled depth. A one-way analysis of variance (ANOVA) with site as a factor was used to determine the differences in measured soil properties between the five sites according to sampled depths. A Tukey LSD test was further used to differentiate the sites if the ANOVA showed significant differences at p-value (0.05)

Chapter 4

Results

4.1 Analysis of Soil Physical and Chemical Properties

4.1.1 Correlation Analysis

Spearman ranks correlation coefficients were computed for each pair of soil properties in each depth. Table 3 shows the correlation matrix result for the top 0-10 cm depth in. The correlation matrices for the subsequent depths can be found in appendix 4. Their results were similar to that of the top soil depth. Of all the chemical properties, CEC showed high positive correlations with its major base cations except for K in the order; Ca(r=1.00), Mg (r=0.86), Na (r=0.69) and also with B (r=0.93). Another positive correlation of CEC with EC (r=0.85) and a negative with Fe (r=-0.94) was observed. CEC increases with increasing pH (r=0.62) as mineral exchange sites will be less saturated by acidic cations at high pH.

The cations Na, Mg, Ca and B had high positive correlations amongst themselves and EC but negative correlations with Fe. pH aside from CEC correlated with Ca (r=0.64), B (r=0.68) and clay (r=0.52). P was only positively correlated with K (r=0.56) and Fe (r=0.59), it correlated negatively with CEC, clay and Na (-0.71). K only correlated strongly with Co (r=0.58) and negatively with Na (r=-0.57). Mn and Zn did not correlate strongly with any properties. Co correlated with Na (r=-0.65) and was the only property to correlate with silt (r=0.44).

Clay positively correlated with CEC (r=0.93) and major cations except K as follows: Ca (r=0.92), Mg (r=0.90), Na (r=0.71) and with B at (r=0.86). Sand showed strong negative correlations with cations: Ca(r=-0.82), Mg (r=-0.81), B (r=-0.81), the CEC (-0.82) and with clay (r=-0.88). Organic carbon (OC) showed only a positive correlation with S (r=0.51). We further used a Principal component analysis (PCA) to deduce the underlying relationship.

Table 3. Spearman ranks correlation coefficient matrix for the log-transformed physical and chemical properties (0-10 cm depth).

	pH	EC	P	K	Ca	Mg	Mn	S	Co	B	Zn	Na	Fe	CEC	%OC	Clay	Sand	Silt
pH	1.00																	
EC	0.57	1.00																
P	-0.25	-0.38	1.00															
K	-0.14	-0.37	**0.56**	1.00														
Ca	**0.64**	**0.86**	-0.58	-0.34	1.00													
Mg	0.39	**0.64**	-0.61	-0.16	**0.86**	1.00												
Mn	-0.36	-0.11	0.33	0.17	-0.32	-0.35	1.00											
S	-0.25	0.18	0.14	-0.11	-0.06	-0.05	-0.09	1.00										
Co	0.26	-0.13	0.33	**0.58**	-0.01	-0.05	0.07	-0.46	1.00									
B	**0.68**	**0.86**	-0.40	-0.17	**0.93**	**0.74**	-0.20	-0.04	0.08	1.00								
Zn	-0.04	-0.34	0.01	0.14	-0.13	-0.09	-0.22	-0.24	0.40	-0.25	1.00							
Na	0.35	**0.64**	-0.71	**-0.57**	**0.69**	**0.65**	-0.25	0.11	**-0.65**	0.58	-0.32	1.00						
Fe	-0.59	-0.86	**0.59**	0.37	**-0.94**	**-0.76**	0.38	-0.09	0.06	**-0.90**	0.14	-0.65	1.00					
CEC	**0.62**	**0.85**	**-0.58**	-0.33	**1.00**	**0.86**	-0.32	-0.05	-0.02	**0.93**	-0.12	**0.69**	**-0.94**	1.00				
%OC	-0.39	0.18	0.21	0.11	-0.04	-0.12	0.34	0.51	-0.02	-0.05	-0.07	-0.14	-0.07	-0.03	1.00			
Clay	**0.52**	0.77	**-0.59**	-0.32	**0.92**	**0.90**	-0.26	-0.02	-0.14	**0.86**	-0.24	**0.71**	**-0.83**	**0.93**	-0.18	1.00		
Sand	-0.45	-0.65	0.37	0.10	**-0.82**	**-0.81**	0.14	-0.05	-0.10	**-0.81**	0.20	-0.43	**0.74**	**-0.82**	-0.03	**-0.88**	1.00	
Silt	-0.07	-0.12	0.17	0.34	-0.05	-0.12	0.05	0.06	0.44	0.00	0.30	-0.37	-0.04	-0.03	0.38	-0.13	-0.25	1.00

4.1.2 Principal Component Analysis

PCA is a multivariate statistical technique used to eliminate multicollinearity in a dataset. The purpose is to extract important variables from a dataset into an orthogonal variable set easier to work with (Bro & Smilde, 2014). PCA is sensitive to the variance of the properties that are being analysed, therefore, in addition to log transforming our data prior to analysis, we performed the PCA on the correlation matrix of the soil properties after the individual properties were standardized to their zero scores. A widely used criterion in selecting the optimum principal component (PC) subset is to select (i) a subset with Eigen values greater than 1 and (ii) a subset that makes up a minimum of 70 % of the variance.

Table 4 shows the results for PCA of the top 0-10 cm soil depth. PCA for depths 10-25 and 25-50 cm can be found in the appendix 5. The first three PCs (73 % of the total variance) were retained as the subset that would explain the significant correlations in the raw dataset. PC1 had the highest loading accounting for 47.8 % of the total variance. CEC and Ca are the highest correlated properties, it can be said that PC1 describes soil properties related to cation exchange capacity (base saturation). As pH increases, so does availability of some major basic cations (Ca, Mg and Na) as well as B and total CEC. Clay and CEC are positively correlated because clay minerals provide the negative charge to attract the cations.

PC2 makes up 15 % of the variance and is highly correlated with Co and silt. An interpretation would be that this PC accounts for Co availability, a primary source of cobalt in soil is mineral weathering and or dust deposits and therefore the high correlation with silt observed. The negative loadings show Kapiti may have Co deficiencies.

S and OC had the highest loadings on PC3. Correlation of OC on this PC makes it logical to describe this PC as related to soil fertility/quality. The major source of S in the soil comes from organic matter additions therefore the high correlation of S and OC seen. A low OC means low organic matter addition/decomposition thus a low S content. The negative loadings of OC and S on the PC may reflect that Kapiti soils receive low organic input additions. Zn is negatively correlated on the PC; some studies suggest high organic matter contents in soils lead to Zn deficiencies (Noulas et al., 2018).

Table 4. PCA of soil chemical and physical properties for the top depth (0-10 cm).

Property	PC1	PC2	PC3
pH	**0.273**	-0.141	0.131
EC	**0.279**	0.012	-0.314
P	-0.219	-0.150	-0.181
K	-0.141	-0.355	-0.116
Ca	**0.335**	-0.051	-0.080
Mg	**0.285**	0.020	0.052
Mn	-0.151	-0.062	-0.165
S	-0.075	0.303	**-0.528**
Co	-0.029	**-0.556**	0.033
B	**0.301**	-0.187	-0.121
Zn	-0.012	-0.263	**0.405**
Na	**0.253**	0.322	0.109
Fe	**-0.313**	0.139	0.109
CEC	**0.335**	-0.062	-0.072
% OC	-0.113	-0.070	**-0.493**
Clay	**0.314**	0.036	-0.028
Sand	**-0.284**	0.100	0.120
Silt	-0.015	**-0.421**	-0.237
% Variance	47.8	15	9.7
Eigen Value	8.6	2.7	1.7

4.1.3 Analysis of Variance

Figure 6 shows results for total SOC stocks for the soil profile (0-50 cm). The heavy grazed sites (1, 2 and 3) had the highest SOC stocks at 132.3 ton C ha^{-1} for site 1, 122.2 ton C ha^{-1} for site 2 and 120.3 ton C ha^{-1} for site 3. These values were however, not significantly different from that of the less grazed sites; 99.9 ton C ha^{-1} for site 4 and 107.7 ton C ha^{-1} for site 5. We performed further analysis by depth to determine any differences.

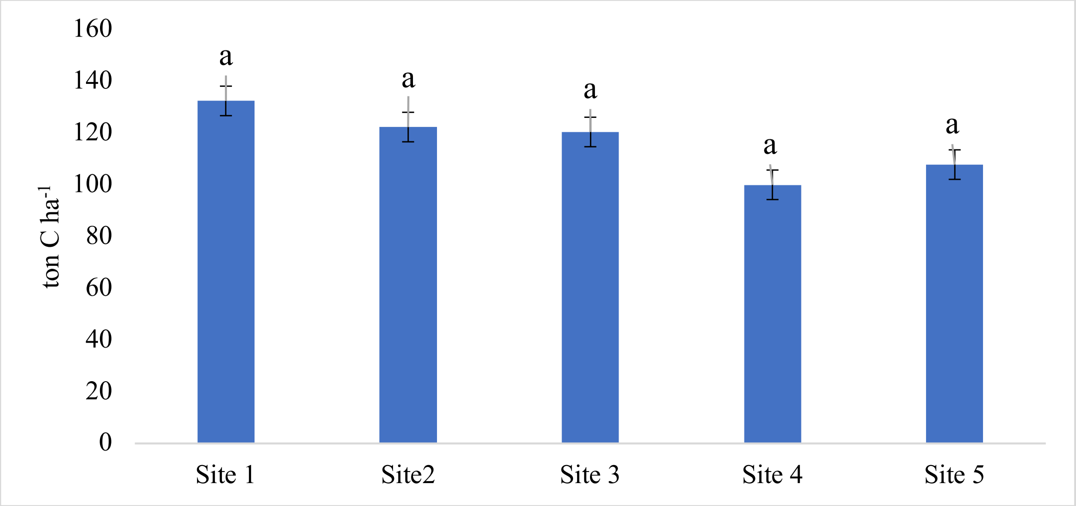

Figure 6.Total SOC stocks through the soil profile 0-50 cm, same letters are not significantly different at p-value of 0.05.

For the purpose of DayCent, we concentrated on the difference between texture, pH, BD, SOC stocks and % OC and therefore we present the results for those in this chapter. Results for the other chemical properties can be found in appendix 6. $\log_{10}$ transformation was kept for properties that did not meet the normal distribution assumptions.

Table 5 shows results for the Tukey-LSD test at a p-value of 0.05. SOC stocks were significantly higher in site 1 and 3 for the top 0-10 cm. Site 1 had a significantly higher SOC stock than sites 4 and 5 in 10-20 cm. Sites 2 and 5 at 25-50 cm had higher SOC stocks than site 4. SOC stocks increased with depth in all sites. The only observed significance in OC was at the 10-25 cm and 25-50 cm depths where sites 1, 2 and 5 had significantly higher OC contents than site 4 which had the lowest. BD was significantly higher in site 3 (heavy grazed) than the remaining sites in the 0-10 cm depth. Site 5 (light grazed) had the lowest BD, which however, was not significantly different from that of site 2 at 0-10 cm. In descending order, the heavy grazed sites- 1, 3 and 2 had the highest BD in the 10-25 cm depth. They did not differ from each other but showed significant difference in comparison with the lightly grazed site 5 which had the lowest BD. There was no difference in BD across sites in the bottom 25-50 cm depth.

Clay content was significantly higher in site 2 than the remaining sites at all depths. Sites 1 and 4 had the lowest clay contents at all depths, which were not significantly different from each other. Sand was significantly higher in site 1 than in sites 2 and 5 across all depths. No difference was observed in silt contents amongst sites and depths. In general, clay content increased with depth while the opposite was true for sand. pH in the top depth (0-10 cm) was significantly higher in sites 2 and 5 than the remaining 3 sites where no significance difference showed. pH for site 5 was significantly higher than for site 1 at 10-25 cm and 25-50 cm.

4.2 Soil Profile Description

The purpose of taking a few samples down 100 cm depth – besides determining soil texture and % OC of these layers (as an input parameter for the biophysical modelling) – was to determine if a bed rock/parent material will be reached. No rock layer was reached in each site for the extra depths sampled.

Table 5. Soil properties by site and depth. Means with same letters in each depth are not significantly different (Tukey-LSD comparisons α: 0.05).

Depth (cm)	Site	Clay	Sand	Silt	OC	SOC	BD (g cm^{-3})	pH
		%				(ton C ha^{-1})		
0-10	1	22.41c	62.81a	14.77a	2.48a	33.13a	1.38ab	6.99b
	2	47.40a	36.82c	15.77a	2.03a	21.67b	1.07c	7.71a
	3	29.48bc	57.46ab	13.04a	2.17a	32.10a	1.44a	6.99b
	4	27.84c	61.02ab	11.13a	2.23a	28.97ab	1.26b	7.12b
	5	38.16b	52.04b	9.80a	2.18a	20.10b	0.96c	7.83a
	Mean	33.06	54.03	12.90	2.22	27.19	1.22	7.31
10-25	1	25.41c	60.81a	13.77a	2.19a	47.63a	1.44a	7.01c
	2	50.40a	36.33c	13.27a	1.99a	37.23ab	1.30a	7.66ab
	3	34.00bc	54.96ab	11.05a	1.94a	37.97ab	1.36a	7.16bc
	4	31.33c	60.54a	8.13a	1.72b	32.80b	1.25ab	7.45abc
	5	41.17b	49.53b	9.30a	2.08a	31.40b	1.03b	7.99a
	Mean	36.46	52.43	11.10	1.99	37.41	1.27	7.46
25-50	1	35.40b	55.82a	8.77a	1.56a	51.57ab	1.40a	7.18b
	2	52.40a	35.32c	12.23a	1.82a	63.30a	1.34a	7.91ab
	3	40.97ab	49.98ab	9.00a	1.51ab	50.30ab	1.40a	7.63ab
	4	35.34b	54.52ab	10.13a	1.20b	38.13b	1.31a	7.33b
	5	47.08ab	44.54bc	8.38a	1.85a	56.20a	1.32a	8.14a
	Mean	42.24	48.04	9.72	1.59	51.90	1.33	7.64

After analysis of chemical and physical properties, we renamed the sites according to the dominant texture type and grazing regime since 1989 for use in DayCent, see table 6. Given the similarity in soil properties, we treated the sand_heavy sites as one site by taking the average of the input parameters required by DayCent. SOC stocks in the top 20 cm was also calculated.

Table 6. Renaming sites based on soil textural class and grazing regime.

Old name	Clay-Sand-Silt (%)	Grazing regime	New name	SOC (20 cm) ton C ha^{-1}
1	28-60-12	Continuous-heavy grazed	Sand_heavy	64.8
2	51-36-13	Continuous-heavy grazed	Clay_heavy	46.5
3	35-54-11	Continuous-heavy grazed	Sand_heavy	55.5
4	31-59-10	Recently-heavy grazed	Sand_recent_heavy	50.8
5	42-49-9	Continuous-light grazed	Sand_light	41.0

4.3 Root Distribution

From visual assessments, roots were distributed throughout the profile especially for site 5. However, about 60 % mainly primary roots were concentrated in the top 40 cm in all five sites. The remaining 40 % consisted mostly of fine secondary roots and extended down to 1 m.

Figure 7. Vertical cross-section of soil showing root distribution down to 1 m.

4.4 Climate

4.1.1 Observed Versus Satellite Derived Low-resolution Climate Datasets

After bias-correction, the satellite derived temperature data (NASA-Tmax and NASA-Tmin) compared sufficiently well to the automatic weather station data from Kapiti (Figure 8 and 9). Observed rain data (Obs-P) was also compared with satellite data (NASA-lowRes-P) after correcting for bias (Figure 10). They all were sufficiently good for further modelling purposes.

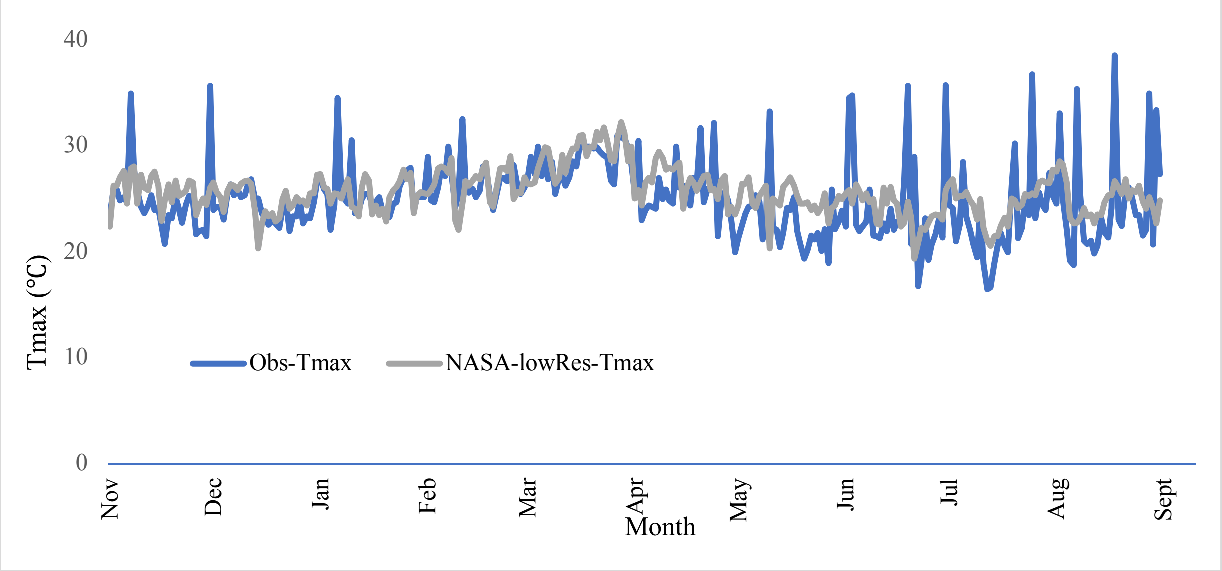

Figure 8. Time series plots of Tmax (Nov 2015- Aug 2016) comparing bias-corrected online Generated Low Resolution (NASA-lowRes-Max) to observed (Obs-Tmax) temperatures.

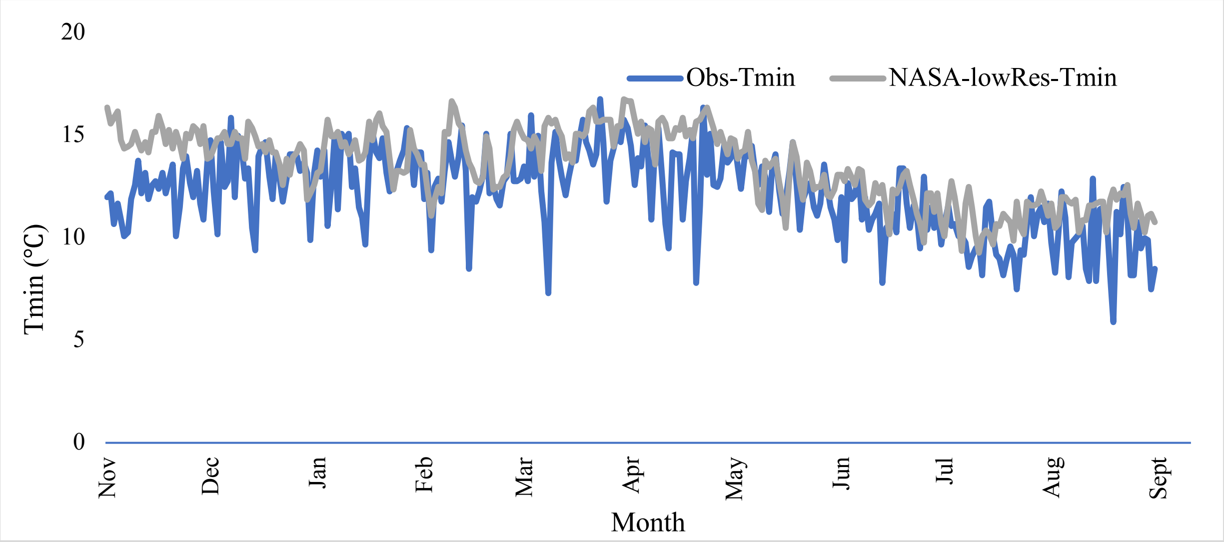

Figure 9. Time series plots of Tmin (Nov 2015- Aug 2016) comparing bias-corrected online Generated Low Resolution (NASA-lowRes-Max) to Observed (Obs- Tmax) temperatures.

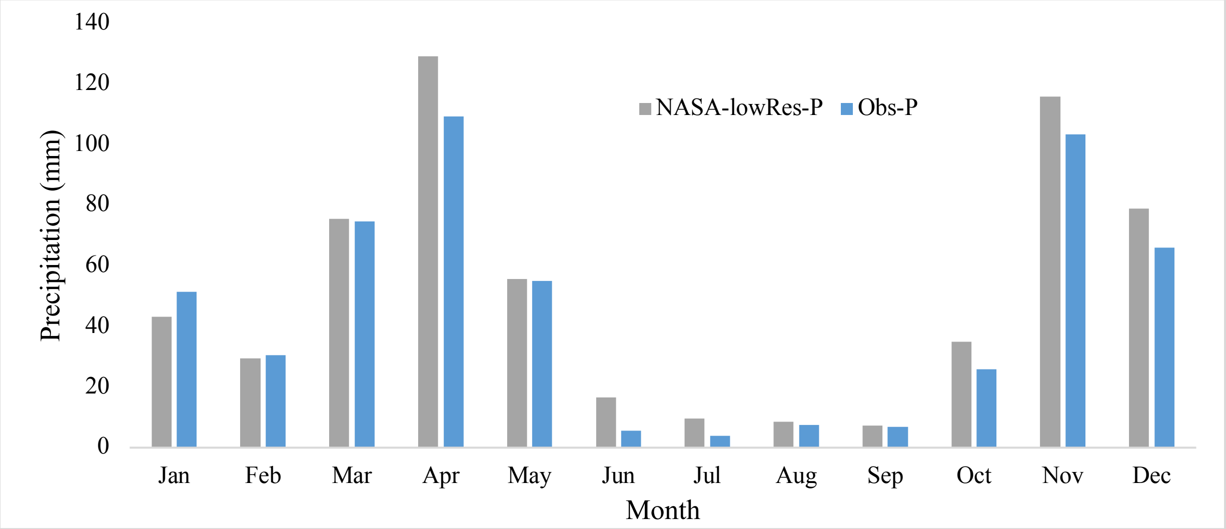

Figure 10. Average monthly precipitation for NASA-lowRes data from January 1997 until October 2015 (19years for the first 10 months of the year and 18years for the last two months).

After correcting for bias, we chose to use the satellite derived dataset (1983-2016) in place of the observed dataset for our historical and present-day simulation because we only had a few years of observed dataset. In addition, the observed dataset had missing values which DayCent does not accept. Also, the LARS-WG needed a minimum of 30 years of historic dataset in order to produce sound estimates of future datasets. Henceforth we will refer to this dataset as "historic dataset".

4.1.2 Present and Future Climate Change Projections

Kapiti rainfall follows the typical bimodal distribution, whereas the long rain season from March to May (MAM) receives more rainfall than the short rainy season from October to December (OND). April is the wettest month with rainfall exceeding 110 mm closely followed by November as the second wettest month. Mean annual rainfall is typically below 600 mm. Dry periods last from June to September and receive very little rainfall if any, July is the driest month with as little as 4 mm rainfall. Annual maximum temperature averages at 24 °C while the minimum is averaged at 14 °C giving Kapiti an annual mean temperature of 19 °C. A mean maximum temperature of 26 °C makes February and March the hottest months, daily temperature averages at 20 °C during this period. The coldest month is July with 13 °C as the average minimum temperature and the average monthly temperature does not exceed 18 °C.

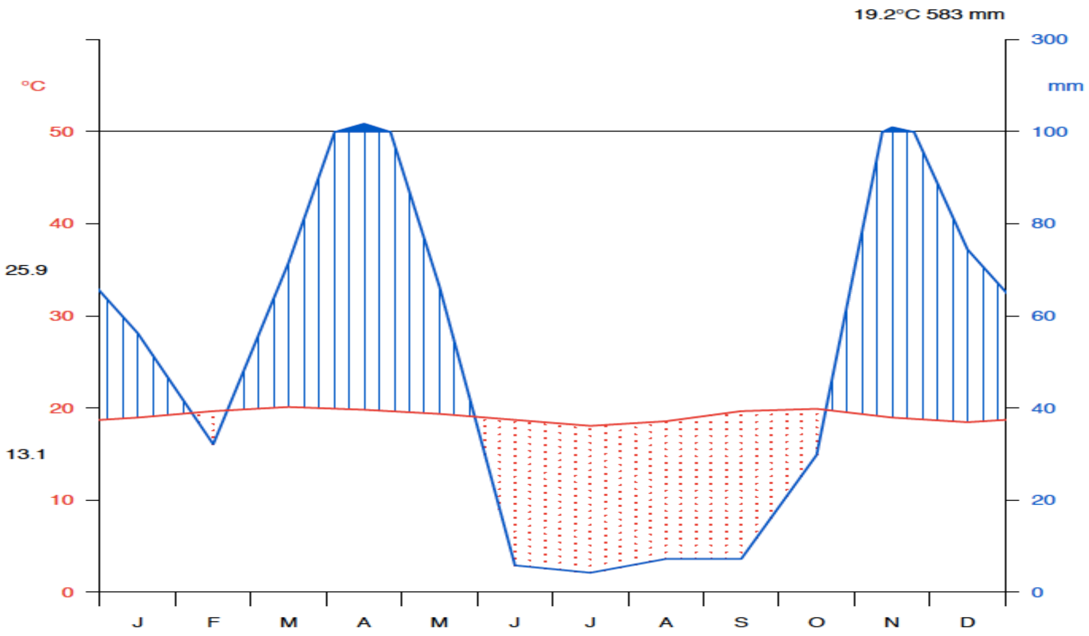

Figure 11. Walter and Leith diagram showing monthly precipitation and monthly mean temperature for the historic dataset.

Most studies on climate projections in East Africa predict a rapid temperature rise of 2 °C midway of the 21st century and 4 °C by the end of the 21st century (Otieno & Anyah, 2013). Global (GCM) and regional climate models (RCM) project 0.3 °C and 0.4 °C increase per decade under RCP4.5 and RCP8.5 in the equatorial region of East Africa (Kenya included) (Shongwe et al., 2011; Tierney at al., 2015). This will lead to a total increase of 2 °C and 2.5 °C by mid 21st century (Otieno & Anyah, 2013). Precipitation on the other hand has been difficult to predict but an increase in its amount is also expected in the 21st century (Shongwe et al., 2011; Tierney at al., 2015). While Rainfall seasonality will not be altered, the long and short rainy seasons are predicted to become wetter under both RCP4.5 and RCP8.5 with the short rain period (OND) experiencing up to 19 % increase by 2060 (Otieno & Anyah, 2013).

Under the RCP4.5 mid-future period (2041-2060) as predicted by the MPI-ESM, the annual mean temperature increased by 1.5 °C with reference to the historic dataset as a base scenario. Mean annual maximum and minimum temperatures increased by 0.7 °C and 1.3 °C. RCP4.5 projects no change in rainfall seasonality but average annual rainfall are to increase by 88 mm under the RCP. The average annual rainfall is projected to increase from 215 mm to 235 mm in the short rain season (OND) and 256 mm to 291 mm for the long season (MAM), an increment of 20 mm and 35 mm.

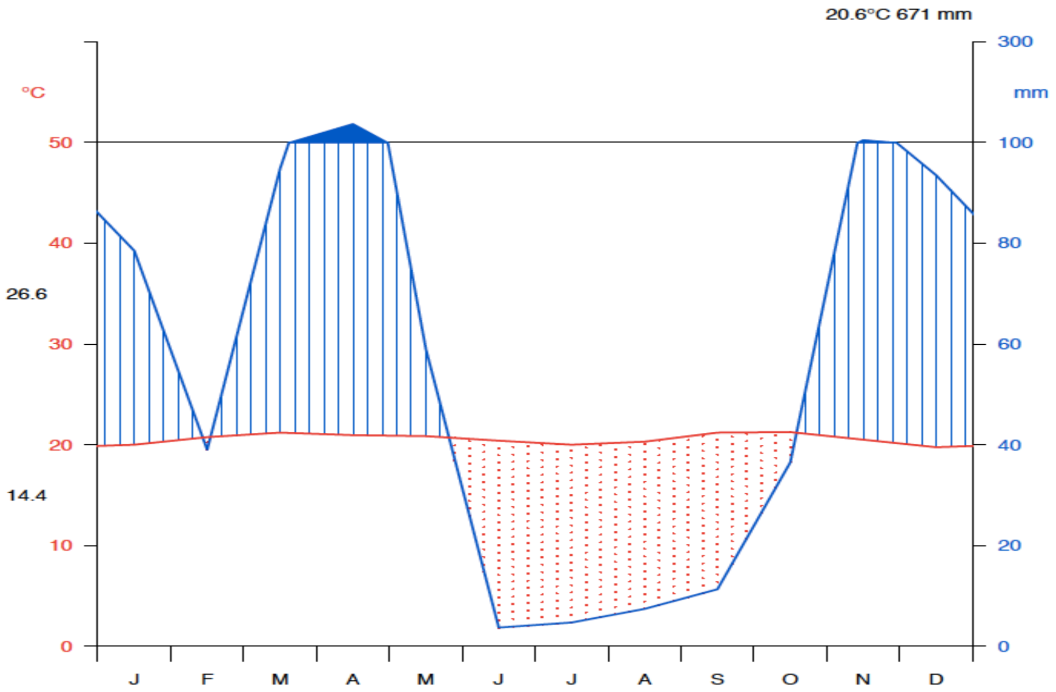

Figure 12. Walter and Leith diagram showing monthly precipitation and monthly mean temperature for the RCP4.5 dataset.

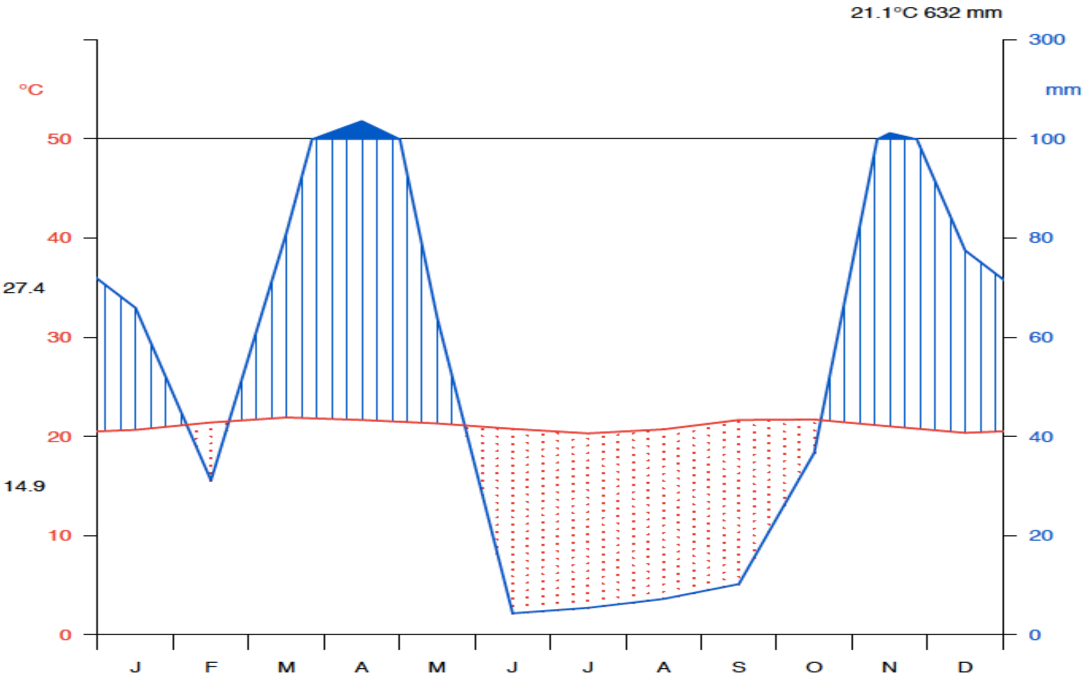

Figure 13. Walter and Leith diagram showing monthly precipitation and monthly mean temperature for the RCP8.5 dataset.

RCP8.5 follows a similar trend as the RCP4.5. Mean annual temperatures are predicted to increase by 1.9 °C, mean maximum and minimum temperatures by 1.8 °C and 1.5 °C, respectively. According to RCP8.5, mean annual rainfall is to increase by 49 mm from the base scenario as opposed to 88 mm under RCP4.5. Rainfall is predicted to increase by some 12 mm for the short season with most of it concentrated in November while that of the long rains is assumed to increase by 26 mm. For both RCP scenarios, rainfall only increased by a small amount of 26 mm in the dry period.

4.5 Model Setup and Initial Simulations

4.5.1 DayCent Model Set-up

We performed a test run for each climate dataset after setting up DayCent with our input parameters. Although we did not have observed data or estimates from literature for evaporation (E), transpiration (T) and PET to evaluate the simulated output, the simulated amounts are comparable with what is to be expected in reality in semiarid grassland ecosystems. The simulated results are shown in figure 14. Aridity index (ratio of total annual P to PET) for semi-arid regions as estimated by Lal (2004) is between 0.20–0.50. Kapiti being a semi-arid area, the aridity index calculated after setting up the model was 0.3 for the historic and RCP8.5 datasets and 0.4 for the RCP4.5 dataset. T alone was higher than E in our modelled output. Average annual T and E for the datasets were; 262 and 115 mm for historic, 329 and 123 mm for RCP4.5 and for RCP8.5 310 and 122 mm. Evapotranspiration (ET) for all months exceeded half the amount of P as to be expected in reality.

Simulated rainfall interception, runoff and drainage out of the soil profile were also reasonable. In all datasets, intensity and frequency of rainfall events was highest during the wettest month (April). This caused runoff as well as excess water drainage out soil profile to occur more frequently. In the dry months however, because very little rainfall events and amounts is received during this period, almost all was intercepted by standing vegetation.

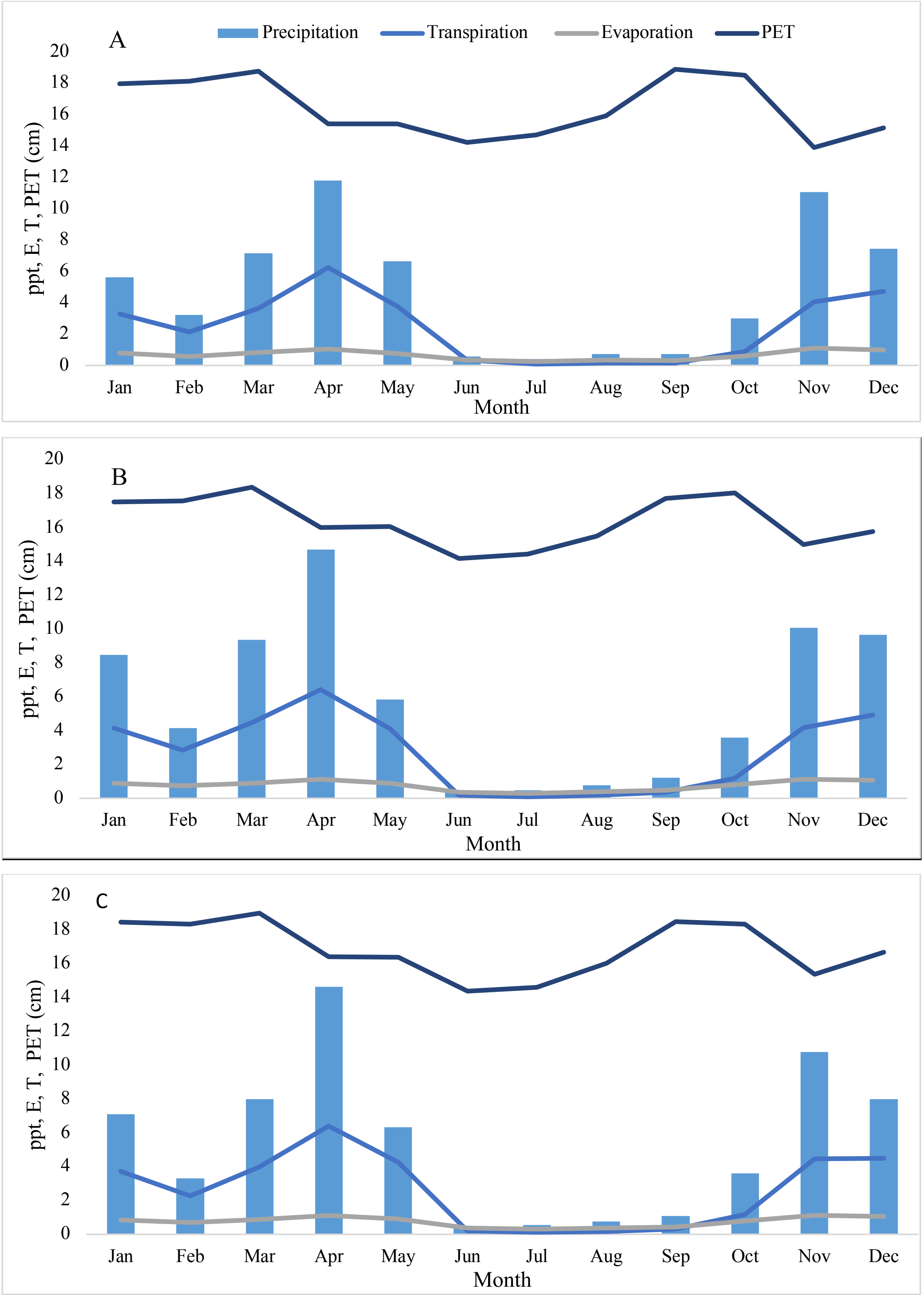

Figure 14. Simulated average evaporation, transpiration and potential evapotranspiration (PET) for historic (A), RCP4.5 (B) and RCP 8.5 (C) climate datasets.

4.5.2 SOM Initialization

There is no fixed nor recommended single value for PRDX (coefficient of radiation use efficiency). PRDX is one of the main parameters that is altered until desired NPP amounts are produced during calibration simulation runs. However, vegetation productivity is assumed to be higher during the spinup period therefore, it is advised to use a higher value for the spinup phase and reduce it during subsequent simulations. PRDX was set at 0.9 for clay_heavy and sand_light sites during the spinup phase but was set at 5 for site sand_heavy in order to arrive at C stocks close to measured values.

After simulating native conditions of 15 % flgrem (fraction of live shoots removed by a grazing event over one-month) for 2500 years, NPP had reached 1020 g C $m^{-2}yr^{-1}$ for Sand_heavy, 664g C $m^{-2}yr^{-1}$ for Clay_heavy and 516 g C $m^{-2}yr^{-1}$ for Sand_light. Aboveground biomass (AGB) had reached 472 g C $m^{-2}yr^{-1}$ for sand_heavy, 383 g C $m^{-2}yr^{-1}$ for clay_heavy and for sand_light, 335 g C $m^{-2}yr^{-1}$.

On all simulated sites, the active (microbial) pool reached equilibrium after about 5 years, the slow pool (structural and metabolic components) also reached equilibrium after 500 years, and the passive pool stabilized at about 1500 years. An extra 1000 years was added, to ensure full equilibrium of this pool. Simulated quantities at the end of the period were 85.9 ton C ha^{-1} for sand_heavy, 64.8 ton C ha^{-1} for clay_heavy and 42.5 ton C ha^{-1} for sand_light site. Figure 15 below shows graphs of the spinup phase for the 3 SOM pools and figure 16 shows the total SOC stocks for the individual sites.

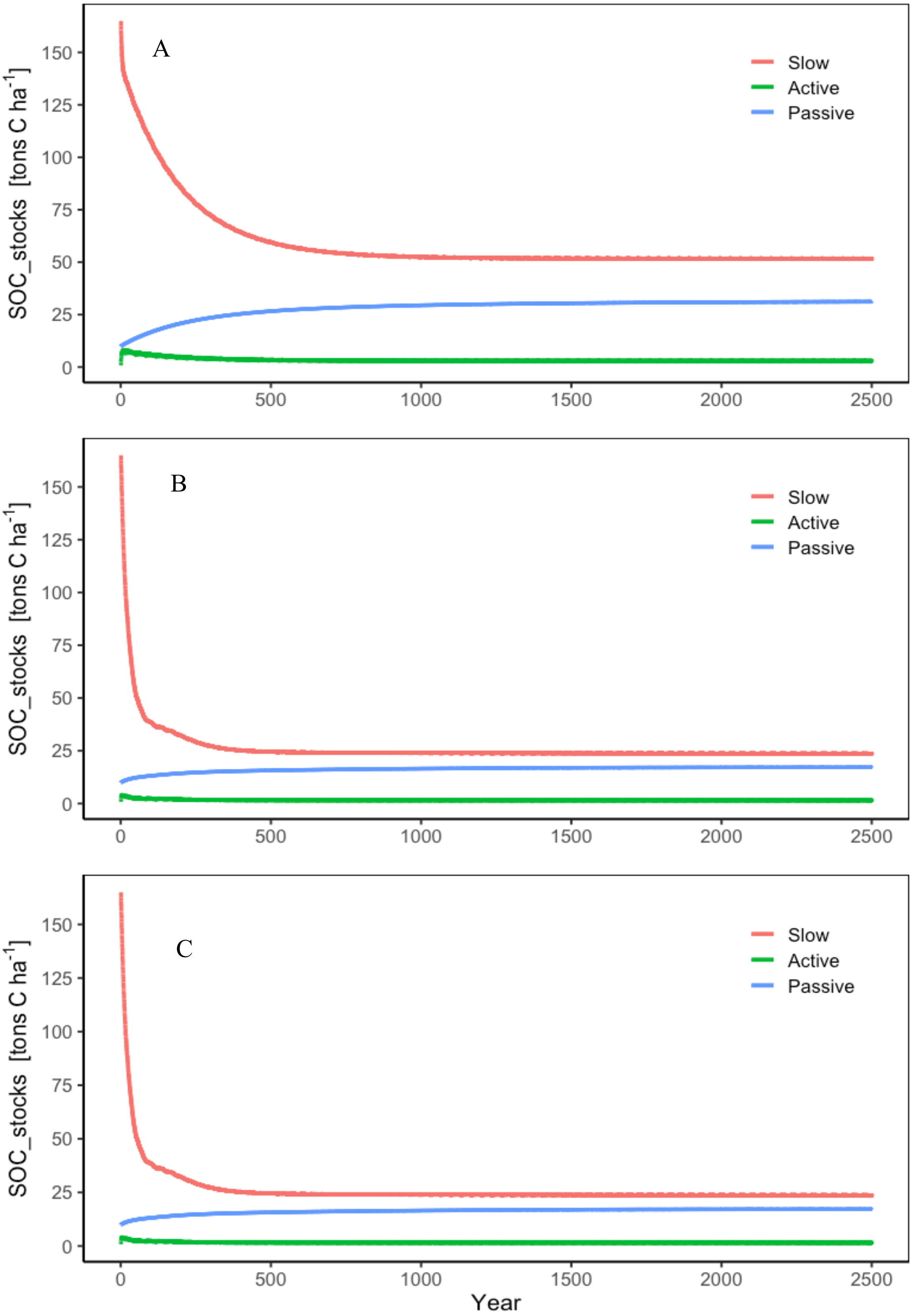

Figure 15. SOM pools (active, slow and passive) for sand_heavy (A), clay_heavy (B) and sand_light (C) after initialization.

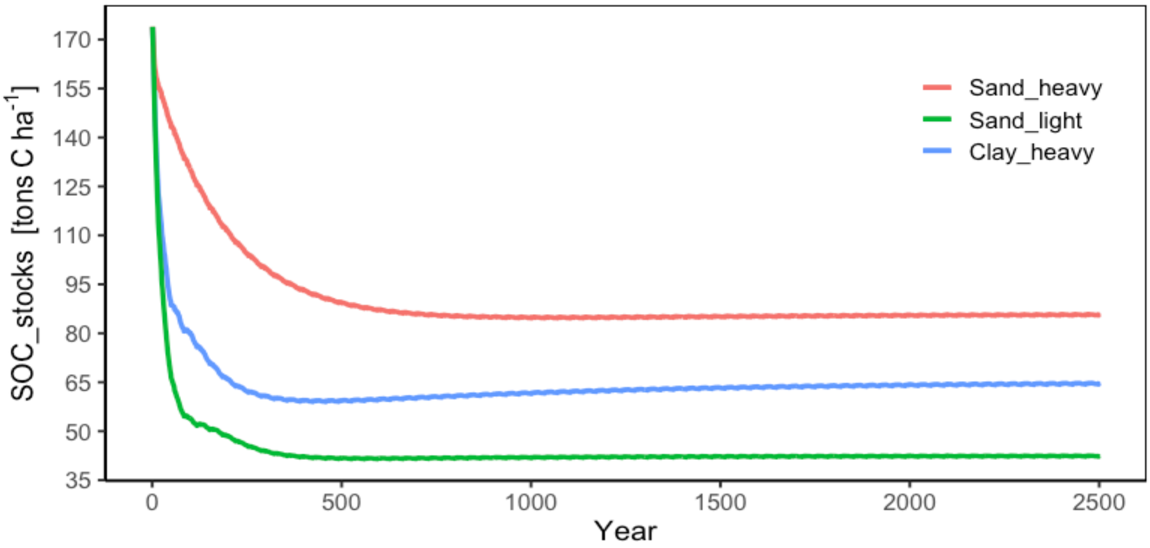

Figure 16. Total SOC Stocks for the three sites after initialization.

4.5.3 Sensitivity Analysis

Our field measures showed variations in important inputs (pH, BD and texture). For this reason, we chose to run sensitivity analysis for each one of them to better understand how changing them will influence our simulations.

Lower BD values produced much more C than higher BD values for the same soil textural class (Figure 17). BD has an effect on the important soil hydraulic properties such as the field capacity (FC) and saturated hydraulic conductivity (Ksat) which in turn affects the key soil processes that control plant growth. Soils with higher BDs are more compact with less pore spaces and therefore have less water infiltration. BD was used in calculating our FC and Ksat values from PTFs, higher BD produced lower values for these properties. This reflected in our simulated results with the lowest BD (1.07) producing the highest water infiltration and lowest runoff amounts when compared with the other two BDs; 1.21 g cm^{-3} and 1.41 g cm^{-3}. In addition, because higher BD restricts root growth, we observed the highest BGB production in the simulation with the 1.07g cm^{-3} BD. The higher root production contributes to higher SOM supply to the SOC stock therefore the results we observed.

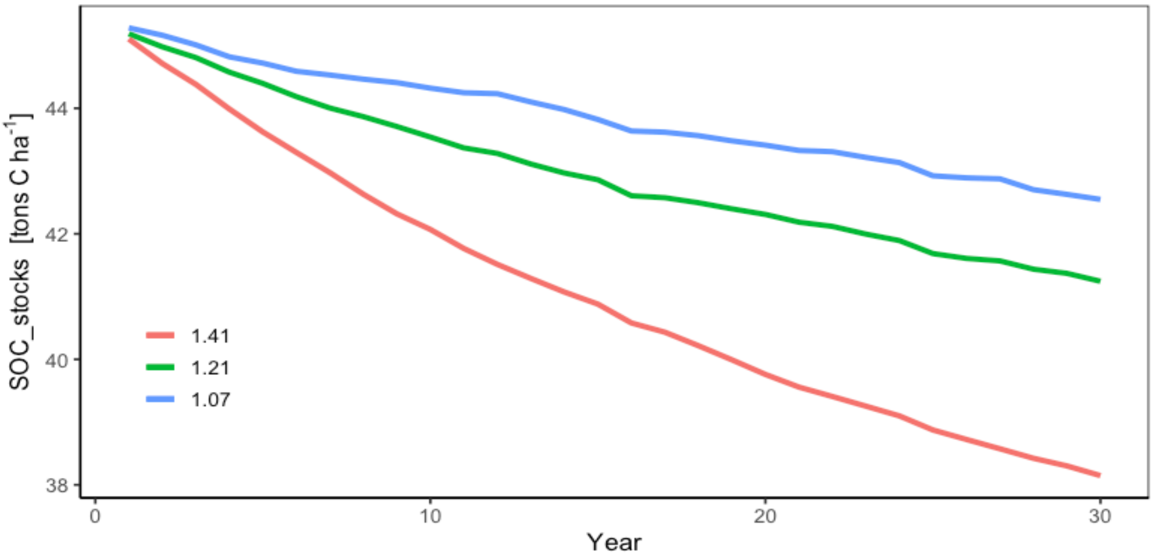

Figure 17. Sensitivity of SOC to varying soil bulk density.

Modifying pH, SOC was observed to decrease with increasing pH until no changes were observed at pH values above 7 (Figure 18). The highest microbial biomass (active pool) was observed in the simulation with the lowest pH. At the same time, the lowest pH simulated the highest slow C pool (structural and metabolic plant components) in comparison with the other pH values. This indicates that even though microbial biomass was higher under the low pH, there was lower microbial activity/decomposition of organic matter added to the slow pool thus a slower turnover rate. Figure 19 shows the graph of heterotrophic respiration for the three pH levels. The graph agrees with the explanation that microbial respiration was higher under higher pH values.

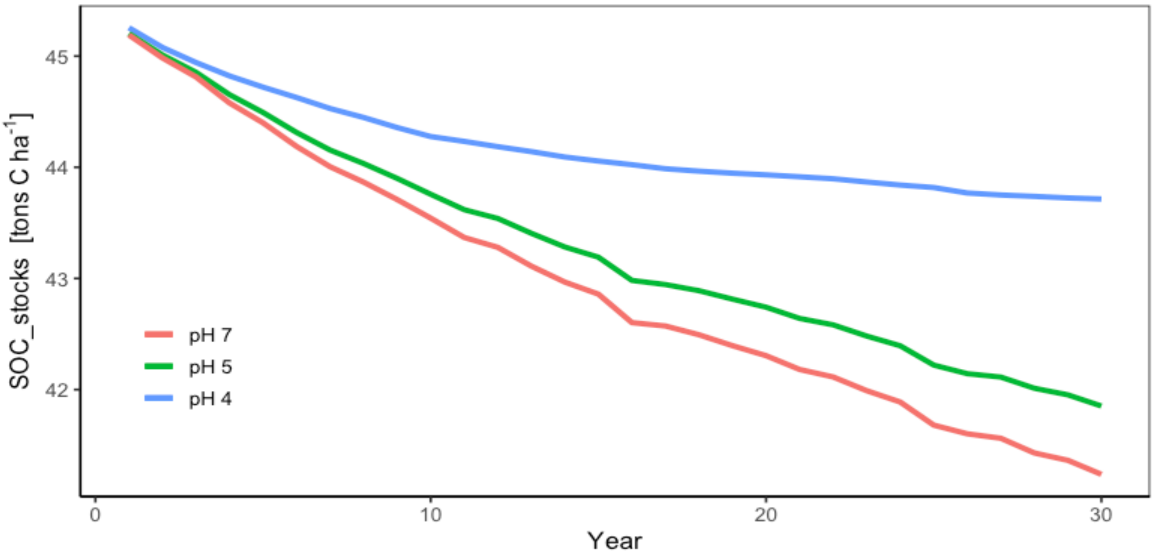

Figure 18. Sensitivity of SOC to changes in pH.

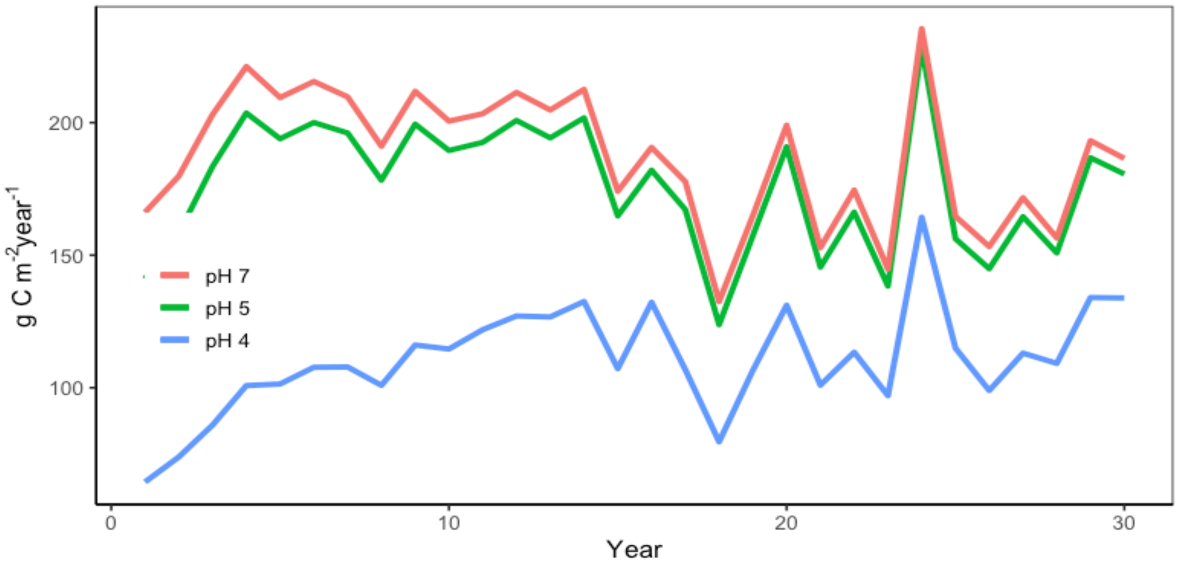

Figure 19. Microbial respiration under different pH values.

In figure 20, we observed the highest SOC stocks at a sand-clay-silt ratio of 25:25:50 shown by the purple line. The red line in the texture ratio- 40:36:24 follows with the second highest SOC stocks. The third line has 55:31:14 and the fourth which has least SOC stocks had the highest sand content- 60:26:14. SOC depletes at a much faster rate in sandy textured soils than in soils with high clay and silt contents. Microbial CO_2 respiration/decomposition was much higher in the sandy textured soils than the clay and silt textured ones. This reflected in the slow SOM pools of the clay and silt textured soils having lower decomposition rates and the sandy textured soils having higher decomposition rates of the slow SOM pool.

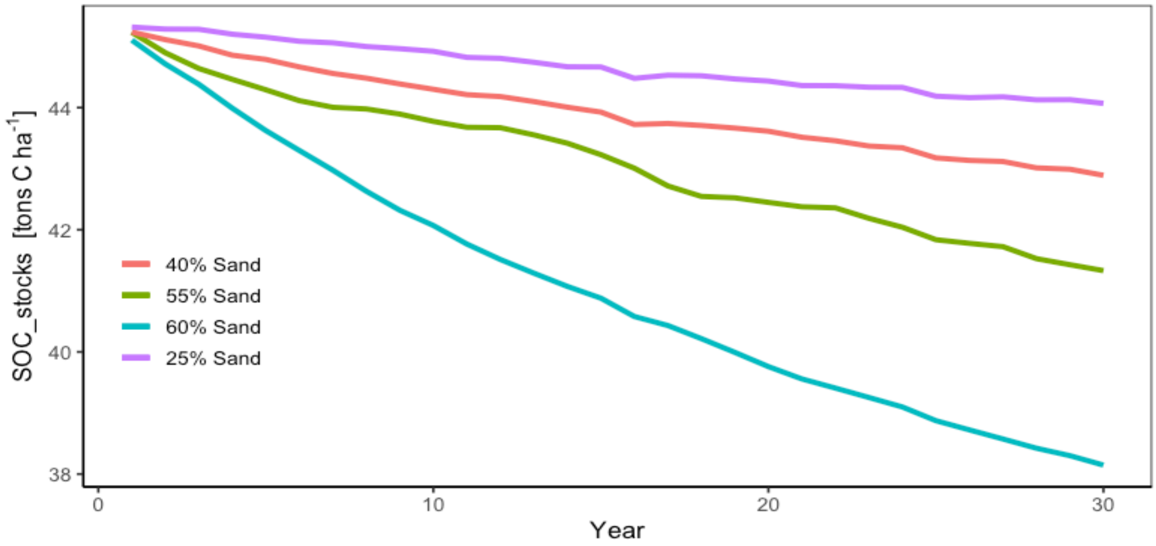

Figure 20. Sensitivity of SOC to texture.

In addition to soil inputs, we tested the model's sensitivity to other parameters. There is no recommendation on the appropriate values to use for some of these parameters, rather, the user has to tweak or change them to suit their site observations, if needed. For example, hours_rain (duration of each rain event) in sitepar.in file is set at a default value of 4 hours. This might not be realistic for our study site as a single rainfall event is usually short and intense. The parameter accepts a minimum value of 2 with subsequent values being a multiple of 2. SOC stock was not affected by changes in this parameter, therefore, we left it to the default value. The most sensitive one is PRDX, SOC increases when this parameter is increased. Figure 21.

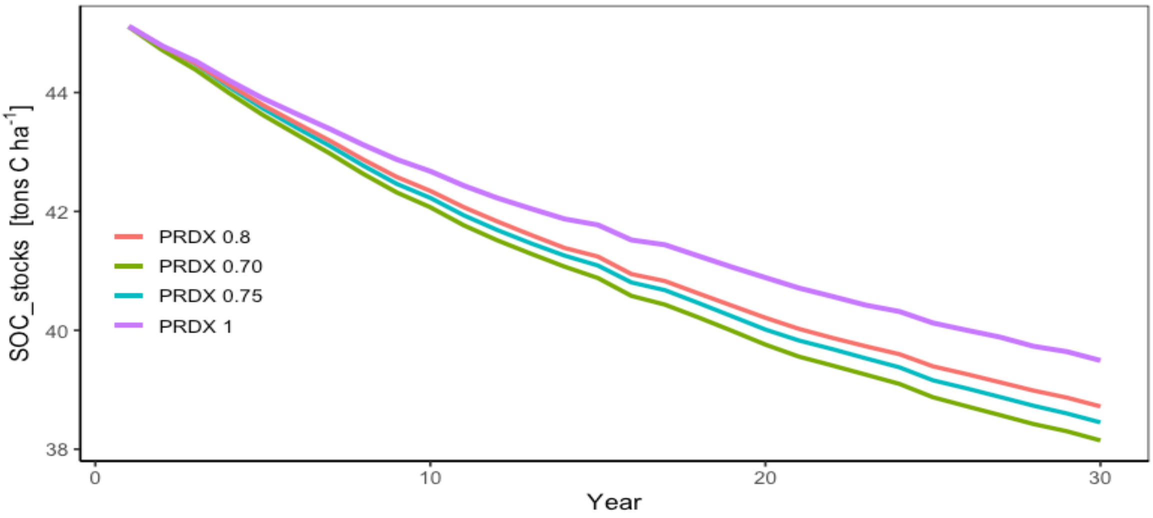

Figure 21. Sensitivity of SOC to PRDX.

4.5.4 Historical to Present-day Simulations

From 1938 to 1989, after 52 years of historical heavy grazing (45 % flgrem) of a lower productivity vegetation (PRDX 0.7) at all sites, SOC stocks reached 57.2 ton C ha^{-1} for sand_heavy, 51.8 ton C ha^{-1} for clay_heavy and 34.2 ton C ha^{-1} for the sand_light site. For the 28 years of present day runs from 1990 to 2017, sand_heavy and clay_heavy – both (still) under heavy grazing management – arrived at SOC stocks of 48.4 and 45.5 ton C ha^{-1}. Sand_light under light grazing (15 % flgrem) lost less C ending with 37.1 ton C ha^{-1} (Figure 22).

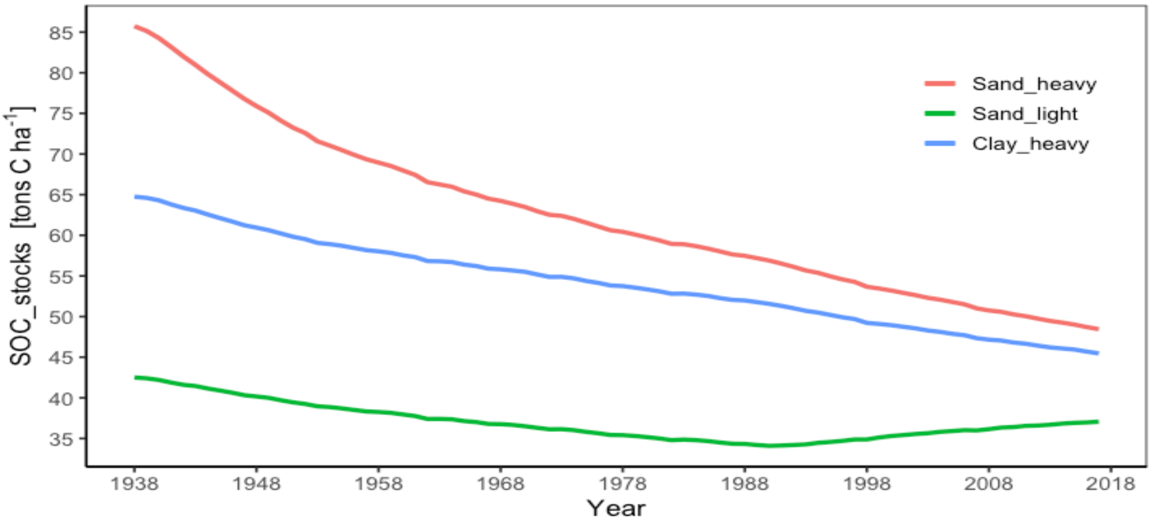

Figure 22. SOC stocks at end of historical and present-day simulations.

4.5.5 No Grazing Alternative from 1990 to 2017

In figure 23, the dashed lines show the alternative of a no grazing management effect on SOC from 1990 to 2017. The sites would have gained additional SOC during the no graze alternative as follows: Sand_heavy an extra 13 ton C ha^{-1}, clay_heavy an additional 11 ton C ha^{-1} and 1.9 ton C ha^{-1} for sand_light because it is already under a light grazing intensity of 15% flgrem.

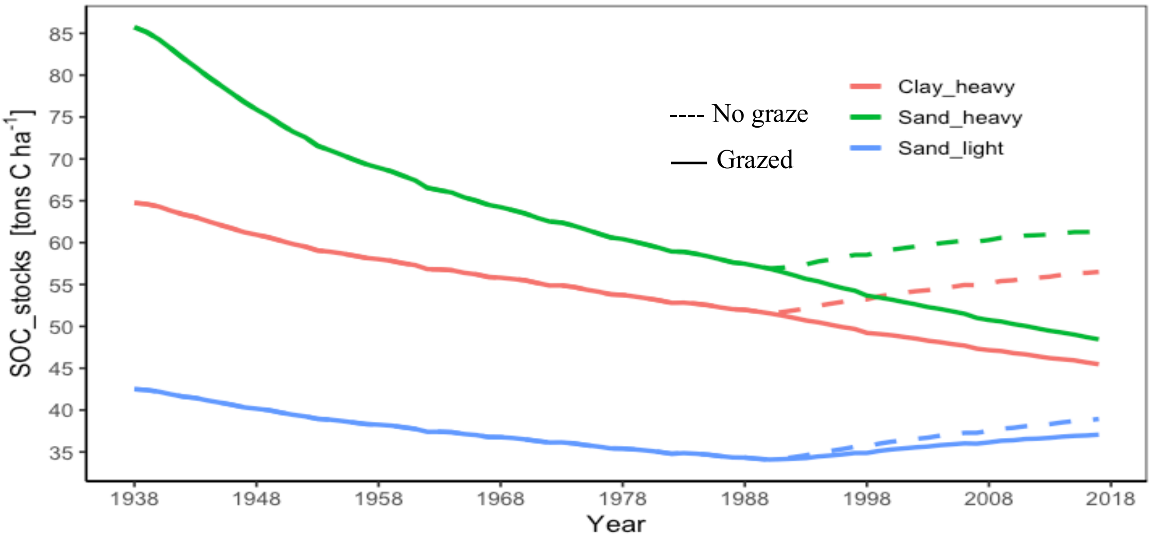

Figure 23. Simulated SOC stocks under no grazed "dashed lines" versus grazed managements "solid lines" for the present-day period (1990 to 2017).

4.5.6 Model Evaluation

Additional no-graze simulations were made for each site during the present-day period (1990 to 2017), and the simulated average NPP of the last 10 years (2008-2017) were compared with NPP estimates from a no graze rangeland exclosure in Nairobi. Two “artificial” harvest events were scheduled in October 2017 and December 2017, the former to mark removal of existing vegetation and the latter to produce an AGB value that could be compared to own measured AGB in December 2017. Table 7 shows the results for the measured means and standard deviation and the corresponding simulated values of AGB, NPP and SOC stocks.

Table 7. Comparison of modelled outputs to measured data at end of the present-day period.

	Aboveground Biomass (g Cm^{-2})		Net Primary Productivity (g C m^{-2})		SOC_stocks (20cm) (ton C ha^{-1})	
Site	Measured mean ± SD	Simulated	Estimated	Simulated	Measured mean ± SD	Simulated
Sand_heavy	39±12.6	45.5	460	492	51.4± 3.1	48.3
Clay_heavy	39±12.6	41.0	460	468	37.0 ± 10	45.4
Sand_light	29±9.5	23.2	460	364	35.0 ± 6	37.0

4.6 Future SOC Trend Under no Graze Versus Present Continued Conditions

In figure 24, if the present grazing intensities were to be replaced with no grazing for the next 30 years, sand_heavy will gain an additional 11.3 ton C ha^{-1} at an annual rate of 330 kg ha^{-1}. Clay_heavy and sand_light will accumulate extra 10.5 and 2.0 ton C ha^{-1} respectively over the 30 year period, i.e. 350 and 67 kg C ha^{-1} $year^{-1}$.

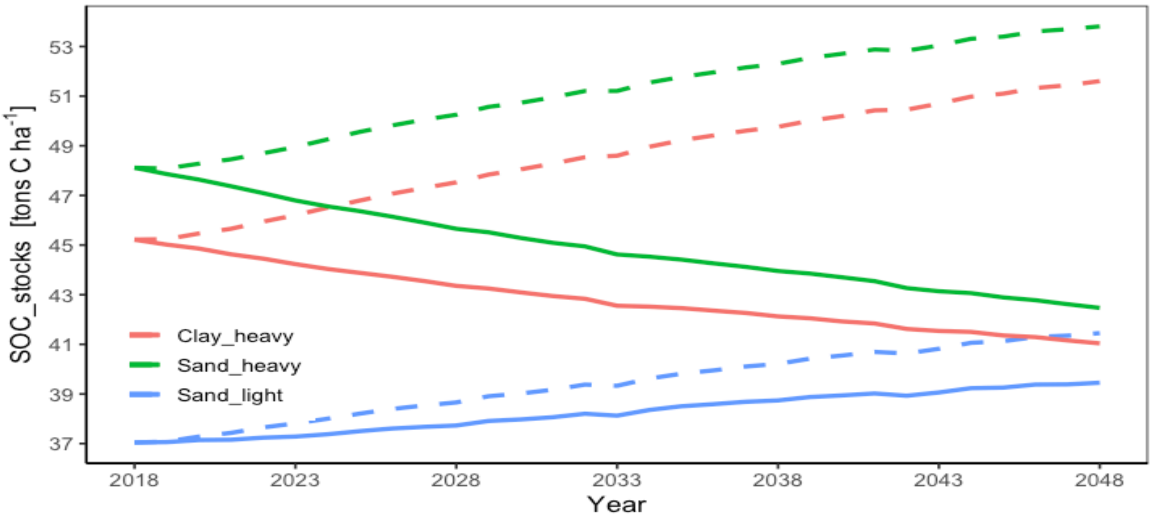

Figure 24. Simulated SOC stocks in the next 30years under continued present-day conditions "solid line" and under ungrazed conditions "dashed lines".

4.7 Future Climate Change Predictions

30 years extended simulations of RCP4.5 and RCP8.5 mid-future scenarios were made for the three sites and the described grazing regimes;

Heavy grazing (HG)- continues grazing of 45 % flgrem removal

Moderate grazing (MG)- continuous grazing of 20 % flgrem removal

Alternating grazing (ALT)- monthly alternating of heavy grazing and no grazing, and

Rotational grazing (RG)- one year of HG and one year of no grazing.

There was no significant difference in SOC stocks between the baseline and CC scenarios for simulations in each case. The result however, suggested SOC stocks will decrease under future climate with more losses under RCP4.5 than RCP8.5 scenarios.

4.7.1 Sand_heavy Site

Figure 25 shows the baseline scenario results for the sand_heavy site and figure 26 shows that for the RCPs. SOC stocks increased from 48.1 to 50.9 ton C ha^{-1} under MG, accumulating approximately 2.8 ton C ha^{-1} at a rate of 93 kg C ha^{-1}yr^{-1}. SOC stocks decreased from 48.1 to 47.3 ton C ha^{-1} at an annual rate of 27 kg C ha^{-1} under the ALT management. For RG, under all climate scenarios, SOC remained approximately the same at the end of the 30 years. We observe the most SOC loss under the HG management, SOC depleted from 48.1 ton C ha^{-1} to 42.6 ton C ha^{-1} at an annual rate of 183 kg C ha^{-1}.

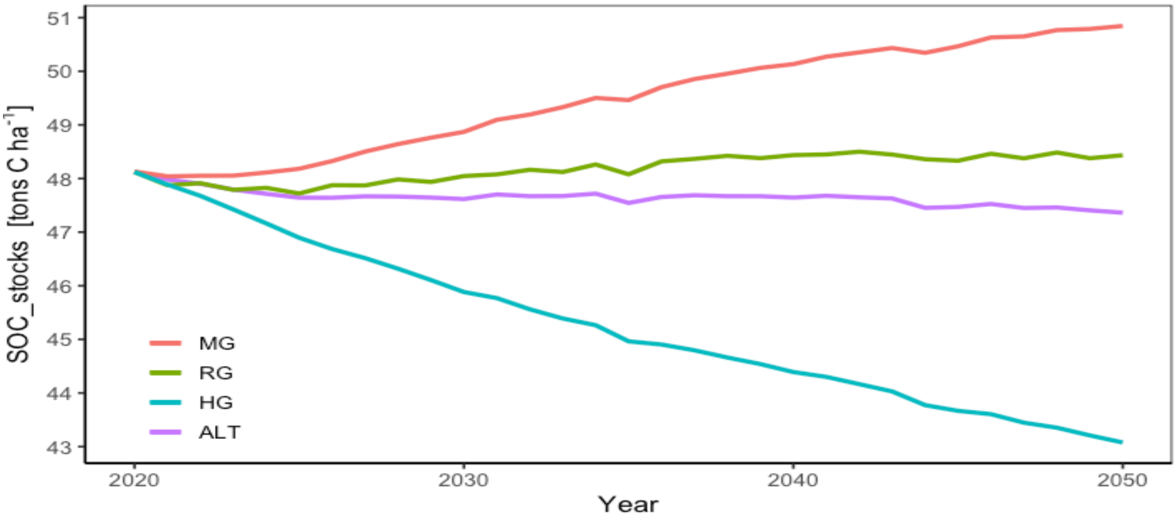

Figure 25. Sand_heavy baseline scenario with historic dataset.

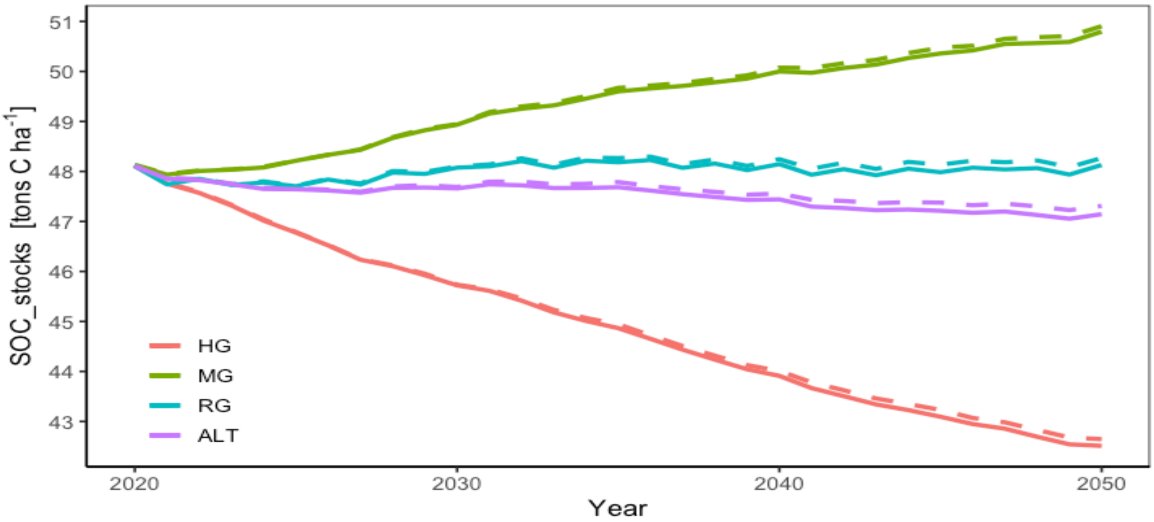

Figure 26. Changes in SOC under the simulated grazing managements and the two climate scenarios for sand_heavy (dashed lines for RCP8.5 and Solid line for RCP4.5).

4.7.2 Clay_heavy Site

MG sequestered the most C compared to the two sandy sites. An additional 4.2 ton C ha^{-1}, which corresponds to an annual rate of 141 kg C ha^{-1}, was sequestered. This was also the only site that showed any increase in SOC stocks out of the 3 sites under RG management. SOC stocks increased somewhat from 45.3 to 47 ton C ha^{-1}, an annual accumulation rate of 57 kg C ha^{-1}. ALT accumulated a total of 0.8 ton C ha^{-1}, the same amount as sand_heavy under the same grazing management. Clay_heavy also lost 3.6 ton C ha^{-1} under HG, which was lower as compared to 5.5 ton C ha^{-1} for sand_heavy and 6.2 ton C ha^{-1} for sand_light. It retained about 1.9 and 2.6 ton C ha^{-1} more than sand_heavy and sand_light respectively.

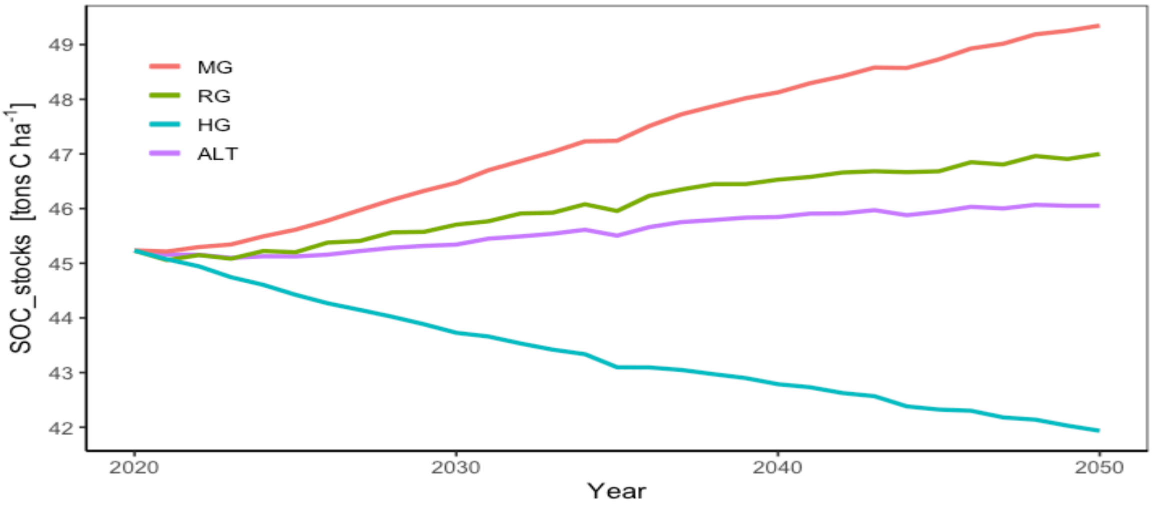

Figure 27. Clay_heavy baseline scenario with historic dataset.

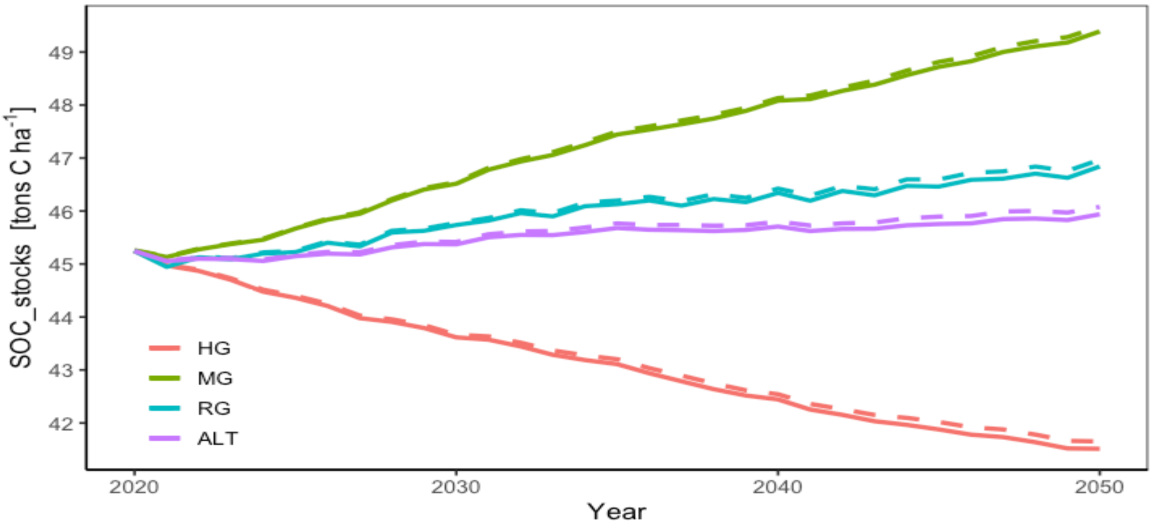

Figure 28. Changes in SOC under the simulated grazing managements and the two climate scenarios for Clay_heavy (dashed lines for RCP8.5 and Solid line for RCP4.5).

4.7.3 Sand_light Site

Figure 30 shows SOC under the four grazing managements and RCPs from an initial stock of 37 ton C ha^{-1}. MG accumulated 1.7 ton C ha^{-1} under RCP8.5 at an annual rate of 57 kg C ha^{-1}. This site accumulated 1.1 ton C ha^{-1} less than sand_heavy and 2.5 ton C ha^{-1} less than clay_heavy. RG lead to a loss of 0.8 ton C ha^{-1} after the 30 years in comparison with sand_heavy which remained steady and clay_heavy which gained additional 1.7 ton C ha^{-1}. However, ALT lost 1.7 ton C ha^{-1} from 37 to 35.3 ton C ha^{-1} as opposed to sand_heavy and clay_heavy both of which accumulated additional 0.8 ton C ha^{-1}. The most C loss under HG across sites was here, about 6.2 ton C ha^{-1} was depleted over the 30year period at an annual rate of 206 kg C ha^{-1}.

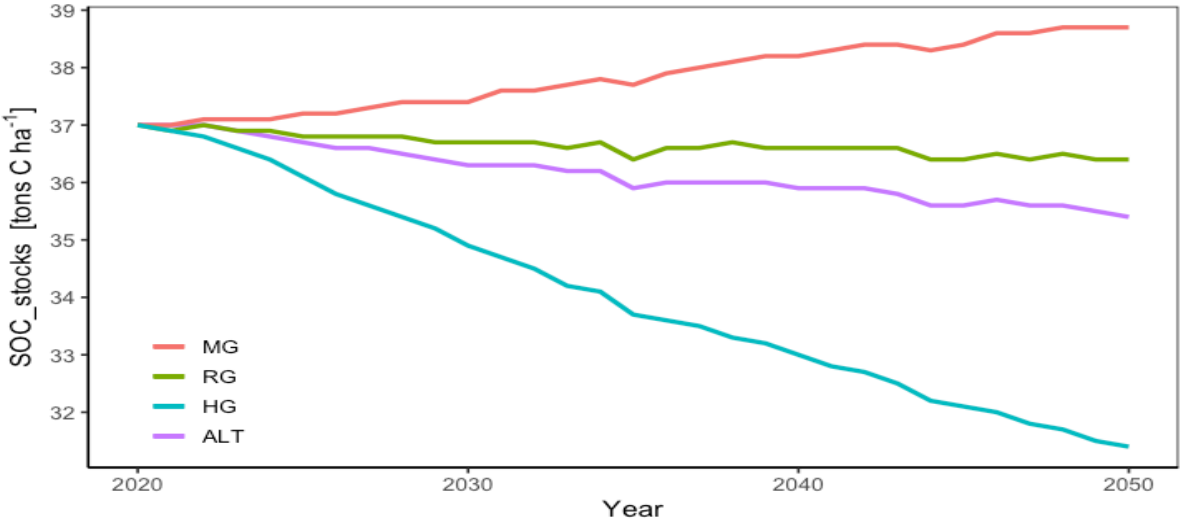

Figure 29. Sand_light baseline scenario with historic dataset.

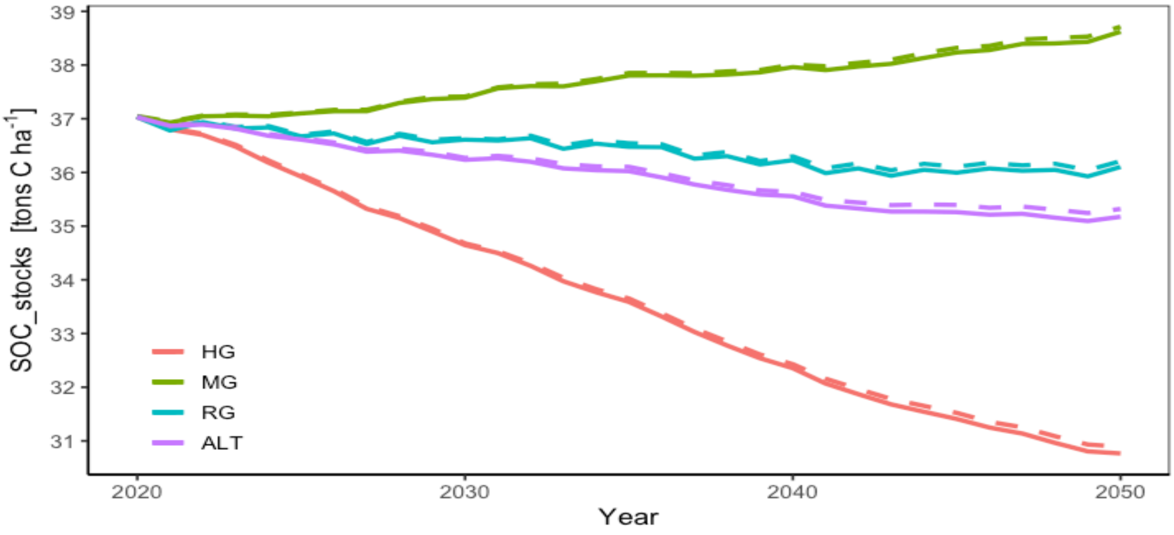

Figure 30. Changes in SOC under the simulated grazing managements and the two climate scenarios for sand_light (dashed lines for RCP8.5 and Solid line for RCP4.

Chapter 5

Discussion

5.1 Measured BD and SOC Stocks

SOC stocks (0-20 cm) ranged from 41 ton C ha^{-1} at the light grazed site to 64.8 ton C ha^{-1} at the heavy grazed site. The study by Rotich et al. (2018) in another rangeland in South Kenya reported similar stocks from 38.4 ton C ha^{-1} at continuous grazed sites to 42.1 ton C ha^{-1} at rotational grazed sites and 45.5 ton C ha^{-1} at a heavy grazed site.

BD values in the top soil depth (0-10 cm) were significantly higher for our heavy grazed sandy sites (sand_heavy) comprising of site 1 and 3 but the 25-50 cm depth showed no significant difference in BD for all the sites under study. Sandy soils are prone to compaction by herbivory activity. Constant heavy grazing by livestock together with wildlife on the sand_heavy sites may have compacted the soils therefore affecting our BD measurements, this in turn affected SOC estimates for these sites because BD was used in the SOC calculations. However, there is no way of telling if this is the case since we have no previous reference BD data from Kapiti with which to correct our measured BD. The study by Rotich et al. (2018) also reported high BD values (1.57 and 1.46) g cm^{-3} for the depths 0-10 cm and 10-20 cm in a continuous heavy grazed site although the soil type was not mentioned. They also attributed the high BD values to compaction. Just like our results, they reported no significant difference in BD in deeper soil depths for heavy grazed versus rotational and no grazed sites. Feyisa et al. (2017) in Ethiopia and Mureithi et al. (2014) in Kenya as well as several other authors also have made the same observations in other grassland ecosystems (Daniel et al., 2002; Savadogo et al., 2007; Stavi et al., 2008). Steffens et al. (2008) in their study on grazing effects on grassland soil properties in Mongolia found that there was no significant difference in SOC between grazed and ungrazed sites when the stocks were calculated from BD. They in addition calculated SOC stocks from equivalent mass using methods described by Veldkamp (1994) instead of BD and found SOC stocks to be significantly lower under the heavy grazed sites.

5.1.1 Effect of Grazing on Measured SOC Stocks

SOC stocks increased with depth for all the sites. This is attributed to the deep root system of grasses as an adaptation mechanism to semi(arid) conditions. SOC sequestrated at lower depths from BGB is less exposed to physical and climatic factors that accelerate rapid degradation

(Kell 2011, 2012; Kane, 2015). Light/moderate grazing drives biomass production particularly BGB thus increasing SOC sequestration. C_4 grass species, especially in tropical grasslands, have rhizomes and other storage organs that enable them compensate for moderate grazing levels (Ritchie, 2014). Although our results showed SOC stocks to be higher at the sand_heavy sites (1 and 3), SOC stocks in the lower depth (25-50 cm) was higher at sand_light (site 5) which has been under continuous light grazing (1989-present) than at site 1. Despite the significantly higher SOC stocks at sand_heavy in the two upper depths (0-10cm and 10-25 cm), their corresponding % OC contents were not significantly different from the remaining sites except for sand_recent_heavy (site 4) in the (10-25 cm and 25-50 cm).

Two possible explanations can be given for the significantly higher SOC stocks found under the heavy grazed sites (in the 0-10 cm and 10-25 cm) as we hypothesized this to be otherwise. First, we attribute the high SOC stocks calculated for the heavy grazed sandy sites to the BD measurements. Additionally, in rangeland ecosystems, plant nutrients are recycled not only through litter decomposition but also by the grazing activities of herbivores (Grant et al., 1995; Hafner et al., 2012). The sand_heavy sites (1 and 3) have constant herbivore activity, bomas are located at site 1 and 3 where cattle and sheep spend the night after grazing. It is safe to say nutrients are constantly returned to these sites through livestock excreta. SOC will rapidly decompose in the top layer of these sandy textured sites under exposure to climatic and physical disturbances but % OC measured at any point in time will be high in the upper depths as a result of continual replenishment from inputs by livestock excreta. Zhang et al. (2017) also made a similar observation, they attributed high SOC stocks to manure returned after grazing.

It was interesting to find that % OC measured in the bottom layers 50-100 cm (BD measurement not available) for the sandy textured soils was highest (2.68 %) at the lightly grazed site-sand_light followed by sand_recent_heavy (1.79 %). The sand_heavy sites had the lowest % OC (1.73 and 1.75 % for site 1 and 3 respectively). This supports the assumption made that the high % OC contents measured in the top depths of the heavy grazed sites (1 and 3) are only as a result of nutrient input from excreta. Not surprisingly, the clay_heavy site had the highest % OC (3.25 %) amongst all the sites, this is the result of the interaction between texture and grazing. The resilient of the clay_heavy site is attributed to the physical and chemical protection of OM through adsorption onto clay minerals and occlusion in aggregates. Aggregates in clay soils increase production of recalcitrant organic compounds which are less prone to rapid decomposition and associated C losses (Balesdent & Balabane 1996; Six et al., 2002; Silver et al., 2010). Potter et al. (2001) while studying grazing effects on SOC stocks found higher SOC amounts under clay soils than under sandy soils.

Nevertheless, the measured field results make it difficult to draw conclusions on the effects of grazing on rangeland C dynamics as what was observed in the top 0-20 cm was different from the stated hypothesis that moderate grazing increases SOC stocks while heavy grazing reduces it. Although we see a trend in our results that suggest a positive effect of moderate grazing on SOC stocks in the sub to bottom soil layer (25-100 cm), there is very limited studies on the vertical distribution of SOC stocks under the influence of grazing to back our claim.

5.2 DayCent Model Performance

In general, the Daycent model performed reasonably well for our study area and conditions. All our modelled outputs were within the range of the standard deviations of our measured and estimated validation datasets for sites clay_heavy and sand_light. The sand_heavy site, however, was challenging to simulate. Adjusting parameters controlling decomposition during the spinup phase made it act as if it was a clay textured soil. Note that it gained more C than the clay site clay_heavy in the no grazing alternative in figure 23 and 24. Limited knowledge of historical events that took place at this site made it difficult to trace and explain discrepancies between observed and simulated SOC stocks. We would for instance not know, whether manure or synthetic fertilizer was added, or a no grazing event introduced, that could have contributed to the high SOC content we observed. Also, our high BD data could have been a result of only very recent soil compaction from livestock. The high BD for this site contributed to a higher total SOC stock in the top 20 cm while the sand content (approximately 60 %) made it impossible to retain as much SOM because of the model being sensitive to texture.

5.3 Climate Change Impact on Future SOC Stocks

SOC was simulated to decrease under CC with stocks under RCP4.5 lower than that under RCP8.5 although the observed differences were not dramatic in comparison to baseline scenarios in all cases. Zhang et al (2017) found no significant difference between SOC under the two CC scenarios for their study site in Mongolia. The small reductions in SOC from the baseline scenario suggest CC will cause small losses in SOC stocks. This is because increased warming and moisture induce rapid decomposition (Jobbagy & Jackson, 2000).

We expected RCP8.5 to have a more negative effect on SOC due to its higher temperatures. Zhang et al. (2017) in Mongolia and Dintwe et al. (2015) in South Africa found negative effect of RCP8.5 on SOC stocks than RCP4.5, however, only temperature and not precipitation was predicted to increase for their study sites. It may seem right to consider the wetter conditions under the generated RCP4.5 scenario relative to that of the RCP8.5 as the main reason we are making this observation (Figure 12 and 13). However, a simulation we made with a C_3 plant under the two CC scenarios that showed the opposite effect of the two CC scenarios (Appendix 7a). SOC stocks under RCP4.5 was slightly more than under RCP8.5 although the difference there also could not be counted as drastically different from the baseline. This led us to explore other possible reasons for the observation made.

Perhaps the first explanation for the slightly higher SOC stocks recorded under RCP8.5 than under RCP4.5 may be because Kapiti is a C_4 species dominant grassland. The additional increase in temperature and not so wet conditions of the RCP8.5 may favour higher photosynthetic primary productivity which in turn will supply the soil with more SOM. Some studies suggest positive response aboveground net primary productivity (ANPP) of C_4 species particularly to elevations in CO_2 amounts (Polley at al., 2014). Nitrogen availability and water use efficiency (WUE) have been reported to increases with increasing CO_2 elevation (Fay et al., 2012). Higher CO_2 elevations under RCP8.5 will make nitrogen available to plants which in turn will make them more productive.

In addition to Kapiti being a C_4 dominant grassland, it may also be that the higher temperatures and not so much wet conditions under RCP8.5 slows down microbial activities. It should be noted that seasonality did not change under the RCPs, the additional rainfall occurred during the rainy seasons. This means the dry period (June to September) experienced even drier conditions under RCP8.5 reducing microbial activity/respiration therefore allowing SOM to accumulate. De Deyn et al. (2008) described plant trait mechanisms that control SOC sequestration. It can also be said that more lignified/carbon concentrated plant tissues are produced under warmer conditions (non-ideal) and therefore the SOM produced is more resistant to decomposition. Appendix 7b shows a graph in which the slow SOC pool (structural +metabolic plant component) under RCP8.5 was slightly higher than that of RCP4.5.

Overall, our results predict that CC in Kapiti will only contribute to small losses in SOC stocks during mid-future period for both RCP scenarios. Below, we discuss the effects of grazing management under CC on SOC stocks. The amounts mentioned below are from the simulations under RCP8.5 which is supposed to be the extreme scenario but the simulated SOC stocks are reasonably high and comparable to SOC stocks under baseline scenarios.

5.4 Grazing Management Impact on Future SOC stocks

For all soil types, heavy grazing (HG) lead to SOC losses while moderate grazing (MG) which drives more BGB allocation resulted in substantial increases in SOC stocks. The clay_heavy site under moderate grazing had the highest SOC accumulation rate of 141 kg C ha^{-1} which is more than the total of the two sandy sites. RG which comprises one year of HG and one year of no grazing lead to steady SOC stocks over the years in one of the sandy textured soils—sand_heavy but very small losses was observed in the other sand_light site. ALT only caused SOC stocks to increase for the clay_heavy site and decrease for the other two sites.

SOC accumulation was observed under the clay_heavy sites for all the grazing regimes tested except for HG. Our simulated SOC stocks amounts are reasonable, average SOC stocks of the three sites under moderate grazing is 97 kg C ha^{-1}, a long-term experiment on a semi-arid C_4 grassland under an aridisol in South Africa by Talore et al. (2016) also found that light/moderate grazing accumulated SOC at 97 kg C ha^{-1}. Ritchie (2014) used the SOC model "SNAP" to predict SOC stocks under grazing in Northern Kenya. His results indicated much higher rate of 0.3-0.4 ton C ha^{-1} y^{-1} (300-400 kg C ha^{-1}) when grazing shifts from 95-99 % to 85-90 % across a predominant sandy loam soil. He, however, did not state at which depth.

5.4.1 Carbon Budget and Policy Implications

Under the assumption that our predicted estimates are reliable and can be extrapolated across the total area of grasslands in Kenya, we can have a rough idea of the average rate at which C can be sequestered. Using the average of the three sites to account for the varying soil texture class across Kenya, a total of 0.1 ton C ha yr^{-1} of SOC can be sequestered under moderate grazing amounting to 0.13 Pg C of SOC (up to 20 cm of soil) in 30 years.

A gram of C is equivalent to 3.664 g of CO_2 (Duong, 2009). Therefore, 0.1 ton C ha^{-1} sequestered translates to 0.4 ton CO_2 per year. The total grassland coverage of Kenya is approximately 46,429,600 ha which further translates to 18.6 Mt[4] of CO_2 sequestered per year

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[4] 1 Megaton (Mt)= 10^6

over Kenya. Ritchie (2014) mentioned a base rate of 5-9 USD per ton of C per year on the open market (Carbon Trade Exchange, http://carbontradexchange.com). Under moderate grazing, a significant amount of revenue estimated at over 23 million USD may be generated in Kenya, not forgetting the added benefit of helping adapt to CC.

The income generated every year can be directed towards poverty reduction and infrastructural development. This, however, will mean some implications for rangeland stakeholders. Policies and economic incentives must be put in place by stakeholders and government agencies to encourage the adoption of appropriate grazing management by land users. Reports show most countries in East Africa lack the institutional capacity needed to promote improved management adoption (Jindal, 2006). The associated increase in ecosystem productivity that tags along adoption of improved grazing management is a gradual process. Therefore, land users may be reluctant to reduce grazing pressure if incentives are not given right at the start of adoption. There is the need to overcome most of the challenges discussed in the literature review chapter for the technical C sequestration potentials of rangelands to be realized.

5.5 Limitations and Uncertainties

Some limitations during the course of this work are worth mentioning. First of all, the estimated grazing rates for the various sites is one of such uncertainties. Kapiti is not divided into paddocks, this makes it impossible to restrict and track wildlife grazing. Encroachment and secret/unknown grazing by Massai cattle herders due to the remote location of some of the sites also adds to the uncertainty making it difficult to assign an exact grazing intensity to a site. To add to this, the lack of proper record keeping for a long period of time even after purchase of the ranch created uncertainties about management at the various sites.

Availability of required data is crucial for use in ecosystem models. Confidence in model simulation is enhanced when users have reliable information on climatic, biomass and management data that control SOC accumulation. We worked with limited data inputs for a fairly complex model like DayCent, this leaves room for doubt on simulated results. Also, although DayCent can estimate SOC stocks with a high level of accuracy, it has its own limitations just like every other ecosystem model. Perhaps the most important one is that aside from returning nutrients to the soil in the form of herbivore excreta, DayCent considers grazing as just a vegetation removal process. It for instance does not take into account effects of herbivore trampling on top soils and grazer effects on shifts in vegetation species composition.

These may be essential factors that are part of the complex processes that influences SOC accumulation and a model that incorporates them will be helping for further studies.

Another important uncertainty has to do with the use of Regional (RGM) and Global Climate Models (GCM) in predicting CC across East Africa. Most of these models under the CMIP5 ensemble of the IPCC including the Max-Planck-Institute Earth System Model (MPI-ESM) which we used in our study predict notable increase in rainfall amounts over East Africa (Rowell et al., 2015). In contrast, there is physical evidence of decline in total rainfall amounts over the region (Liebmann et al 2014; Viste et al., 2013). This difference between observation and simulation in rainfall is often referred to as the “East African paradox” and raises doubts over the reliability of climate models in predicting future trends (Rowell et al., 2015). We may be fooling ourselves with the thought that rainfall is going to increase in the region under CC which means wrong predictions of future SOC stocks.

Little previous studies on rangeland SOC sequestration carried out in Kenya and East Africa proved to be a limitation for us, we did not have enough studies with which to compare our results. Most of the literature reviewed (not just in Africa) did not provide all the necessary/important information which made it difficult to compare results. In order to make good comparison of studies across several sites, there is the need to know exact grazing intensities (% of biomass removal), soil type, profile-depth and many more. This will assist in gaining a better knowledge of the complex interaction of SOC sequestration.

Chapter 6

6.1 Conclusion and Recommendations

In this study, we aimed to investigate on a plot scale, the long-term effects of four grazing management regimes on SOC stocks under RCP4.5 and RCP8.5 CC scenarios and varying soil texture types. Heavy grazing (HG) resulted in up to 206 kg C ha^{-1} loss in SOC in sandy textured soils. The highest SOC sequestration rate of 141 kg C ha^{-1} occurred in a clay soil. RG (yearly rotation) lead to a small increase of 57 kg C ha^{-1} only for the clay site. ALT (monthly rotation) caused small increases of 30 kg C ha^{-1} in SOC stocks for clay and one sandy textured soil. We observed small reductions in SOC stocks under CC with more negative effects of RCP4.5 than RCP8.5 on SOC stocks although there were no drastic differences in all instances. We conclude that grazing is an important management that affects SOC sequestration in grasslands. However, a better knowledge of the factors that interact together with grazing and soil texture to enhance SOC accumulation is required in order to accurately interpret results from field measurements and draw sound conclusions. Our results support reports that suggest clay textured soils have higher SOC sequestration potentials than sandy soils. Grazing and soil texture will be the major factors controlling SOC dynamics in the future as much more difference was observed in those than was observed under the two RCP CC scenarios.

Further ground truthing work is required to better quantify SOC stocks estimates and grazing intensities on the site. The use of soil and vegetation mapping by GIS and remote sensing prove to be reliable means of quantifying SOC stocks. Spatial and timescale changes in vegetation may be estimated by some simple methods. NDVI images can be taken over time and space to estimate grazing rates. The influence of grazing on measured SOC stocks needs to be further explored at the study site before future predictions on C sequestration are made by use of model simulations. This will ensure that the model is being fed the right information so as not to produce false estimates that otherwise would not be observed in reality.

Data availability limits knowledge and studies of C dynamics in rangelands of East Africa. Stakeholders may team up together to create databases that are easily accessible by the scientific community for studies concerning rangeland SOC sequestration.

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Appendix

Appendix 1

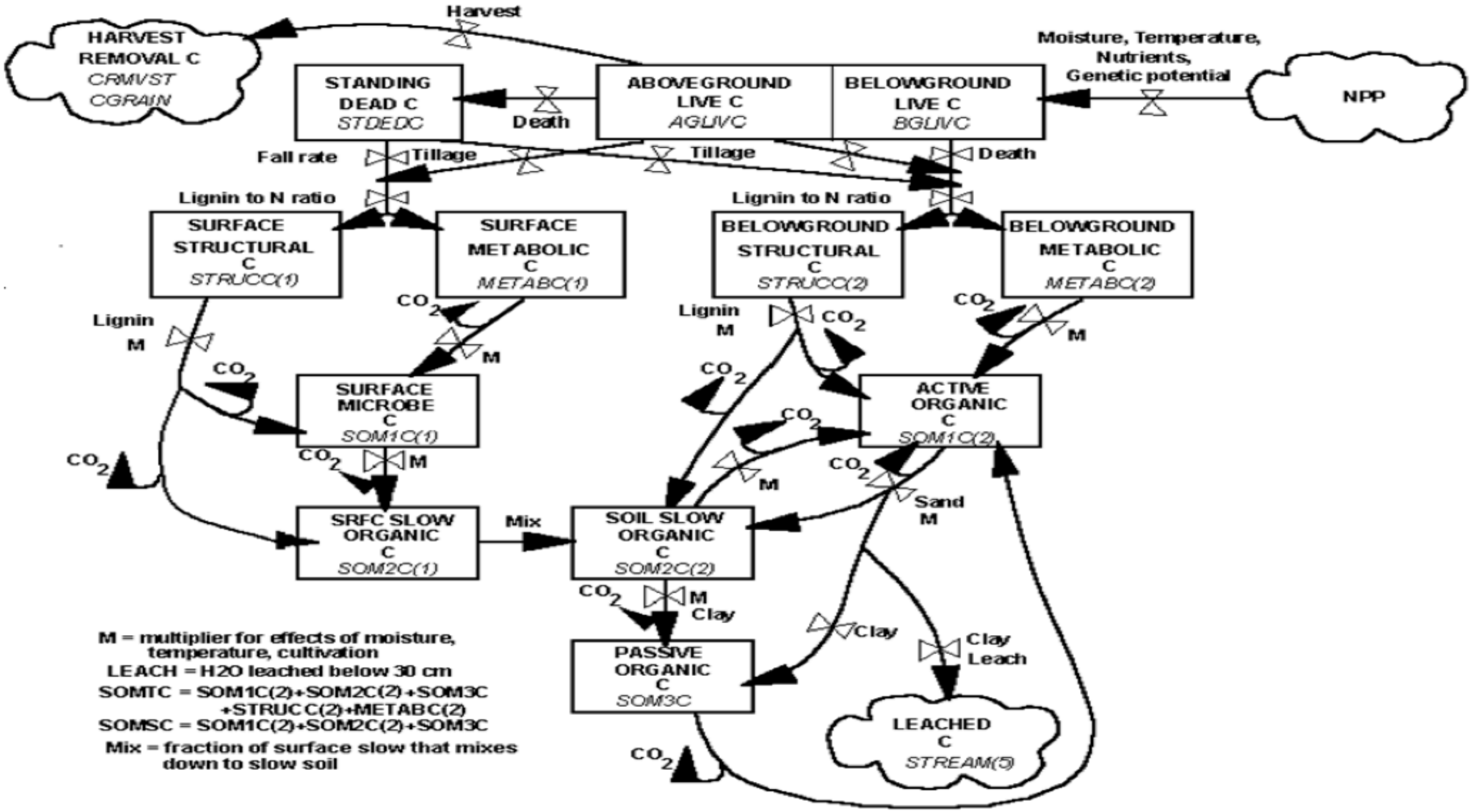
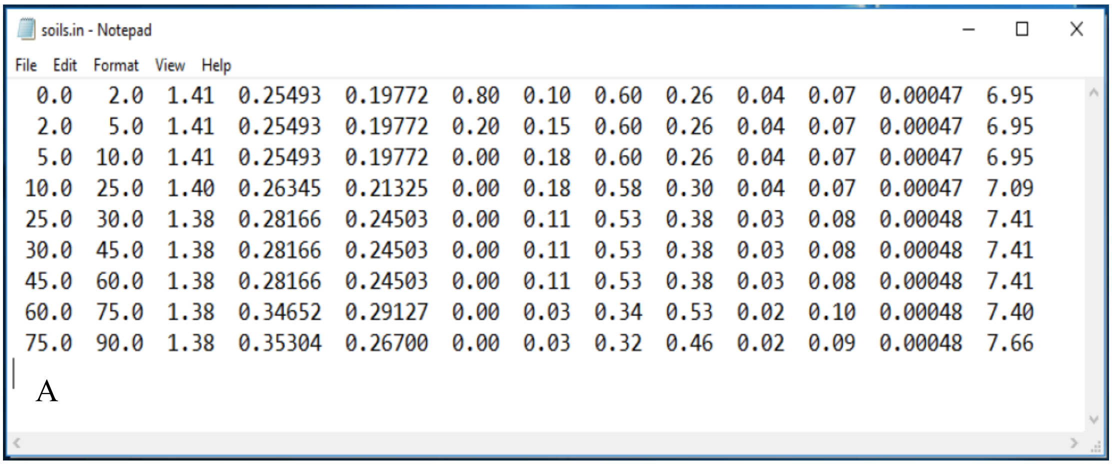


Figure 31. DayCent SOM sub-model (Del Grosso et al., 2008).

Appendix 2



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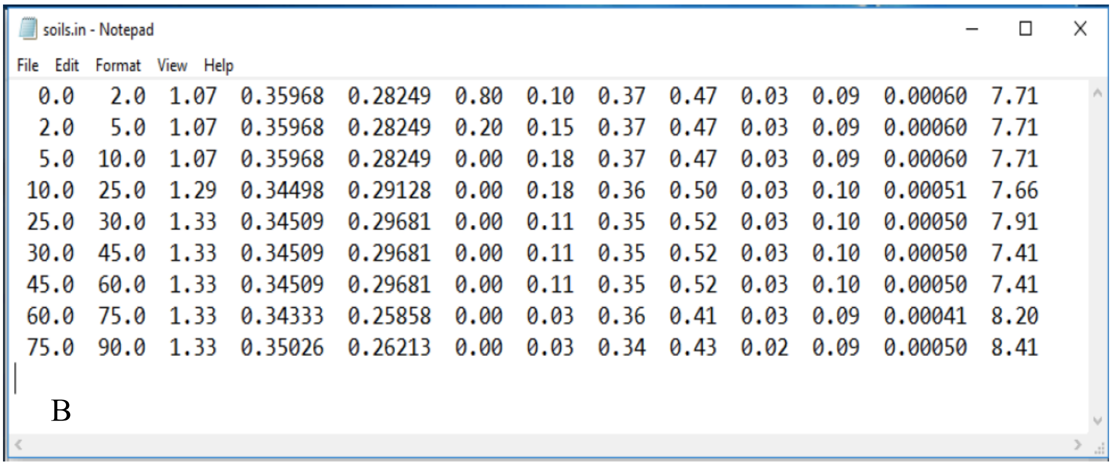
  2.0   5.0 1.41 0.25493 0.19772 0.20 0.15 0.60 0.26 0.04 0.07 0.00047 6.95
  5.0  10.0 1.41 0.25493 0.19772 0.00 0.18 0.60 0.26 0.04 0.07 0.00047 6.95
 10.0  25.0 1.40 0.26345 0.21325 0.00 0.18 0.58 0.30 0.04 0.07 0.00047 7.09
 25.0  30.0 1.38 0.28166 0.24503 0.00 0.11 0.53 0.38 0.03 0.08 0.00048 7.41
 30.0  45.0 1.38 0.28166 0.24503 0.00 0.11 0.53 0.38 0.03 0.08 0.00048 7.41
 45.0  60.0 1.38 0.28166 0.24503 0.00 0.11 0.53 0.38 0.03 0.08 0.00048 7.41
 60.0  75.0 1.38 0.34652 0.29127 0.00 0.03 0.34 0.53 0.02 0.10 0.00048 7.40
 75.0  90.0 1.38 0.35304 0.26700 0.00 0.03 0.32 0.46 0.02 0.09 0.00048 7.66
```

A



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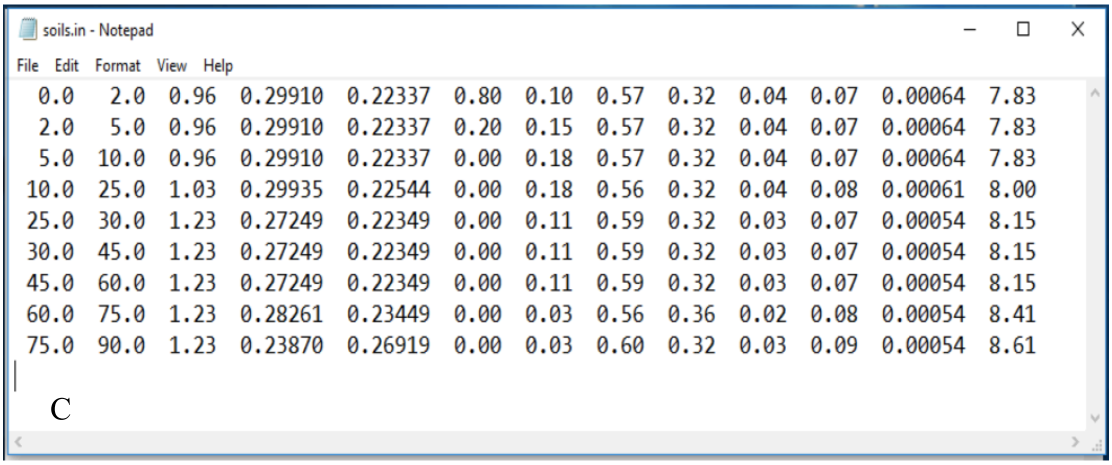
  2.0   5.0 1.07 0.35968 0.28249 0.20 0.15 0.37 0.47 0.03 0.09 0.00060 7.71
  5.0  10.0 1.07 0.35968 0.28249 0.00 0.18 0.37 0.47 0.03 0.09 0.00060 7.71
 10.0  25.0 1.29 0.34498 0.29128 0.00 0.18 0.36 0.50 0.03 0.10 0.00051 7.66
 25.0  30.0 1.33 0.34509 0.29681 0.00 0.11 0.35 0.52 0.03 0.10 0.00050 7.91
 30.0  45.0 1.33 0.34509 0.29681 0.00 0.11 0.35 0.52 0.03 0.10 0.00050 7.41
 45.0  60.0 1.33 0.34509 0.29681 0.00 0.11 0.35 0.52 0.03 0.10 0.00050 7.41
 60.0  75.0 1.33 0.34333 0.25858 0.00 0.03 0.36 0.41 0.03 0.09 0.00041 8.20
 75.0  90.0 1.33 0.35026 0.26213 0.00 0.03 0.34 0.43 0.02 0.09 0.00050 8.41
```

B



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  2.0   5.0 0.96 0.29910 0.22337 0.20 0.15 0.57 0.32 0.04 0.07 0.00064 7.83
  5.0  10.0 0.96 0.29910 0.22337 0.00 0.18 0.57 0.32 0.04 0.07 0.00064 7.83
 10.0  25.0 1.03 0.29935 0.22544 0.00 0.18 0.56 0.32 0.04 0.08 0.00061 8.00
 25.0  30.0 1.23 0.27249 0.22349 0.00 0.11 0.59 0.32 0.03 0.07 0.00054 8.15
 30.0  45.0 1.23 0.27249 0.22349 0.00 0.11 0.59 0.32 0.03 0.07 0.00054 8.15
 45.0  60.0 1.23 0.27249 0.22349 0.00 0.11 0.59 0.32 0.03 0.07 0.00054 8.15
 60.0  75.0 1.23 0.28261 0.23449 0.00 0.03 0.56 0.36 0.02 0.08 0.00054 8.41
 75.0  90.0 1.23 0.23870 0.26919 0.00 0.03 0.60 0.32 0.03 0.09 0.00054 8.61
```

C

Figure 32. Soils.in files for (A) Sand_heavy, (B) Clay_heavy and (C) Sand_light sites.

Column 1 – Upper soil boundary (cm)

Column 2 – Lower soil boundary (cm)

Column 3 – BD of layer (g cm-3)

Column 4 – Field capacity (volumetric fraction)

Column 5 – Wilting point of soil layer (volumetric fraction)

Column 6 – Coefficient of evaporation (currently not in use)

Column 7 – Fraction of roots in soil layer (total=1)

Column 8 – Sand fraction

Column 9 – Clay fraction

Column 10 – Organic matter in soil layer (fraction)

Column 11 – Volumetric SWC below wilting point (Δ, volumetric fraction)

Column 12 – Saturated hydraulic conductivity (cm sec-1)

Column 13 – pH of soil layer

Appendix 3

Table 8. Options for grazing effects on biomass production (DayCent User Manual., 2018).

Grazing option (GRZEFF)	Grazing effect on aboveground production	Grazing effect on root production	Grazing effect on root to shoot ration
0	No direct impact	No direct impact	No direct impact
1	Linear decrease as flgrem increases	Linear decrease as flgrem increases	Constant
2	Increased for moderate grazing and decreasing sharply for heavy grazing levels above 40 % flgrem	Increased for light to moderate grazing and decreasing sharply for heavy grazing levels above 25 % flgrem	Increased for light to moderate grazing and decreasing sharply for heavy grazing levels above 20 % flgrem
3	No direct impact	Increased for light to moderate grazing and decreasing sharply for heavy grazing levels above 30 % flgrem	Increased for light to moderate grazing and decreasing sharply for heavy grazing levels above 30 % flgrem
4	No direct impact		Linear decrease if gremb (graze effect multiplier) is greater than zero otherwise constant
5	Increased for moderate grazing and decreasing for heavy grazing levels above 40 % flgrem		Linear decrease if gremb is greater than zero otherwise constant
6	Linear decrease as flgrem increases	Linear decrease as flgrem increases	Linear decrease if gremb is greater than zero otherwise constant

Appendix 4a

Table 9. Spearman ranks correlation coefficient matrix for the log-transformed physical and chemical properties (10-25 cm depth).

	pH	EC	P	K	Ca	Mg	Mn	S	Co	B	Zn	Na	Fe	CEC	OC	Clay	Sand	Silt
pH	1.00																	
EC	0.83	1.00																
P	-0.47	-0.33	1.00															
K	-0.37	-0.45	**0.62**	1.00														
Ca	**0.86**	**0.74**	**-0.65**	-0.45	1.00													
Mg	**0.69**	**0.55**	**-0.59**	-0.30	**0.72**	1.00												
Mn	-0.42	-0.24	0.14	0.07	-0.20	0.01	1.00											
S	0.06	0.45	0.17	-0.16	-0.09	-0.15	-0.12	1.00										
Co	-0.07	-0.28	0.24	0.54	-0.03	-0.36	-0.26	-0.42	1.00									
B	**0.97**	**0.84**	-0.46	-0.36	**0.91**	**0.66**	-0.38	0.06	-0.02	1.00								
Zn	-0.18	-0.27	-0.19	-0.34	-0.09	-0.05	0.14	-0.10	-0.31	-0.25	1.00							
Na	**0.74**	**0.75**	-0.54	**-0.55**	**0.62**	**0.81**	-0.09	0.13	**-0.57**	**0.70**	-0.11	1.00						
Fe	**-0.81**	**-0.74**	**0.69**	0.52	**-0.95**	**-0.65**	0.28	-0.05	0.06	**-0.86**	0.16	-0.61	1.00					
CEC	**0.88**	**0.75**	**-0.65**	-0.45	**1.00**	**0.73**	-0.22	-0.10	-0.04	**0.92**	-0.10	**0.65**	**-0.94**	1.00				
OC	0.00	0.19	-0.24	-0.34	0.13	0.11	0.06	0.20	-0.26	0.04	-0.17	0.18	-0.26	0.11	1.00			
Clay	**0.71**	**0.66**	**-0.75**	-0.52	**0.92**	**0.80**	-0.02	-0.11	-0.29	**0.75**	0.06	**0.70**	**-0.85**	**0.92**	0.18	1.00		
Sand	-0.51	-0.41	**0.70**	0.28	**-0.77**	-0.54	0.03	0.25	-0.04	-0.54	-0.09	-0.34	0.70	-0.76	0.00	**-0.84**	1.00	
Silt	-0.26	-0.23	-0.12	0.09	-0.05	-0.34	-0.06	0.00	0.36	-0.22	0.04	-0.43	-0.11	-0.08	-0.05	-0.10	-0.29	1.00

Appendix 4b

Table 10. Spearman ranks correlation coefficient matrix for the log-transformed physical and chemical properties (25-50 cm depth).

	pH	EC	P	K	Ca	Mg	Mn	S	Co	B	Zn	Na	Fe	CEC	OC	Clay	Sand	Silt
pH	1.00																	
EC	**0.65**	1.00																
P	-0.12	0.11	1.00															
K	**-0.59**	-0.50	0.38	1.00														
Ca	**0.80**	**0.71**	-0.22	**-0.69**	1.00													
Mg	0.55	**0.59**	-0.41	-0.48	**0.64**	1.00												
Mn	-0.04	-0.19	0.25	-0.14	-0.10	-0.05	1.00											
S	-0.10	0.42	0.21	-0.16	0.04	0.06	-0.17	1.00										
Co	0.07	-0.25	0.16	0.39	-0.03	-0.21	0.02	**-0.69**	1.00									
B	**0.73**	**0.81**	-0.11	**-0.69**	**0.72**	**0.76**	0.03	0.13	-0.20	1.00								
Zn	-0.42	-0.27	-0.14	0.17	-0.32	-0.37	-0.25	0.05	-0.07	-0.24	1.00							
Na	0.56	**0.80**	-0.09	**-0.68**	**0.63**	**0.66**	-0.09	0.43	-0.54	**0.82**	-0.16	1.00						
Fe	**-0.76**	**-0.65**	0.27	**0.80**	**-0.92**	**-0.61**	-0.07	-0.09	0.14	**-0.74**	0.34	**-0.57**	1.00					
CEC	**0.80**	**0.72**	-0.22	**-0.65**	**0.99**	**0.65**	-0.12	0.00	-0.02	**0.71**	-0.33	**0.62**	**-0.90**	1.00				
OC	0.51	0.37	-0.42	**-0.61**	**0.63**	0.38	-0.09	0.02	0.07	0.51	-0.18	0.32	**-0.77**	**0.60**	1.00			
Clay	**0.60**	0.40	-0.56	**-0.55**	**0.59**	**0.81**	0.14	-0.09	-0.17	**0.69**	-0.35	0.50	**-0.67**	**0.58**	**0.58**	1.00		
Sand	**-0.67**	-0.37	0.44	0.53	**-0.68**	**-0.69**	-0.20	0.11	0.15	**-0.64**	0.31	-0.45	**0.73**	**-0.67**	**-0.56**	**-0.92**	1.00	
Silt	0.05	-0.17	0.17	0.18	0.13	-0.25	0.13	-0.25	0.21	-0.24	0.19	-0.25	0.03	0.15	-0.25	-0.25	-0.05	1.00

Appendix 5a

Table 11. PCA of soil chemical and physical properties for the top depth (10-25 cm).

Property	PC1	PC2	PC3
pH	**0.273**	0.187	-0.270
EC	**0.281**	-0.080	**-0.300**
P	-0.230	0.041	-0.240
K	-0.210	0.264	-0.140
Ca	**0.325**	0.125	0.030
Mg	**0.276**	-0.070	0.060
Mn	-0.090	**-0.330**	0.260
S	-0.040	-0.240	**-0.440**
Co	-0.110	**0.549**	-0.060
B	**0.318**	0.014	-0.190
Zn	0.012	-0.250	**0.430**
Na	**0.279**	-0.260	-0.150
Fe	-0.310	-0.200	-0.030
CEC	**0.326**	0.126	0.030
% OC	0.067	-0.260	0.040
Clay	**0.306**	0.005	0.160
Sand	**-0.270**	-0.100	**-0.330**
Silt	-0.030	**0.364**	**0.340**
% Variance	48.5	13	11
Eigen Value	8.7	2.3	2

Appendix 5b

Table 12. PCA of soil chemical and physical properties for the top depth (25-50 cm).

Property	PC1	PC2	PC3
pH	**0.277**	0.126	-0.110
EC	**0.252**	**-0.370**	-0.070
P	-0.110	-0.240	**-0.580**
K	**-0.250**	0.072	-0.270
Ca	**0.324**	-0.040	-0.110
Mg	**0.271**	0.027	-0.130
Mn	-0.010	0.106	**-0.430**
S	0.048	**-0.600**	-0.030
Co	-0.110	**0.353**	**-0.300**
B	**0.327**	-0.070	-0.020
Zn	-0.100	-0.100	**0.408**
Na	**0.298**	-0.230	0.061
Fe	**-0.310**	-0.070	0.035
CEC	**0.325**	-0.040	-0.120
% OC	**0.225**	0.264	0.225
Clay	**0.261**	0.297	-0.050
Sand	**-0.250**	-0.220	0.058
Silt	-0.050	-0.090	-0.180
% Variance	48.6	14	9.8
Eigen Value	8.7	2.5	1.8

Appendix 6a

Table 13. Soil properties by site and depth. Means with same letters in each depth are not significantly different (Tukey-LSD comparisons α: 0.05).

Depth (cm)	Site	K	Fe	Mn	B	Zn	Co	CEC (Meq/100g)
		ppm						
0-10	1	729.25ab	125.00a	337.75a	0.36b	7.85a	2.54a	16.06b
	2	478.25b	51.55b	328.50a	0.91a	7.26a	2.34a	50.67a
	3	803.25a	126.72a	376.00a	0.43b	7.99a	2.56a	20.45b
	4	870.75a	124.82a	356.00a	0.46b	7.18a	2.37a	19.3b
	5	664.50ab	59.90b	326.25a	0.89a	7.73a	2.60a	45.50a
	Mean	709.20	97.60	334.90	0.61	7.61	2.5	30.40
10-25	1	723.50ab	129.62a	338.75a	0.43c	8.32a	2.56a	17.70b
	2	417.25c	56.22b	343.50a	0.92ab	10.60a	2.23b	50.87a
	3	856.75a	131.07a	370.50a	0.56bc	7.12a	2.98a	23.72b
	4	870.50a	128.62a	337.75a	0.67bc	5.50a	2.74ab	23.47b
	5	567.2bc	53.92b	339.25a	1.10a	5.54a	3.00a	52.50a
	Mean	687.00	99.89	345.90	0.74	7.41	2.7	33.66
25-50	1	803.50ab	144.97a	270.50b	0.57b	13.34a	2.74a	24.55b
	2	422.50b	50.30b	360.00a	1.37a	6.44b	2.23a	52.12a
	3	870.50a	125.32a	362.00a	0.84ab	7.28b	2.77a	29.55b
	4	885.50a	116.02a	338.00ab	0.75ab	6.76b	2.70a	32.85b
	5	486.50ab	42.72b	316.75ab	1.32a	7.30b	2.87a	57.17a
	Mean	693.70	95.87	329.40	0.97	8.22	2.7	39.25

Appendix 6b

Table 14. Soil properties by site and depth. Means with same letters in each depth are not significantly different (Tukey-LSD comparisons α: 0.05).

Depth (cm)	Site	P	Ca	Mg	Na	S	EC (μS cm^{-1})
		ppm					
0-10	1	1.17b	3.27b	2.57c	1.50b	0.71ab	1.74b
	2	0.88b	3.91a	2.81a	2.15a	0.57ab	2.20a
	3	1.37b	3.38b	2.66abc	1.67ab	0.44ab	1.83b
	4	1.89a	3.37b	2.65bc	1.73ab	0.81a	1.80b
	5	0.93b	3.83a	2.80ab	2.13a	0.24b	2.32a
	Mean	1.25	3.55	2.70	1.83	0.55	2.00
10-25	1	1.10bc	3.32b	2.59b	1.60a	0.66a	1.71a
	2	0.80c	3.90a	2.84a	2.40a	0.59ab	2.27b
	3	1.27b	3.45b	2.70ab	1.71a	0.36ab	1.83ab
	4	1.94a	3.47b	2.71ab	1.87a	0.76a	1.98ab
	5	0.88bc	3.89a	2.84a	2.40a	0.14b	2.18ab
	Mean	1.20	3.61	2.73	2.00	0.50	2.00
25-50	1	0.69b	3.40c	2.70b	1.90a	0.71ab	1.84a
	2	0.83b	3.91ab	2.83ab	2.58a	0.74ab	2.33a
	3	1.11b	3.54c	2.74ab	2.07a	0.18b	1.91a
	4	1.80a	3.60bc	2.76ab	2.13a	1.60a	2.39a
	5	0.77b	3.96a	2.88a	2.46a	0.06b	2.46a
	Mean	1.04	3.69	2.78	2.23	0.66	2.19

Appendix 7a

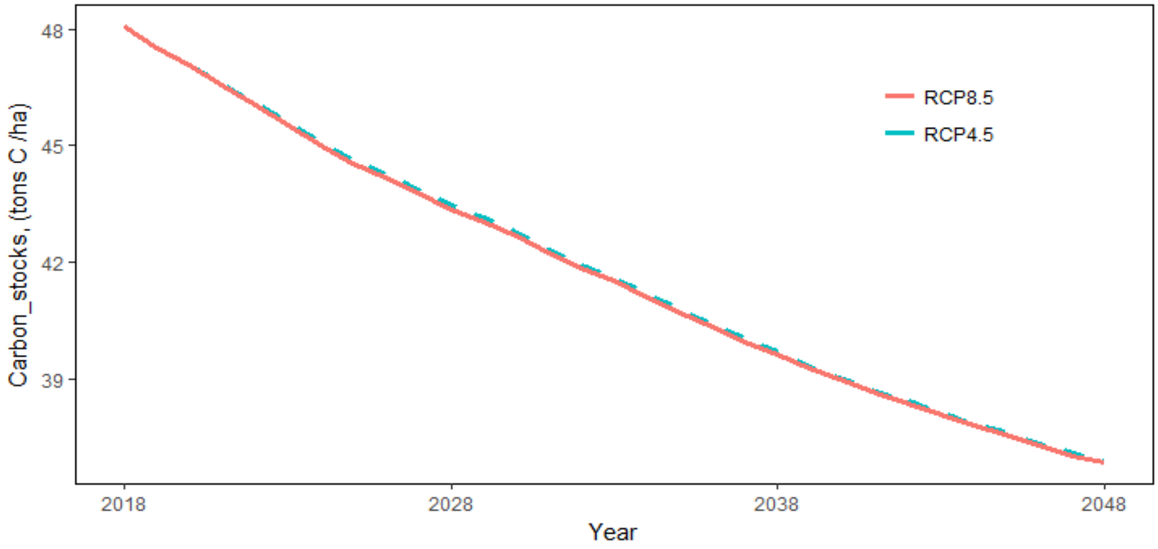

Figure 33. climate change scenarios for a C_3 *crop.*

Appendix 7b

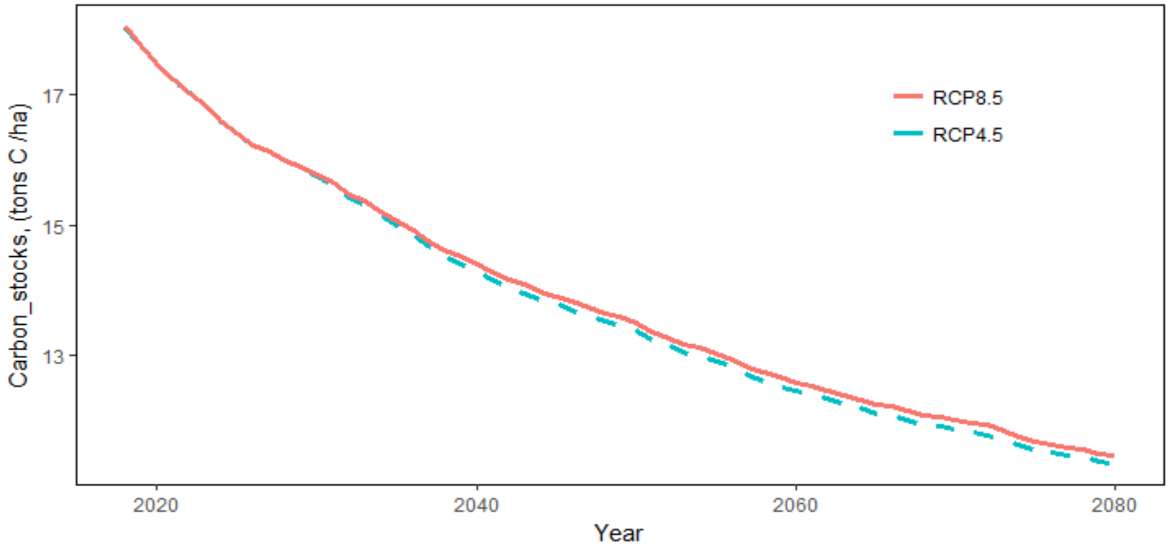

Figure 34. Slow SOC pool (structural and metabolic) under RCP8.5 and RCP4.5 for Kapiti.