Redirection of the carbon cycle by households in a savanna socio-ecological system in rural South Africa

By

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JOHANNESBURG

Academic Supervisor

Professor Wayne Twine

DECLARATION

This thesis is my original research work undertaken towards the Degree of Doctor of Philosophy in Environmental Science, and to the best of my knowledge, contains no material previously published by another person, except where specifically acknowledged within the body of the text. The work has not been submitted for examination elsewhere. For the purposes of consistency, all references cited are formatted to align with the style used for the journal Ecology and Society.

Signed:

Date: 23 April 2021

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DEDICATION

I dedicate this thesis to my late mother meme Klaudia Panduleni Iita-Iiyambo. I am because you were!

ABSTRACT

This study investigated the redirection of the carbon cycle by households in a savanna socio-ecological system in rural South Africa. Through land-based activities such as resource harvesting and agriculture, rural households influence the carbon cycle by co-opting a proportion of annual plant biomass production, referred to as Human Appropriation of Net Primary Production (HANPP). Most HANPP data is at global, continental, or national scales, and there is currently a lack of data at the local level, particularly in rural African savanna settings. Such data are important for understanding context-specific human-environment dynamics, especially in significant and rapidly transforming socio-ecological systems, such as African savannas. This study addresses the above gap by 1) quantifying the mass of carbon redirected annually from the local ecosystem by rural households via key land-based livelihood activities, namely fuelwood harvesting and, livestock foraging, and requesting of carbon from the atmosphere through maize crop production, 2) exploring statistical relationships between household carbon redirection and selected household socio-economic and demographic characteristics, and 3) upscaling carbon redirection to village and landscape scales to assess carbon demand relative to carbon stocks in the local environment in a South African rural socio-ecological system. The study was conducted in the Agincourt Health and Socio-Demographic Surveillance System (AHDSS) study site in Bushbuckridge, South Africa, and used longitudinal household socio-demographic and livelihood data from the SUCSES (Sustainability on Communal Socio-Ecological Systems) household panel study, involving a cohort of 590 households that were surveyed annually from 2010 to 2014.

The annual mass of fuelwood used, cattle and goats owned, and maize produced, were converted into gross and net mass of carbon redirected per household per livelihood activity per year, after accounting for carbon backflows to the environment from these activities, such as in emissions and animal dung. Trends in carbon redirection by households over a five-year period were assessed. Multiple logistic and linear regression models were used to determine the influence of household socio-economic and demographic characteristics on the likelihood of households engaging in specified land-based livelihood activities, and the mass of carbon redirected through these activities, respectively. Total household carbon demand from the local environment was then upscaled to the village level using two methods; the *summed model* method which used statistical models to predict carbon demand for each household in

each of nine villages which were then summed, and the *multiplied mean* method which simply multiplied the mean household level carbon values by the number of households per village. The multiplied mean method was used to calculate annual gross and net carbon demand and carbon backflows to nature for the livelihood activities at the landscape level (420 km^2 and 20 villages) from 2010 – 2014. MODIS NPP (MODerate resolution Imaging Spectroradiometer Net Primary Production) data were used to calculate total available carbon within 1.5 km of each of the nine SUCSES villages and across the entire AHDSS landscape in order to quantify carbon redirected as a proportion of available carbon stocks.

While fuelwood use was the most prevalent of the land-based activities studied, more carbon was redirected from the environment at a household level by cattle and goat ownership. The highest gross redirection of carbon at household level was by cattle, peaking at 10 972 kgC±1 297 per user-household in 2014, while that from fuelwood harvesting was second highest at 1 183 kgC ±1 995 in 2012. Carbon backflows (emissions and animal dung) at household, village and landscape levels were dominated by fuelwood harvesting, followed by cattle farming, while the least came from goat farming and maize production. Household socio-economic and demographic characteristics such as household size and age of the head of household had significant positive associations with the likelihood of households engaging in all land-based livelihood activities and subsequently the carbon redirection associated with these; while others such as proportion female and number of assets owned were positively associated with some livelihood activities (e.g. fuelwood use and proportion female) and negatively with others (e.g. fuelwood use and assets owned). Humans redirected roughly 11% of the total NPP at the village level, while at the landscape level, they redirected approximately 13%. The proportion of NPP redirected in this lived-in landscape increased steadily over the five-year study period.

This study provides new insights regarding the influence of households on the carbon cycle in rural African socio-ecological systems. It fills a gap in the literature concerning HANPP at the household local level and is novel in that it considers carbon backflows to assess net carbon removal from the local environment by rural households. To this end, the data give a new perspective on the sustainability of savanna socio-ecological systems that are important for carbon mitigation policies.

Key words: Household; village; carbon cycle redirection carbon backflows, Human Appropriation of Net Primary Production; socio-economic determinants; village and landscape NPP

DISCLAIMER

This thesis is organized such that the data chapters are written in journal article format. As such, repetition of information in some sections is inevitable.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	DESCRIPTIONS
HANPP	Human Appropriation of Net Primary Production
AHDSS	Agincourt Health and Socio-Demographic Surveillance System
SUCSES	Sustainability on Communal Socio-Ecological Systems
MODIS	MODerate resolution Imaging Spectroradiometer
NPP	Net Primary Production
HANPPluc	Human Appropriation of Net Primary Production land use change
HANPPharv	Human Appropriation of Net Primary Production harvest Pg/yr
SLF	Sustainability Livelihoods Framework
NTFP	Non-Timber Forest Products
MRC	Media Research Council
ESKOM	Electricity Supply Commission
SSA	Sub-Saharan Africa

THESIS STRUCTURE

The thesis structure for this study is shown in **Figure 1.1** below. The thesis comprises six chapters. Chapter 1 is the general introduction, giving the background of the savanna socio-ecological system, and how land-based activities have an impact on the carbon cycle through appropriating NPP. What follows is Chapter 2 which describes the general methodology used in the study, including a description of the study area. This is followed by three data chapters, each addressing one of the project objectives. In Chapter 3, I quantify annual gross and net household carbon removal from the local ecosystem in relation to NPP using detailed data on household natural resource harvesting, crop production, and livestock farming. In Chapter 4, statistical relationships between household carbon redirection and household socio-economic and demographic characteristics are analysed. In Chapter 5, I explore local carbon demand at village and landscape levels by upscaling from the household level using statistical models and detailed household data for entire villages from a health and demographic surveillance systems. Carbon removed at these scales is analysed in relation to available NPP. Chapter 6 presents a general discussion and synthesis of findings from all data chapters, as well as conclusions and recommendations. References are presented in one combined list at the end of the thesis.

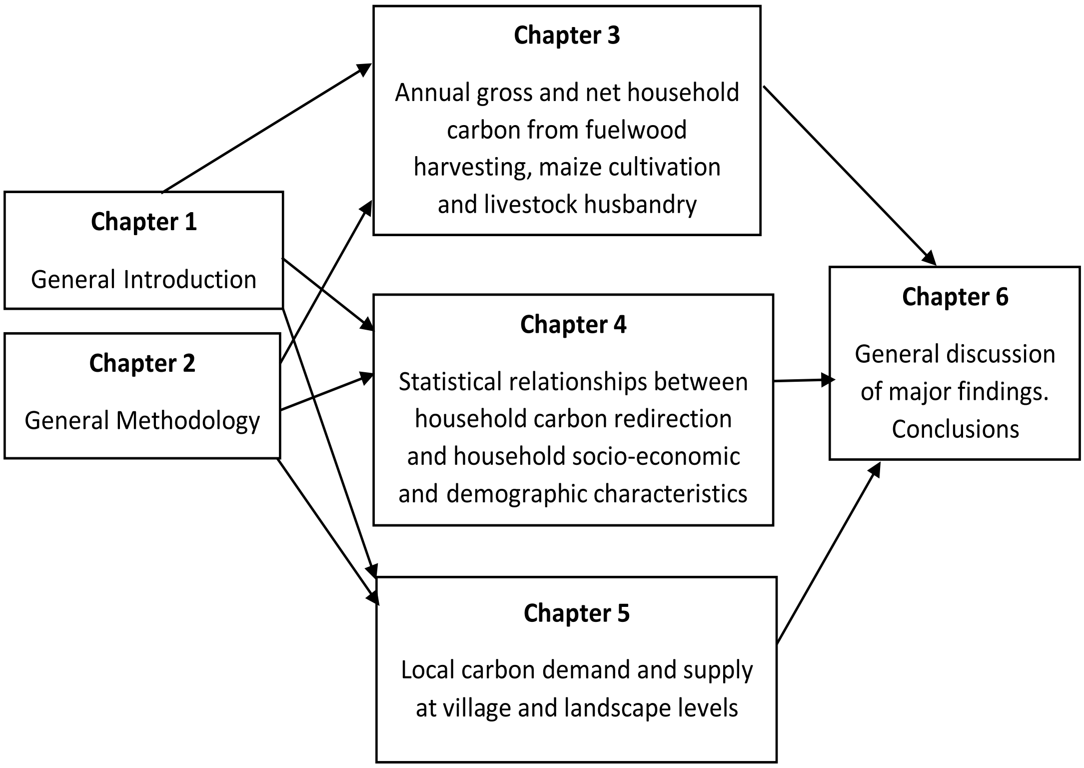


Figure 1.1: Thesis structure

CHAPTER 1

GENERAL INTRODUCTION

1.1 RATIONALE OF THE STUDY

Savannas are the most widespread biome in Africa, covering 15.1 million km^2, or half of the continent (Grace *et al.*, 2006; Woollen *et al*., 2012). They pre-date the evolution of *Homo sapiens,* but have been strongly influenced by human beings, initially through fires and then through agriculture, livestock grazing and the use of natural resources (Ryan *et al*., 2011). The long history of interactions between humans and the natural environment have shaped them into complex socio-ecological systems (Marchant, 2010). The simultaneous occurrence of trees, shrubs and grasses, and the seasonal variations driven by water availability make savannas diverse and dynamic ecosystems (Urbazaev, 2015). As in the rest of the continent, savannas are the most extensive ecozone in southern Africa, and also home to most of the sub-region's wildlife, livestock, as well as human populations (Eriksen and Watson, 2009). In South Africa, savannas are also the largest biome (Shackleton and Shackleton, 2006).

The savanna biome plays a key role in ecosystem services provision and thus sustains livelihoods as well as economic growth in Africa (Eriksen and Watson, 2009). Despite South Africa's economic strength due to its wealth of natural assets, most South Africans live in poverty. Hence, about 9.2 million rural South Africans depend upon the goods and services offered by the savanna biome for their livelihood (Shackleton *et al.*, 2007). For example, 90% of rural households in South Africa are still dependent on fuelwood as their dominant energy, with as much as 93% of current fuelwood demand being harvested as live wood (Wessels *et al.*, 2010; Matsika *et al*., 2013). Also, livestock farming remains one of the most important land-based source of livelihood for many households in rural South Africa (Scholtz *et al.*, 2013). Land-based activities supplement various formal and informal cash sources among rural South African households (Dovie *et al.*, 2003). Fuelwood harvesting as an example of direct use of savanna resources, and livestock farming as an indirect use of these resources by humans, shape the composition, structure, and functioning of savannas (Marchant, 2010).

Through these land-based activities, rural households have an influence on the savanna carbon cycle by co-opting a proportion of Net Primary Production (NPP), referred to as Human Appropriation of Net Primary Production (HANPP) (Pritchard *et al.*, 2018). NPP entails the amount of atmospheric carbon fixed during photosynthesis and accumulated as biomass, and it represents available carbon in the form of plant material consumed as food, fuel and feed (Abdi *et al.*, 2014).

Although the African continent's role in the global carbon cycle is now recognised, human influence on the carbon cycle in Africa remains under-studied (Ciais *et al.*, 2011). The pressure on savanna resources by humans continues, through among others, cattle grazing, goat grazing/browsing, crop production and resource extraction, which are associated with high population densities. Savannas have been, to some extent, ignored in relation to the global carbon cycle, and carbon inventories have more frequently been focusing on forests (Grace *et al.*, 2006). This is because sufficient long-term observations of the savanna ecosystem has not yet taken place which has led to uncertainties of their carbon budget and its projected changes (Berger et *al.*, 2019). Also, there is a lack of data on African carbon budget which makes the numerical models of the carbon cycle highly uncertain when it comes to Africa (Bombelli *et al.,* 2009). Thus, it is essential to monitor carbon fluxes and pool sizes in order to track anthropogenic climate change and predict future human-carbon-climate system trajectories in Africa (Scholes *et al.*, 2009). In turn, climatic systems are also important as they influence the provision of ecosystem services to rural livelihoods.

Increasingly, savanna lands have been put under intensive use through cattle grazing, agricultural activities and resources extraction, leading to environmental risks such as the over-extraction of fuelwood (Grace *et al.*, 2006). As such, there is a need to quantify household carbon redirection from the local ecosystem to inform carbon management of savanna ecosystems. It is equally essential to supplement this with an understanding of drivers of carbon removal and release rates that occur as a result of household land-based activities in order to deepen the understanding of human-environmental relationships. Such data are lacking at the household level in Africa.

The influence of key rural livelihood activities on the carbon cycle in a savanna socio-ecological system is analysed in this study. The livelihood activities under this study – fuelwood harvesting, cattle and goat farming, and crop production – are considered significant in appropriating NPP and redirecting the release of carbon as they are key land-based livelihood activities among rural communal households across sub-Saharan Africa. This study provides quantification of human carbon redirection via HANPP, using a bottom-up approach since it analyses carbon redirection through the land-based activities mentioned above first at household level, then village, and finally landscape levels in a communal socio-ecological system. Importantly, unlike most HANPP studies which only focus on removal of biomass by humans, this study also considers carbon returned to the atmosphere as emissions or the soil as animal dung, termed "backflows" here. This knowledge is crucial to predict feedback between ecosystem response to unceasing pressure to disturbances such as land-use change on one hand and atmospheric greenhouse gas concentrations, which influence climatic systems, on the other (Science Partnerships for the Assessment of Complex Earth System Processes, 2014).

1.2 LITERATURE REVIEW

1.2.1 The global carbon cycle

Carbon, which is a basic building block of life on earth, is captured by ecosystems through photosynthesis (Dellasala, 2018). Thus, the carbon balance of terrestrial ecosystems is the result of the balance between carbon uptake by photosynthesis and the release by respiration by plants, animals and soil organisms (Grace, 2004) . The terrestrial carbon cycle encompasses the exchange of carbon among the terrestrial biosphere, geosphere, and atmosphere of the earth (Xiao *et al.*, 2019). The carbon dioxide (CO_2) that makes up a small but crucially important part of the atmosphere is part of a huge planetary cycle where carbon circulates between the atmosphere, the oceans and the terrestrial systems (Post *et al.* 1990). Carbon is cycled at various levels of biological organisation such as living organisms to ecosystems to the global carbon budget where carbon sinks are those that store or sequester atmospheric carbon, while sources are emitters of CO_2 (Dellasala, 2018). There are concerning uncertainties with regard to terrestrial ecosystems to act as either a net source or sink of carbon in estimates of present and future global carbon budget and its role in climatic dynamics of the earth (Pugh *et al.*, 2016). Since the measurements of the atmospheric concentration of CO_2 in 1958, the size of the atmospheric carbon reservoir (which is crucial to the carbon cycle together with the terrestrial reservoir) has been rapidly increasing since then

(Post et al., 1990) . As part of the carbon cycle, most biological and human activities are driven by the biochemical transformation of carbon through CO_2 uptake and energy fixation in organic compounds through photosynthesis, and by the subsequent oxidation of organic compounds and release of energy and CO_2 through respiration as indicated in **Figure 1.2** (Scholes and Walker, 1993).

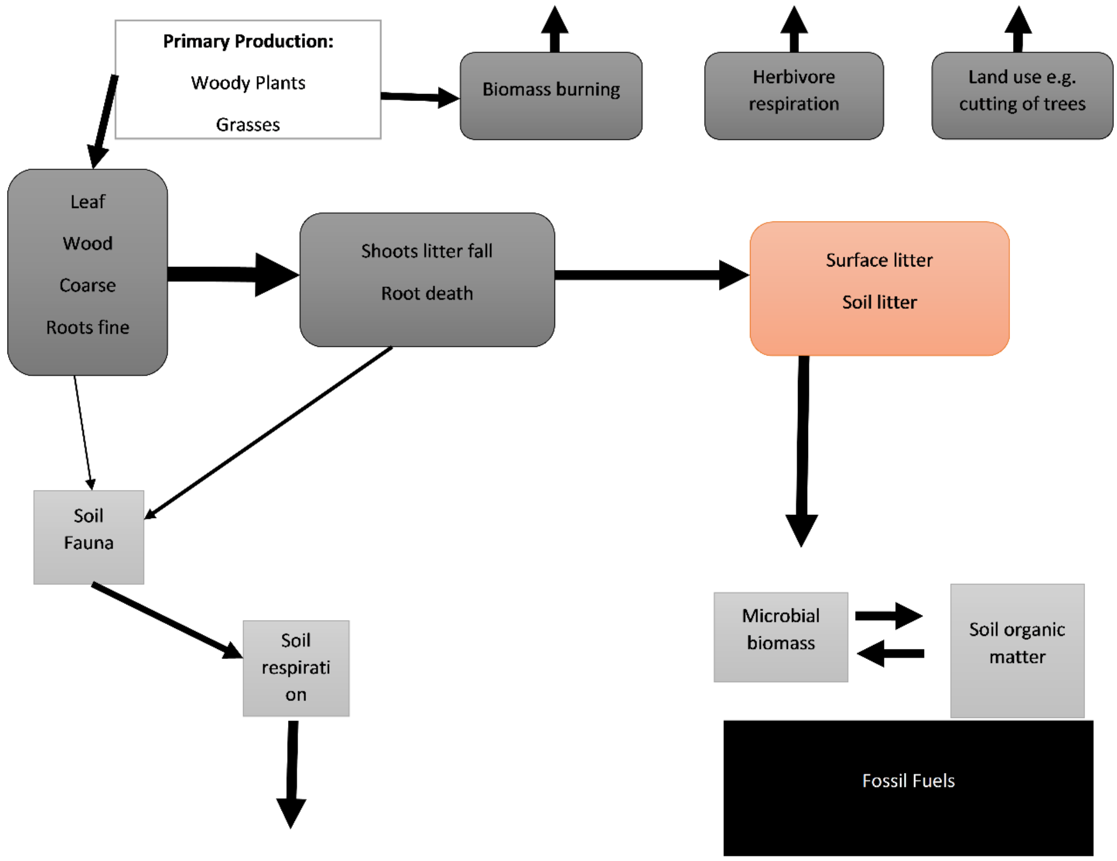


Figure 1.2: The savanna carbon cycle (Source: Scholes and Walker, 1993)

Nearly 50% of the earth's land surface is used by humans and 23% of NPP for agriculture and domestic animal grazing (Luo and Weng, 2011). Over the past 200 years, the global carbon cycle has been altered significantly by human activities, such as land use change which plays a key part in the carbon source/sink dynamics (Falkowski *et al.*, 2000). Changes in land cover and land use impact on the greenhouse gas emissions and sinks, and on social carbon pools. These are global phenomenon that have the potential to affect a wide range of activities and functions (Tomlinson *et al.*, 2018). The growing pressure to increase fibre and food production in the developing world through the conversion of forests and savannas for agricultural use, upsurges the flux of carbon to the atmosphere while at the same time reducing the land area available for active carbon sinks (Falkowski *et al.*, 2007). Hence, monitoring the variability of primary production is crucial because NPP provides vital services for human survival (Khalifa *et al.*, 2018).

Of all disturbances, land use remains the most significant as it affects the carbon cycle through its associated continuous changes (Luo and Weng, 2011). For instance, the introduction of agriculture that involves cultivation, has had major impacts on carbon pools and fluxes in large regions of the world (Cole, 1993). Another example is that, when the cutting down of trees occurs, fuelwood is burned and this carbon goes to the atmosphere where it becomes a greenhouse gas pollutant (Dellasalla, 2018). As a result of the uptake of global CO_2 by terrestrial ecosystems, a substantial amount of anthropogenic CO_2 emissions is removed from the atmosphere on an annual basis (Pugh et al. 2016). Disturbances destabilise the carbon cycle by either depleting or adding carbon in pools and sinks by carbon residence times through respiration and decomposition changes (Luo and Weng, 2011). Thus, disturbances are critical ecosystem processes that influence carbon cycle dynamics (Xiao *et al.*, 2019).

The CO_2 concentration has increased in the atmosphere from nearly 277 parts per million (ppm) to 407 ppm between 1750 and 2018 (Friedlingstein *et al.*, 2019). The removal of vegetation as well as the burning of biomass are some of the activities responsible for a substantial transfer of carbon to the atmosphere (Grace, 2004). To that end, owing to present trends in energy demands, a lack of global, resolute, alternative energy production strategies, and human population growth projections, concentrations of atmospheric CO_2 appear destined to increase throughout the coming century (Falkowski *et al.*, 2000). The anthropogenic CO_2 terrestrial sink is approximately 30% of emissions, but its sensitivity to inter-annual climate variations has implications for the long-term land carbon sink (Butterfield *et al*., 2020). The switch to low-carbon energy sources and optimisation of carbon stores in ecosystems for instance have the potential to avoid climate variability (Dellasala, 2018).

The above indicates that human activities have had effects on each major biogeochemical cycle, but the effects of these impacts on the interactions between these elemental cycles are poorly understood (Falkowski *et al.*, 2000). Therefore, quantifying land use activities accurately is of key importance in understanding the effects of land use change and implementation of climate change mitigation policies (Tomlinson *et al.*, 2018). This explains why global CO_2 emissions and sinks estimations are a major effort by the carbon cycle research community, it thus requires a careful compilation and synthesis of measurements, statistical estimates, and model results (Friedlingstein *et al.*, 2019). A better understanding of the terrestrial carbon cycle has important implications for climate projections (Xiao *et al.*, 2019).

1.2.2 Human Appropriation of Net Primary Production (HANPP)

Ecological structures and processes are changed by societies through the use of land for the optimisation of goods and services provided by ecosystems (Niedertscheider *et al.*, 2012). Human population numbers and per capita consumption of ecosystem services such as food, fibre, shelter, and to an extent biomass-derived energy, are estimated to have increased over the decades (Haberl *et al.*, 2007). On top of that, humans, with all other heterotrophic organisms compete for a share of NPP as their source of trophic energy (Krausmann *et al.*, 2012). As such, their consumption of NPP has significant implications both in terms of its proportion relative to planetary NPP and its impact on a wide range of ecological and biophysical processes (Imhoff and Bounoua, 2006). Thus, there are concerns that humanity is already outside its safe operating space and it is believed to be near other critical limits such as land use or biomass production of green plants (Krausmann *et al.*, 2013). This indicates that human activities are having unprecedented influence on the global land system (Pritchard *et al.*, 2018).

There is a dynamic and complex interaction between factors such as socio-economic drivers, pressures, ecological state changes, and impacts, that has motivated scholars to appeal for not only integrated, but also interdisciplinary perspectives for studying various aspects of land system and change over time (Niedertscheider *et al.*, 2012). The human domination of the earth's ecosystems has led to the re-conceptualisation of humans as integral components and engineers of the global biosphere and the need for original integrated approaches, breaking down historic barriers between natural and social science, to have a better understanding of the drivers and consequences of land use change (Pritchard *et al.*, 2018). HANPP is an indicator of the extent to which humans interfere in the productivity of terrestrial ecosystems by appropriating a fraction of NPP for their own use (Haberl *et al.*, 2014). HANPP focuses on the annual flow of biomass and represents a key component of the global socio-economic energy system (Niedertscheider *et al.*, 2012). Thus, HANPP has recently gained attention as an indicator capable of linking natural systems to socio-ecological conditions, which is a major goal for sustainability science (Krausmann *et al.*, 2012).

The difference between the NPP of the potential natural vegetation and the vegetation that is predominant as a result of land use at a particular point in time is referred to as $HANPP_{luc}$ (Kastner *et al*., 2016). HANPPluc is thus the modification of NPP, also measured as annual carbon flow resulting from land use change caused by humans (Krausmann *et al.*, 2013). On the other hand, the actual activities associated with land use that harvest biomass for human use reflected as the quantity of carbon in biomass harvested is called $HANPP_{harv}$ (Krausmann *et al.*, 2013). Most HANPP studies sum these two components of HANPP (Temper, 2016).

Changes in HANPP over time, attributed to population density, food consumption, livestock farming, agricultural intensity, and deforestation and forest management, have been a major focus on HANPP research for more than a decade (Haberl *et al.*, 2014). Global HANPP is estimated to be 31% of the total amount of NPP generated on land, and human biomass use at a global level including crops, by-products, grazing by livestock, fibre consumption, and forestry products amounted to about 12 Pg/yr in the year 2000 (Imhoff *et al.*, 2004; Krausmann *et al.*, 2012). To understand the influence better, the conversion of natural ecosystems into croplands globally, has resulted in a NPP reduction of 23% as far as their natural NPP is concerned (Niedertscheider *et al.*, 2016). Through its dependence and feedback on socio-economic conditions, ecosystem function, and climate, the portion of the earth's NPP supporting human activities occupies a key position in the carbon cycle (Imhoff and Bounoua, 2006). The terrestrial carbon cycle plays a critical role in global climate change and thus in the consequent development of related international treaties; which has heightened the need for accurate assessments of terrestrial carbon stores at landscape levels (Woollen *et al*., 2012).

1.2.3 HANPP and land-based activities in African savannas

The African continent, inhabited by roughly 13% of the world population and constituting 22% of the global terrestrial surface, is facing multidimensional challenges, with characteristics of high population growth, a severe lack of food, inferior agricultural performance, poverty, and inappropriate land management and land degradation (Fetzel *et al*., 2016). The African savannas in particular have been modified by human activities such as grazing and harvesting of wood (Räsänen *et al.*, 2017). Savanna ecosystems offer goods and services to humankind such as food, and less tangible commodities such as carbon storage and regulation of the carbon cycle and the moderating flows of energy and water (Marchant, 2010). Thus, land use intensification research in sub-Saharan Africa has been of particular interest recently because HANPP has increased more steeply in Africa over the last century than on any other continent, although staple crop yields remain below potential levels (Pritchard *et al.*, 2018). African rural subsistence livelihoods are concentrated on crop production, livestock rearing, and collecting of wild-sourced resources such as fuelwood, which are directly linked and highly sensitive to changes in ecosystem properties (Pritchard *et al.*, 2018). As such, NPP appropriated from the local environment plays an important role in the provision of food security and household energy in sub-Saharan Africa (Abdi *et al.*, 2014).

The high density of humans in mixed land use areas, often under communal tenure, is responsible for high levels of HANPP in the savanna regions (Imhoff *et al.*, 2004). In general, Africa has witnessed the steepest increase in HANPP over the last century (Krausmann *et al.*, 2013); and because of its unique history and its dependence on natural resources and a future that will include substantial industrial, agricultural and social development, Africa will become a key player in the carbon cycle of the 21st century (Williams *et al.*, 2007). There are noticeable key processes of change affecting the sustainability of Africa's savannas such as livelihood transformation and changing variability of farming (Eriksen and Watson, 2009). Therefore, with its high variability of rainfall, the fact that it is sensitive to natural and anthropogenic pressures and future climate, there is a need for continued and enhanced observations of Africa's carbon stocks (Williams *et al.*, 2007). This is because Africa, which is dominated by the largest area of savanna ecosystems in the world, is considered a main source of uncertainty in the global terrestrial carbon cycles due to a lack of intensive studies on this continent (Jin *et al.*, 2013).

In general, anthropogenic activities such as the conversion of natural to agricultural ecosystems are said to lead to the depletion of the terrestrial carbon pool and enrichment of the atmospheric carbon pool (Lal, 2004). Particularly, clearance for subsistence agriculture is widespread across Africa, and is the major anthropogenic influence on the African carbon cycle (Ryan, 2009). Currently, knowledge of Africa's carbon pools is limited in spite of its importance in the global carbon budget, especially through fire and land use change (Ryan, 2009; Woollen *et al.*, 2012). Therefore, directing human efforts toward atmospheric CO_2 stabilisation requires detailed knowledge regarding both the natural fluxes and human perturbations of the carbon cycle (Scholes *et al.*, 2009).

Thus, quantifying ecosystem carbon stocks brings us closer to understanding the relationships between changes in the land-use and CO_2 emissions (Ryan *et al.,* 2011). To consolidate that understanding appropriately, the ecosystem's NPP which is helpful in describing ecosystems needs to be quantified (Scholes *et al.*, 2009). Whether approached on the basis of 'bottom-up' livelihoods and development perspectives or 'top-down' global change and conservation perspectives, understanding of the processes and impacts of land use intensification in sub-Saharan Africa is a research priority (Pritchard *et al.*, 2018). Similarly, Williams *et al.*, (2007) also identified a need for continent-wide observations that are in support of both bottom-up and top-down methods of estimating carbon sources and sinks. In addition, a predictive knowledge of the relationships between land-use practices, the composition, structure and function of vegetation, and the supply of ecosystem services is required (Higgins *et al.* 1999). Land-use and land-use change emissions from Africa are likely to be underestimated because of widespread livestock farming, shifting cultivation, and domestic fuelwood harvesting across the continent which are often assumed to be inconsequential (Williams *et al.*, 2007). Estimations indicate that 20% of the global NPP comes from Africa (Ciais *et al.*, 2011). It is estimated that the net carbon release from land use in sub-Saharan Africa is 0.4 Pg C/yr , while fuelwood collection appropriate is about 2% of NPP from the African savanna biome (Stringer *et al.*, 2012).

1.2.4 Sustainable Livelihoods Framework

Households appropriate NPP and influence the carbon cycle through their livelihood activities. A livelihood can be defined as the assets (capital) and activities or strategies used by a household to secure the necessities for making a living (Carney, 1998; DFID, 2000). The Sustainable Livelihoods Framework (SLF) is a useful conceptual framework for understanding and assessing how households, particularly the poor, make a living in a holistic and integrated manner (DFID, 2000) (**Figure 1.3**). The framework recognizes five livelihood capitals, namely financial (income, savings, insurance), physical (equipment, appliances, infrastructure), human (number, age, gender, and education levels of household members), social (social relations and networks) and natural (land, water, biodiversity) capital (DFID, 2000). In the context of HANPP, the NPP generated by the local ecosystem is a component of natural capital available to rural households.

To make a living, households engage in a portfolio of livelihood activities that draw on or build these various capitals. Rural households typically engage in land-based livelihood activities that depend on natural capital, such as harvesting of natural resources, livestock farming, and crop production, as well as off-farm activities such as entrepreneurial activities and employment (Babulo *et al.*, 2008; Ragie *et al.*, 2020). Households' choice of livelihood strategies, including level of dependence on natural capital to meet day-to-day needs and to cope with crises, vary across households, depending on their characteristics, access to capitals, and their experience of livelihood shocks and stresses (Babulo *et al.*, 2008; Tibesigwa *et al.*, 2016; Mbiba *et al*., 2019). The capitals available to households and the strategies they use, together determine livelihood outcomes, such as food security, and environmental sustainability, which in turn, reshape the capitals available to the household. Livelihoods are deemed sustainable when the household can cope with and recover from stresses and shocks and maintain or enhance assets, without eroding local natural capital (Carney, 1998). Policies, institutions and processes are recognized in the framework as being important in influencing the relationship between livelihood capital and activities, such as by regulating natural resource use.

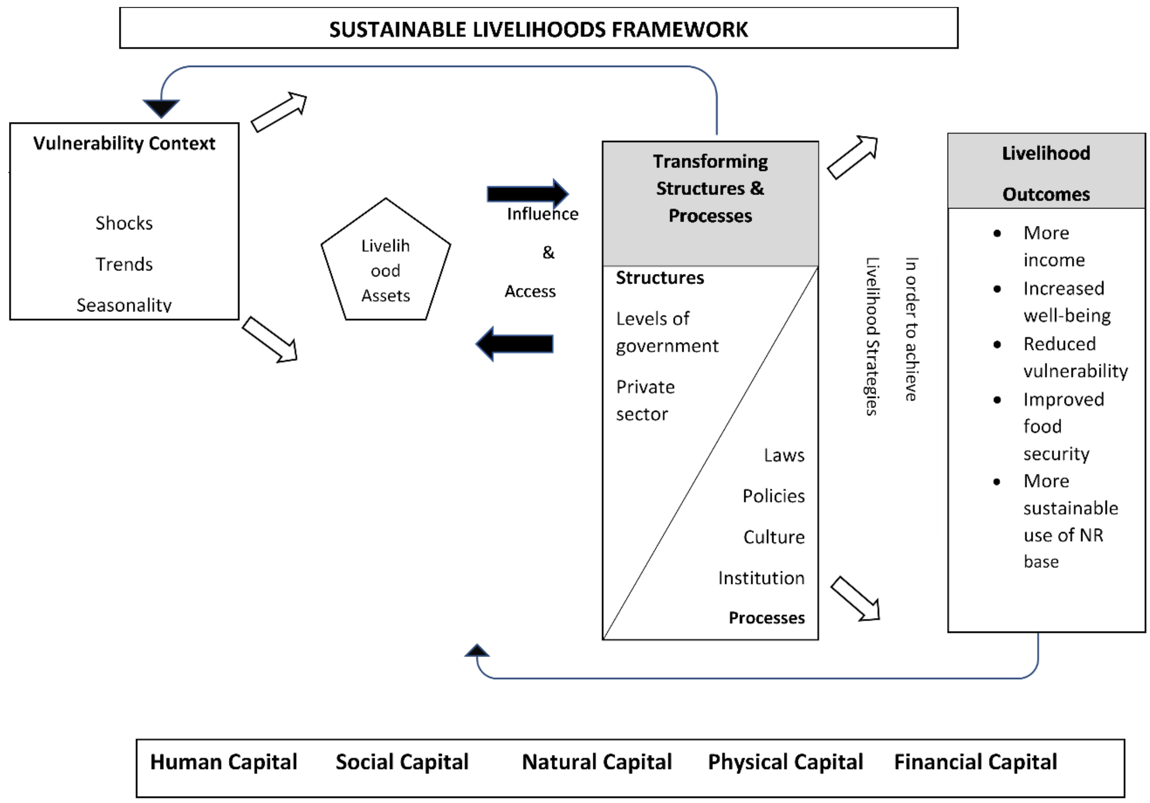


Figure 1.3: Sustainable Livelihoods Framework (Source: DFID, 2000)

1.2.5 South African savanna socio-ecological systems

1.2.5.1 Land-based livelihoods

Southern African savanna communal lands support nearly 80% of rural populations, many of whom live below the poverty line, and studies indicate that land and natural resources within communal systems play a substantial role in the livelihoods and household economies of rural people (Wessels *et al.,* 2013; Shackleton *et al.,* 2000). In South Africa, the apartheid era saw large-scale relocation of black populations into Bantustans (homelands) which resulted in high population densities, limited household access to other forms of livelihood capital, and a continued dependency on a limited and declining natural resource base (Shackleton *et al.*, 2002; Findlay and Twine, 2018). These areas, which were created as reserves in which the majority of the black population was forced to reside, constitute 13% of the total land in South Africa (Bennett and Barrett, 2007). Historically, chiefs and their headmen, controlled access to natural resources in South African communal land; however, the traditional authorities have become increasingly weakened and marginalised in resource management (Twine, 2005).

Rural livelihoods in South Africa, characterised by a diverse portfolio of activities for enhancing household income, food security, health, social networks and savings, are complex and dynamic (Shackleton *et al.,* 2001). Among these households, few are entirely removed from the natural resource economy and most harvest and process various woodland resources for both household consumption and trade (Shackleton *et al.*, 2002). In the savannas, rural communities are provided with a great variety of resources from natural vegetation such as fuelwood, poles for construction, poles for fences and animal pens, wood for carving utensils, edible fruit, bark and roots for traditional medicine and leaves for livestock fodder among others (Twine, 2005). The most commonly used non-timber forest products (NTFP) among rural households in South Africa are indigenous wood for fuel and fencing (70-100%), wild fruits (72-100%), wild herbs (93-100%), medicinal plants (50-100%), wood for utility items (90-100%), and grazing for livestock (30%) (Shackleton *et al.,* 2001). In South Africa's savannas, communities use up to 200-300 plant species on a regular basis (Shackleton and Shackleton, 2004). Thus, a large number of rural households still depend on natural resources for their basic living requirements (Shackleton et al. 2001). The South African landscape in general has been exposed to human land use through grazing by domestic livestock, cropland, and unsustainable resource harvesting land-use practices, which put pressure on the intactness of the prevalent savanna ecosystem (Niedertscheider *et al.,* 2012). Hence, land-based livelihood strategies are clearly more important than is usually recognised, especially in direct provisioning and as part of the rural safety net (Shackleton *et al.,* 2001).

1.2.5.2 Fuelwood harvesting

Fuelwood continues to be the main energy source for most rural households in Africa (Kaschula *et al.,* 2005). Fuelwood is an important consideration for the carbon cycle because it is the main driver of the removal of wood biomass from the savanna ecosystem, which is a major store of carbon (Bartels et al. 2016). The burning of fuelwood is also a source of carbon emissions which, although understudied, are likely to be small in comparison to other emission sources in savannas, such as vegetation fires. Fuelwood, occupies an enviable place for providing many people, especially the poor and rural households, with a primary source of energy, being used for heating, cooking and lighting purposes (Dovie *et al.,* 2004). Although the majority (2.4 million) of rural households have access to electricity in South Africa (Pereira *et al.*, 2011), 54% are still using wood as their main source of energy (Madubansi and Shackleton 2007)). Mean annual per capita consumption of fuelwood in rural South Africa ranges from 491 kg to 1 173 kg, which translates to 3-4 tonnes of fuelwood per household per annum in the communal areas of South Africa (Shackleton and Shackleton, 2004). The fuelwood is usually collected from village commons by women, either in bundles on their heads or in wheelbarrows (Twine, 2005).

While fuelwood is a renewable resource, population growth, development activities, and over-utilisation poses a challenge to the sustainability of fuelwood resources (Vasicek and Gaugris, 2014). The widespread use of fuelwood for instance is linked to a number of environmental problems such as deforestation, biodiversity loss, climate change and land degradation (Madubansi and Shackleton, 2007). Unsustainable harvesting of fuelwood causes changes in woodland biomass and fuelwood quality, negatively impacting human well-being, as well as social and economic capital (Wessels *et al.*, 2013). Research conducted in Bushbuckridge, South Africa, indicates that the availability of local fuelwood has decreased in recent years, evidenced by decreases in overall tree density, higher proportions of mature tree stems chopped and reduced availability of preferred fuelwood species (Findlay and Twine, 2018). If harvested within sustainable limits, fuelwood could continue to supplement rural energy requirements and represent a valuable renewable energy source (Wessels *et al.*, 2013). This is more so in light of the fact that except for very high harvesting levels, savannas are resilient and relatively stable, largely due to re-sprouting (Tredennick and Hanan, 2015; Twine and Holdo, 2016).

1.2.5.3 Livestock husbandry

Low input, small-scale livestock husbandry remains a primary land use option in communal areas of Southern Africa (Dovie *et al.,* 2006). This livelihood activity has relevance for the carbon cycle since NPP is appropriated as biomass grazed and browsed by from the natural vegetation (Bartels *et al.*, 2016). Stocking rates in the former-homeland areas are typically double the recommended rates (Hoffman and Ashwell, 2001) and are thus probably much higher than historical densities of indigenous herbivores. Over-stocking is blamed for the widespread rangeland degradation and severe soil erosion observed in the communal areas (Wessels *et al.*, 2007). In rural South Africa, nearly 30% of rural households in the former homelands possess cattle and approximately 60% own goats (Shackleton *et al.,* 2001). Rural households depend on cattle for manure, fuel and floor polish in traditional dwellings, and draught power to cultivate crops and for transportation of goods in communal areas. Among some rural communities, cattle are also used for spiritual practices such as in connection with and exorcism of spirits (Musemwa *et al.,* 2008), and for sacrificial offerings to appease avenging spirits; culturally, they are also used for strengthening relationships with in-laws and for maintaining family contacts by entrusting them to other family members (Haag and Hadju, 2005). Also, cattle are a source of employment, and collateral and insurance against natural calamities (Musemwa *et al.*, 2008). With regard to goats, they have a number of uses too such as to maintain social bonds such as the payment of dowry (lobola), exchange with relatives, ceremonies, provide an income, and for meat and milk (Braker *et al.,* 2002). Although only a minority of households own cattle, the benefits are broadly distributed through among others bride wealth payments, loaning of animals, cooperative ploughing arrangements, meat and milk sharing, and selling of goods and services (Shackleton *et al.,* 2001). In a study in Bushbuckridge, most cattle-owning households had between 6-20 head of cattle (Giannecchini *et al.*, 2007).

1.2.5.4. Crop production

Traditionally, small-scale crop production has always been the backbone of rural livelihoods and a primary strategy in the alleviation of poverty and food insecurity in South Africa (Dovie *et al.,* 2003). Through agriculture, NPP is appropriated through biomass harvesting on cropland, which is a process of redirecting the carbon cycle. This is in addition to the initial removal of NPP by clearing the indigenous vegetation for cropland. The cultivation of crops in South African rural villages involves two major foci: the homestead food garden and larger arable fields beyond the village (Shackleton *et al.,* 2001). The production system comprises agroforestry and inter-cropping that involves the use of different crops, including varieties of fruit trees, around which the staple cereal crop (maize or sorghum) is planted (Shackleton *et al.*, 2002). At least 93% of farming households do so mainly to produce food for their own consumption; access to arable land is therefore important as a rural safety net (Shackleton *et al.,* 2001). Communal woodlands are continuously being transformed for subsistence cultivation around growing human settlements and there is concern that these areas may be over-utilised to the point of the ecosystem not being able to sustain services for subsistence livelihoods (Wessels *et al.*, 2010). The expansion of cultivated lands in South Africa between 2001 – 2010 represents one of the main drivers of landscape change as far as percent change in area is concerned (Department of Environmental Affairs, 2016).

1.2.5.5 Communal resource governance

Land tenure in the former-homelands of South Africa, as in most rural areas across Africa, is communal. As stated earlier, black South Africans were resettled in newly formed villages in "homelands" starting in the 1950's, with each village allocated common property roughly 500 – 1 000 hectares (Kirkland *et al.*, 2007). South Africa is no exception to the general observation where changes in the political landscape have resulted in impacts on local resource control which in turn have been linked to reports on unsustainable use of resources such as fuelwood (Findlay and Twine, 2018). Hoffmann and Todd (2000) give an overview of South African communal land governance as follows: in some areas, traditional authorities are the custodians of land and determine how it is managed; in others, control of the land is in the hands of democratically elected institutions; yet in others, there is conflict between traditional authorities and democratically elected institutions on who should manage the resources; while in other areas, there a situation close to 'open access' because all management authority has broken down.

Decline in respect for traditional authorities by community members, as a result of social and political transitions, has resulted in a breakdown in the management of communal woodlands by traditional authorities in many parts of South Africa (Kirkland et al., 2007). Thus, a shift to advocate for a more active role in the management of natural resource by local users is necessary (Campbell and Shackleton, 2001). However, Shackleton *et al.* (2002) indicate that tenure reforms that give power of land to chiefs with a history of corruption and abuse of authority will undermine natural resource-based livelihood activities of the rural poor and promote the capture of key resources by local elites. In addition, there is an emerging phenomenon of plunder and theft of rural resources by outsiders which in the end undermines the rights of local resources and the rule of law operation in supporting these rights (Shackleton *et al.,* 2001).

In light of the above, there is concern about environmental degradation of the communal woodlands in the former homeland districts (Kirkland *et al*., 2007). For example, the use of natural resources and general human disturbance have significantly impacted on the vegetation in communal savannas resulting in changes in species demography and land-cover, invasion of alien plant species and vegetation homogenisation (Twine, 2005). The communal areas are thus characterised by high human and livestock populations, overgrazing, soil erosion, excessive wood removal and the loss of more palatable grazing species, and are therefore broadly regarded as degraded (Wessels *et al.*, 2007). There is a strong sense that rangeland degradation is a serious problem, and this urgently needs attention in communal areas (Hoffmann and Todd, 2000). The contemporary land degradation in South Africa suggests that a number of inappropriate decisions have been made on land issues in the past, and if these mistakes are not to be exaggerated or repeated in the future, then ecologically sound practice should not be compromised for political expedience (Meadows and Hoffman, 2002).

1.3. AIMS AND OBJECTIVES

1.3.1 Aim

The aim of this study is to quantify the redirection of the carbon cycle by rural households in a savanna socio-ecological system in rural South Africa.

1.3.2 Objectives

a) To quantify annual gross and net household carbon removal from the local ecosystem.
b) To determine statistical relationships between household carbon redirection and household socio-economic and demographic characteristics.
c) To determine local carbon demand relative to carbon supply at village and landscape levels by up-scaling from the household level.

CHAPTER 2

DESCRIPTION OF STUDY AREA AND METHODOLOGY

2.1 STUDY AREA

2.1.1 General description

The study was conducted in the study site of Agincourt Health and Socio-Democratic Surveillance System (AHDSS) operated by the University of the Witwatersrand and the Medical Research Council, spanning 20 villages in Bushbuckridge Local Municipality, Ehlanzeni District, in the Mpumalanga Province of South Africa. The Bushbuckridge Local Municipality, which covers an area of 2 417 km^2, is located at 31^{o}00' - 35^{o}31'S; 24^{o}30' - 25^{o}00'E, and lies between the Drakensberg escarpment in the west and the Kruger National Park in the east (Shackleton *et al.,* 2004). Under the apartheid system, Bushbuckridge was part of the former Bantustan (homeland) districts of Mhala in Gazankulu and Mapulaneng in Lebowa. It became a single rural municipality after the democratic change in 1994 (Giannecchini *et al.*, 2007). The municipality, which consists of 65 settlements varying in size from fewer than 500 households to over 2000, has a high population density with an average of 150 – 350 people per square kilometre (Shackleton *et al.,* 2004; Pollard 2003). Apartheid land allocation policies and the large influx of refugees from Mozambique in the 1980s are responsible for these high population densities (Shackleton *et al.*, 2002).

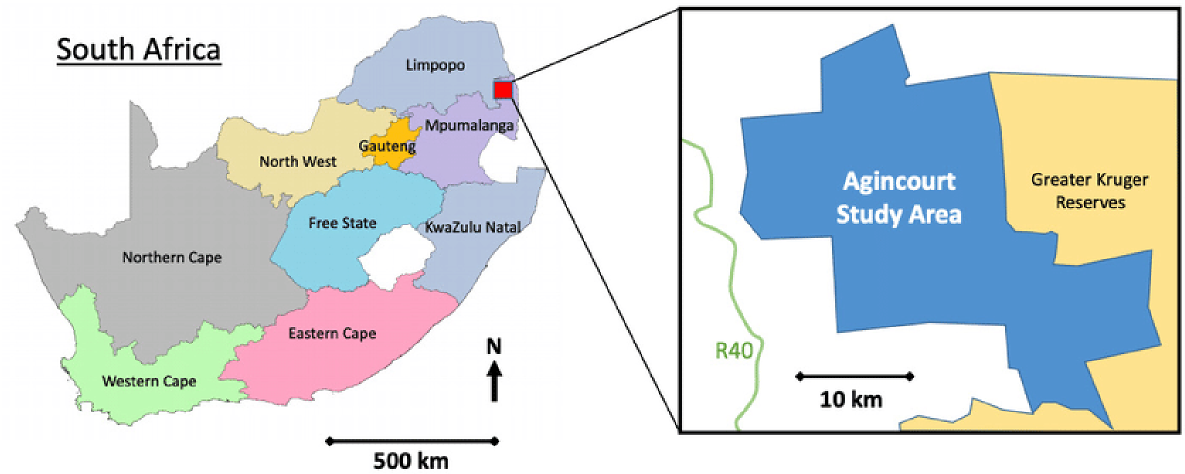


Figure 2.1: Map of the Agincourt Health and Socio-Demographic Surveillance Systems site (Source: Wariri *et al.,* 2017).

2.1.2 Climate, topography and vegetation

The Bushbuckridge region has a subtropical climate, with hot, humid summers and cool dry winters, with summer rainfall mostly falling between October and April (Giannecchini *et al.*, 2007; Coetzer *et al.,* 2010). Rainfall varies from 800 mm per year in the west to 500 mm per year in the east (Giannecchini *et al.*, 2007). Mean annual temperature is approximately 22^{o}C and increases from southwest to northeast (Madubansi and Shackleton, 2007).

The topography is gently undulating with a slowly decreasing terrain height toward the east, with an average height above sea level of 450 m (Wessels *et al.*, 2010). The underlying geology is characterised by Basement Complex geological strata of the Bandelierkop Complex, typified by nutrient-poor potassic granites, granodiorites, and Timbavati gabbro intrusions (Kaschula *et al.,* 2005) (Kaschula *et al.,* 2005; Fisher *et al.,* 2011). The most extensive soil types are shallow sandy lithosols, and nutrient-poor except towards the base of the landscape catenas where deep duplex soils are common. Closer to the escarpment, deep, apedal soils prevail (Kaschula *et al.,* 2005).

Bushbuckridge region is part of the savanna biome (Fisher *et al.*, 2011). The indigenous vegetation is characterised by a mixture of trees, shrubs and grasses (Madubansi and Shackleton, 2007). There are three specific vegetation types, namely, granite lowveld which is dominant, gabbro grassy bushveld and Legogote sour bushveld. Typical species in the granite lowveld include *Terminalia sericea, Combetrum zeyheri* and *C. apiculatum* on the deep sandy uplands, while *Acacia nigrescens, Dichrostachys cinerea* and *Grewia bicolor* (Venter *et al.,* 2003) grow in the more clay-rich lowland soils. In the two other vegetation types, additional common species include *Sclerocarya birrea, Lannea schweinfurthii, Ziziphus mucronata, Dalbergia melanoxylon, Peltophorum africanum,* and *Pterocarpus rotundifolius* (Rutherford *et al.*, 2006)

2.1.3 Land use

Most of the land in Bushbuckridge is used as communal rangelands (64.7%), followed by plantation forestry (10.8%), dry-land arable agriculture (6.6%), irrigated-arable agriculture (2.2%), and residential and nature conservation at 2.8% and 12.9%, respectively (Dovie *et al.,* 2004). Boundaries of village communal lands are defined by the original boundaries of the farms upon which the settlements were established, and consist of a residential area, arable fields and communal woodlands (Matsika *et al.,* 2013). The communal land is used by village residents for cultivation, grazing of livestock, and harvesting of a wide range of non-timber forest products (Matsika *et al.,* 2013). Land utilisation tends to be higher closer to the villages (Fisher et al., 2011). Nearly all households cultivate small plots with rain-fed crops such as maize, around the homestead and 30 – 40% of households also cultivate larger demarcated arable fields on the boundary of the village or further afield (Shackleton *et al.*, 2002; Wessels *et al.*, 2010). Residents are allowed free access for grazing livestock (Fisher *et al.*, 2009).

As is the case in all former homelands, the land tenure in the region is communal, and the land falls under the authority of traditional authorities who determine local land use patterns (Matsika *et al.,* 2013). Historically and culturally, the harvesting of live trees for medicine, as well as fruit and culturally important trees was prevented. However, the demand for fuelwood and timber now outweighs these values as they have no alternatives in the face of high electricity prices and localised shortages of fuelwood (Fisher *et al.*, 2015). Although chiefs are regarded as the ultimate authorities for regulating firewood harvesting, overall fuelwood management appears weak across the region (Findlay and Twine, 2018). In general, the emergence of modern institutional structures has not had as much impact on the perceived functional roles of traditional authorities in natural resource management as expected (Findlay and Twine, 2018).

2.1.4 Socio-economic context

Subsistence agriculture is widely practiced, but unlike rural areas across the rest of the sub-Saharan Africa, this is not the backbone of livelihoods, with shortages of land being a key factor (Matsika *et al.,* 2013). A large proportion of adults (50% males and 14% of people between the ages of 30 and 49 years) are migrant labourers because of limited employment opportunities in the formal sector (Hunter *et al.,* 2011). Thus, the region is highly dependent on remittances, in addition to elderly residents' state pension (Wessels *et al.*, 2010). As a result, households engage in diverse informal activities in support of their livelihoods, that includes crop production in arable fields and home-gardens, livestock farming, collection of natural resources (e.g. fuelwood, thatch grass, medicinal plants), casual work, migrant labour, and small-scale enterprises (Madubansi and Shackleton, 2007). Mean household size is six to seven members (Madubansi and Shackleton, 2007). Although most villages are now electrified, dependence on fuelwood remains high, with more than 90% of all connected households using fuelwood to meet their thermal needs (Matsika *et al.,* 2013).

2.2 GENERAL METHODS

This chapter presents the study design and methods used that are common to all data chapters. The method sections of the data chapters give more detail and describe methods specific to those chapters.

2.2.1 APPROACH OF THE STUDY

This study fell under work package 5 of the multi-institutional 'Adaptive Resilience of southern African Ecosystems' (Ars Africae) research project which focused on quantifying the impact of disturbances on the exchange of greenhouse gases between savanna ecosystems and the atmosphere. The Ars Africae study followed a functional approach based on quantifying ecosystem services as 'natural capital' (Science Partnerships for the Assessment of Complex Earth System Processes, 2014). To this end, this study focused on land-based activities that are part of the savanna ecosystem services of fuelwood harvesting, maize cultivation, and cattle and goat farming as indicated in **Figures 2.2 and 2.3** respectively. The study used a bottom-up approach which started with analysing the redirection of the carbon cycle at the household level based on the afore-mentioned livelihood activities, which was aggregated to the village and landscape levels. Gross and net carbon redirected by these activities are analysed. Gross carbon entailed the amount of carbon in harvested wood, maize cultivated, and biomass consumed by livestock. To determine net carbon redirected, the mass of carbon returned as "backflows to nature", such as emissions, was subtracted from the gross mass of carbon redirected from these activities.

The redirection of the carbon cycle through fuelwood harvesting entailed the removal of the wood from the ecosystem, and the subsequent burning of the wood which results in the release of CO_2, methane (CH_4), carbon monoxide (CO), and non-methane hydrocarbons (NMHC) into the atmosphere. Carbon from burnt wood is returned to the soil in ash, although this is usually in a rubbish tip in the homestead yard, rather than being a backflow to the surrounding environment. Likewise, through livestock grazing, the carbon cycle is redirected through the removal of grass and tree leaves from the rangeland by cattle and goats. Through livestock respiration, CO_2 is emitted and through livestock digestion, methane is emitted into the atmosphere and carbon is returned to the soil in the form of livestock dung. Lastly, maize cultivation activity redirects the carbon cycle through the removal of maize crops during harvesting which ultimately result into carbon loss from the system. All these activities are considered as disturbances to the savanna socio-ecological system.

A deeper understanding of the functional consequences of ecosystem changes caused by the above-mentioned disturbances was targeted by this approach. The study thus analyses land-based livelihood activities and how they influence the carbon cycle of the savanna ecosystem by appropriating NPP through the processes of biomass removal and the release of greenhouse gases at the household and landscape levels. It further investigates relationships between land-based activities and household socio-economic and demographic characteristics.

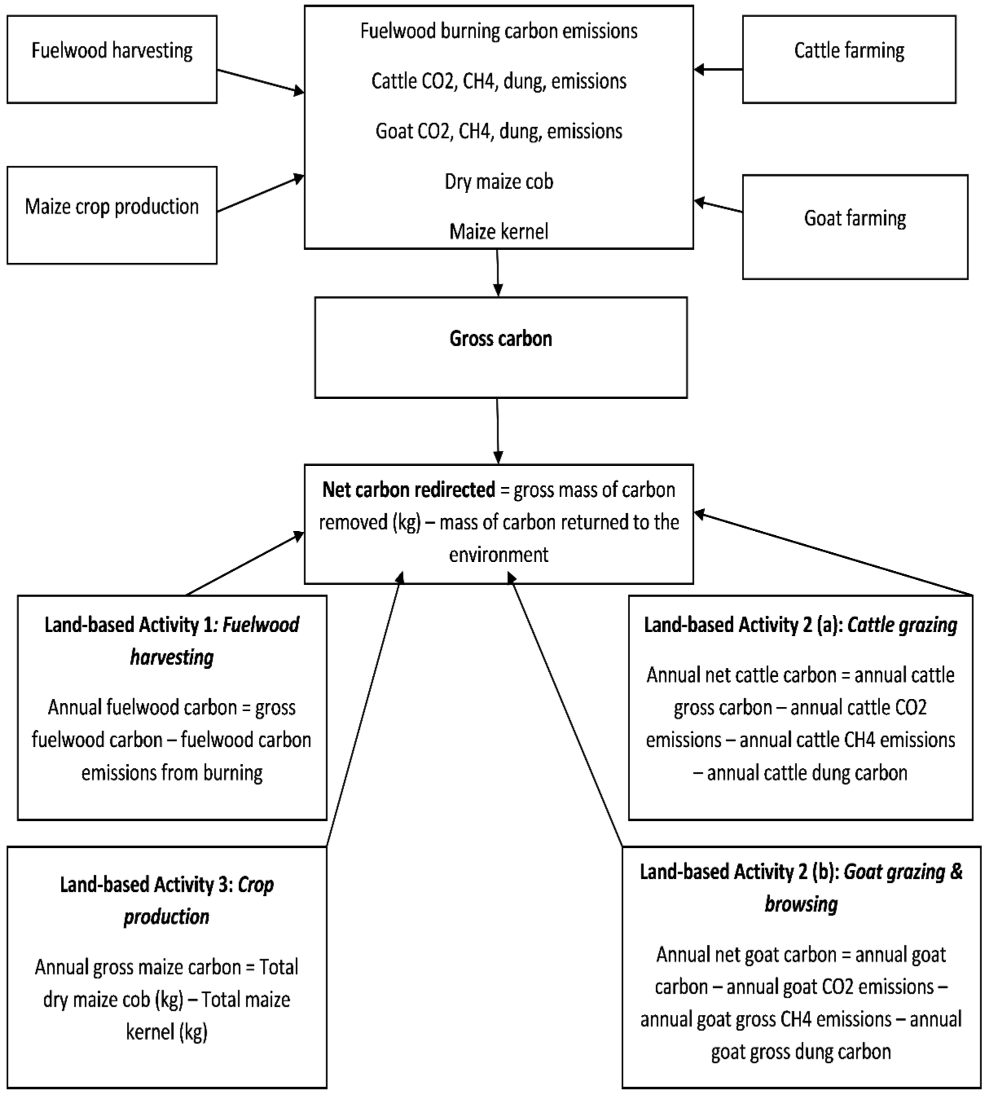


Figure 2.2: Conceptual model of carbon pools and fluxes of land-based livelihood activities of the savanna socio-ecological system – fuelwood harvesting; livestock husbandry; and crop production.

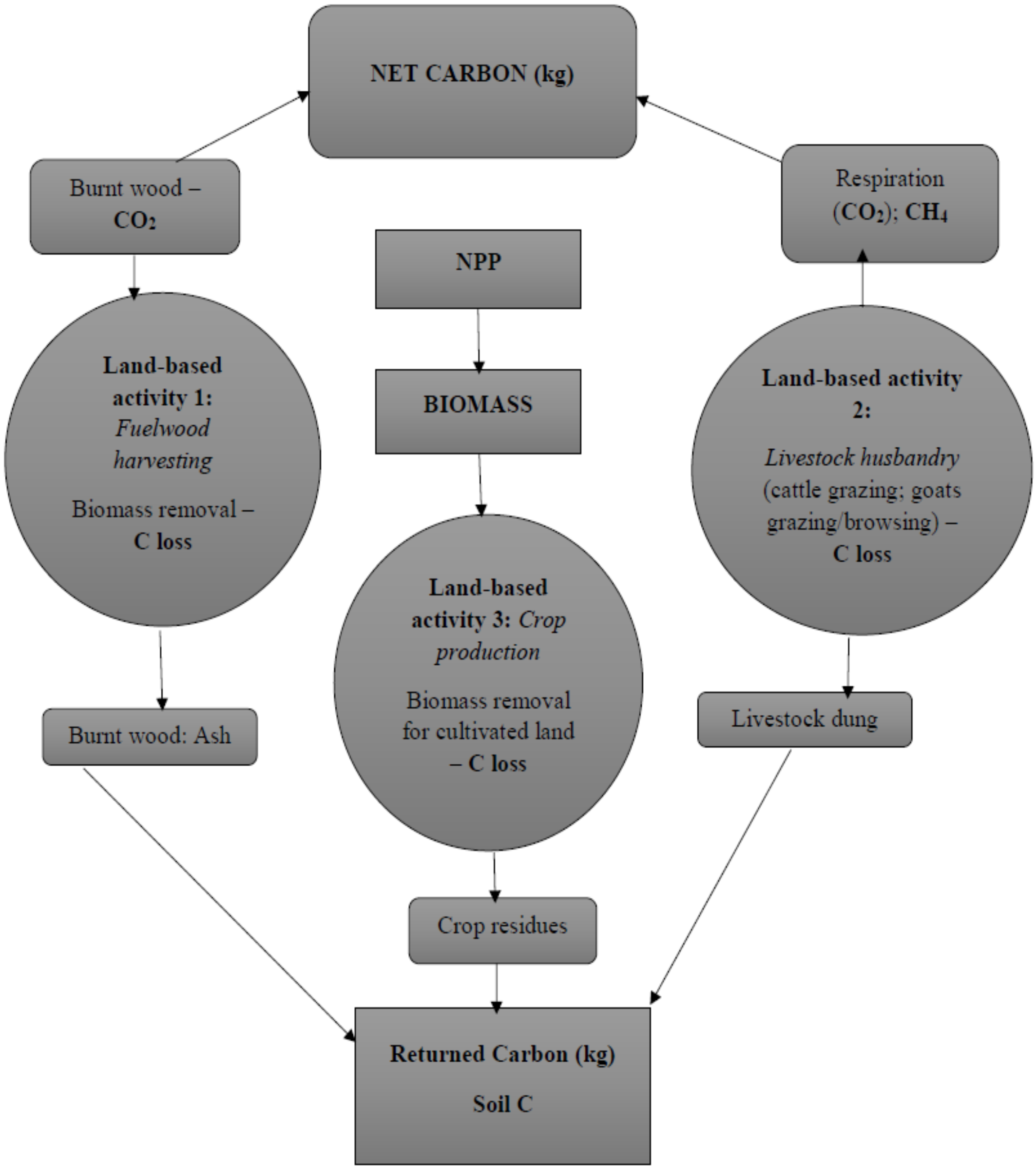


Figure 2.3: The carbon flow diagram of land-based livelihood activities of this study

2.2.2 Study design

This study focused on the redirection of the carbon cycle by rural households in a savanna socio-ecological system in Bushbuckridge. For this purpose, the study used data from the Sustainability in Communal Socio-Ecological Systems (SUCSES) research project which is nested in the Agincourt Health and Socio-Demographic Surveillance System (AHDSS) of the MRC (Media Research Council)/Wits Rural Public Health and Health Transitions research unit. SUCSES is a longitudinal household study with the aim of gaining a deeper understanding of the dynamic interactions between people, their livelihoods, and the natural environment in rural communities, with particular emphasis on the consequences of these interactions on ecological sustainability. The present study used the existing SUCSES household panel data set obtained through an in-depth survey of 590 households repeated annually over a 5-year period from 2010 to 2014.

The SUCSES cohort of households was derived from a random stratified sample of 600 households representing an 8% sample of the households drawn from a subset of nine villages. These selected villages span a west-east rainfall gradient in the AHDSS study site, divided into three rainfall zones: >700 mm/year, 700 – 600 mm/year, <600 mm/year. The villages were selected to represent the range of settlement sizes per rainfall zone as indicated by **Table 2.1** below. Accounting for households that had either refused to participate or had dissolved by the time of the survey, 590 of the selected households were interviewed.

Table 2.1: Sample of study villages in the Bushbuckridge area and their rainfall zones

Village names	Rainfall zone
Xanthia, Agincourt & Cunningmore B	>700 mm/year
Kildare, Ireagh A & Ireagh B	600 – 700 mm/year
Justicia, Lillydale B & Huntington	<600 mm/year

2.2.3 Data collection

Data were collected through a structured questionnaire in a survey conducted yearly from 2010 to 2014. The interviews were conducted by experienced local fieldworkers in the

Shangaan language but the questionnaires were filled in English. The interview was conducted with the person responsible for over-seeing day-to-day activities such as resource collection, cooking, and shopping in the household. The questionnaire was divided into four sections, namely: 1) livelihood capital (human capital and income generation; financial capital); 2) livelihood activities (use of natural resources, livestock farming, crop production); 3) livelihood shocks and stresses (negative shocks, positive shocks); 4) livelihood outcomes (food and nutrition security). Of relevance to present study the livelihood section of the questionnaire included questions on firewood use, ownership of cattle and goats, and maize production by households. This study focused on cattle and goats which are the most widely owned livestock that feed in the rangeland in Bushbuckridge (Ragie *et al.*, 2020). These were the principal land-based activities that were the focus of this study used to assess the redirection of carbon from the surrounding environment.

The study also focused on household characteristics influencing the land-based activities, namely, household size, gender of the household members, age of the head of the household, and the number of assets owned by households. These variables were derived from household demographic and asset data collection. Such socio-economic variables have been shown to influence natural resource dependence of households in similar settings (Dovie *et al.,* 2004; Shackleton and Shackleton, 2006; Giannecchini *et al.*, 2007). Proportional number of females in the household was calculated as a variable to express the gender composition, and number of assets were aggregated to represent wealth status of households. Not all households in sub-Saharan African rural households can afford assets such as electrical/gas stove, TV, satellite dish, cellular phones, sewing machines, cars, tractors, ploughs, etc. Thus, the affordability and ownership of these assets differentiates one household from the other economically. The number of assets a household owns were aggregated to represent the wealth status of a household. With all demographic household characteristics mentioned above, statistical relationships were established between them and land-based activities in this study.

2.2.4 Carbon calculations

The data on maize cultivation, fuelwood harvesting, and cattle and goat ownership were all derived from the livelihood activities section of the questionnaire. Data on crop production were provided when households were asked if they planted any crop or not, from which maize was one of the options. Information was also collected on the total amount of maize harvested per year and the corresponding volume unit to that amount. Household fuelwood consumption profiles were determined through data relating to whether households used fuelwood or not, total amount of fuelwood used in a month, the corresponding volume unit to the amount used, and the number of months in a year fuelwood was used. Household cattle and goat ownership profiles were derived from data concerning whether households owned cattle and goats or not; and how many they owned per year. Land-based livelihood and related livelihood data were averaged across both user-households and all households in the sample. User-households referred to households that were either involved in the production of maize, in the use of firewood, or in the ownership of cattle and goats, respectively.

In order to calculate the gross and net mass of carbon redirected by the livelihood activities, biomass of the edible maize consumed, firewood used, and forage consumed by livestock were first calculated. Based on these consumption figures, gross carbon was calculated based on the carbon content of maize ears, wood and grass and browse forage. Net carbon redirected was calculated by subtracting the mass of carbon returned to the environment (e.g. as gaseous emission from combustion, respiration, or as dung) from gross carbon mass following Eq. (1).

$$C_n = C_m - C_r \quad (1)$$

Where Cn represents the net carbon redirected (kg), C_m gross mass of carbon (kg) harvested/consumed and C_r mass (kg) of carbon returned to the environment, either to the atmosphere or the soil.

2.2.4.1 Fuelwood harvesting

Fuelwood consumed in kilograms per household per year, proportional percentage of carbon in wood, and harvest season factor were calculated to derive annual gross carbon from fuelwood. Annual fuelwood carbon emission factors were calculated and subtracted from annual gross carbon to determine annual net carbon from fuelwood consumption. Fuelwood was measured in kilograms; households described amounts used in headloads, wheelbarrows, or pick-up truck loads. The weight of a headload was determined to be 14.5 kg, the weight of the wheelbarrow load 39.6 kg and the weight of the pick-up truck 532 kg (Twine *et al.*, 2003). In order to determine the amount of firewood collected by each household per year, fuelwood used per month was totalled. It is generally recognized that 35% more of wood are used by households per month in winter compared to that in summer (Matsika *et al.,* 2013). Then this percentage was incorporated in the final formula. Since the SUCSES study was conducted from April late to mid-June of each year from 2010 to 2014, annual fuelwood consumption *(AFC)* was reflective of the cool dry season ***(Eq. 2, Appendix 1).***

To determine annual gross fuelwood carbon *(CF_g)* redirected by a household (kg), annual fuelwood consumption (kg) was halved because the carbon content of wood is approximately 50% ***(Eq. 3, Appendix 1)*** (Niedertscheider, 2011; Bartels, 2014).

To account for the amount of carbon released in the atmosphere as wood is burned, Brocard and Eva (1998) assert that there are 400 g of carbon in the form of CO_2, 30 g of carbon in the form of carbon monoxide, 1.5 g of carbon in the form of methane, and 2.5 g of carbon in the form of non-methane hydrocarbons (NMHC), in 1 000 g of savanna fuelwood burned. These highlighted amounts were converted into kilograms to give a total of 0.434 kg as a carbon emission factor *(CEF)* ***(Eq. 4, Appendix 1).*** Subsequently, the annual net fuelwood carbon *(CF_n)* ***(Eq. 5, Appendix 1)*** was arrived at by subtracting firewood carbon emissions from gross fuelwood carbon harvested. Net carbon appropriated by the use of fuelwood essentially equates to the solid carbon remaining after burning in the form of ash.

2.2.4.2 Cattle ownership

In order to account for gross mass of carbon appropriated from the herbaceous vegetation by cattle owned by households, daily matter intake (DMI) by cattle had to be determined per household owning cattle. Factors included in the calculations were sex, weight and growth stage of cattle and the percentage of carbon grass dry matter consumed by cattle. Carbon backflows to the environment in the form of greenhouse gasses (GHG) and dung were subtracted from the gross carbon intake to calculate net carbon redirected permanently out of the system by humans. This methodology therefore describes the steps involved in arriving at annual cattle gross and net carbon redirection: followed by the calculation of annual cattle gross carbon consumption per household, then the calculation of annual cattle carbon dioxide (CO_2) emissions per household, the calculation of annual cattle methane (CH_4) emissions per household, the calculation of carbon in dung and finally the calculation of annual cattle net carbon redirection.

DMI in cattle was estimated by Smith et al. (2006) for cattle in Ethiopia to be between 68 and 95 g DM per kg $M^{0.75}$ where 0.75 represents the exponent of which body weight should be raised. The average of the two highlighted masses (80.5 g) was used in this study. However, Meissner (2014) specify that the exponent to which body weight should be raised when intakes of animal species are compared across forage qualities should be between 0.75 and 1.0. The Smith *et al.*, (2006) methodology was considered appropriate for this study because of the similarities in climatic conditions that exist between the two places of study (Ethiopia and Bushbuckridge, South Africa). Their study was conducted under African traditional grazing systems, which is similar to grazing conditions of Bushbuckridge. Additionally, the amount of rainfall (736 mm) received in the southern central highlands of Ethiopia where the study took place, is about the same amount of rainfall received in Bushbuckridge. Therefore, the quality of forage and digestion of cattle in the two places are potentially comparable.

According to Adamovics *et al.*, (2018), grass biomass contains 45% of carbon. Hence, herbaceous plants consumed by cattle in this study were considered to have 45% of carbon. The first stage of analysing carbon redirected through cattle farming involved determining the sex, growth stage and weight of cattle. Such data were not available for the households in this study dataset, so gender and age proportions from published data for the region had to be applied to the herds owned by households as follows: cows (60%), calves (21%), and bulls (19%) (Shackleton *et al.*, 2005). As is common among subsistence farmers in Southern African rural communities, the main cattle breed reared in these communities is the indigenous Nguni breed. An average Nguni cow weights 352 kg, a bull weights 390 kg (Scholtz *et al.*, 2008); and a weaning Nguni calf weights 164 kg according to Lepen (1993).

At the outset, DMI (kg), metabolic weight, and carbon percentage of herbaceous vegetation per animal were calculated ***(Eq. 6, Appendix 2).*** To apportion how carbon is redirected according to the sex, weight, and growth stage of cattle per household per day, the following values was obtained after calculation: 1.7 kg/calf + 2.9 kg/cow + 3.1/bull per household per day. These quantities were further multiplied by the number of cattle and then the proportional percentage of each cattle group, to determine first daily gross carbon, then annual gross carbon from cattle per household. To that end, daily carbon consumption in cattle per household *(DCCC, kg*) was calculated ***(Eq. 7, Appendix 2).***

The cattle annual gross carbon consumption *(CC_g)* was obtained by multiplying the daily carbon consumption by 365, which represents the number of days in year. Cattle emit carbon dioxide through respiration. They also emit methane as a by-product of digestion in the rumen. In this study, only cows and bulls' carbon dioxide and methane emissions are considered, and they constitute 79% of the cattle population. According to McGinn *et al.* (2014) an adult cow or bull respires 4.2 kg of carbon dioxide per day. Carbon dioxide consists of 27.3% of carbon, which translates to 1.15 kg of carbon per adult cattle per day (McGinn *et al.*, 2014). This means, one adult cattle emits 420 kg of carbon per year through carbon dioxide emissions. Cattle in developing countries emit 35 kg of methane per animal, which is lower than cattle in developed countries because the latter's diet is in most cases supplemented with extra feed (Kinsman *et al.,* 1995). Since methane consists of 75% of carbon, each adult cattle emits 26 kg of carbon per year through methane emissions. Parsons and Rowarth (2009) assert that 25% of carbon consumed is returned to the ecosystem by livestock through their dung. As a result, the annual gross carbon for this study was multiplied by 0.25 to account for the returned carbon from cattle dung (CC_d) ***(Eq. 10, Appendix 2).*** Accordingly, cattle annual carbon dioxide emission per household *(CC_c, kg)* was calculated ***(Eq. 8, Appendix 2).*** Cattle annual methane emissions *(CC_m kg)* was also calculated ***(Eq. 9, Appendix 2).*** Net carbon from cattle *(CC_n, kg)* was then arrived at by subtracting carbon from carbon dioxide emissions, carbon from methane emissions, and annual cattle dung carbon *(ACDC),* from annual gross carbon redirection from cattle ***(Eq. 11, Appendix 2).*** Net cattle carbon is the carbon stored as animal biomass that is eventually either eaten or sold by the user households.

2.2.4.3 Goat ownership

To determine the redirection of carbon through goat farming, the following needed to be analysed: the browse-grazing ratio of goats, daily matter intake in goats, carbon dioxide and methane emissions from goats, and carbon from goats' dung. Similar to the cattle study, the goat breed type under this study was also indigenous. The proportional population of goats according to their sex and growth stage, in this study as assumed based on literature comprises of ewes (64%), kids (18%), and rams (18%) (Shackleton *et al.*, 2005).

Goats, unlike other livestock species, alternate between browse and herbaceous plant species in their diet (Bakare and Chimonyo, 2011). To this end, Nyamangara and Ndlovu (2019) indicated that goats that are raised on savanna vegetation browse for 52% of their feeding time and spent the rest (48%) of the time grazing. Thus, the browsing-grazing ratio of the Nguni goats in this study was considered as 52/48. However, Nyamangara and Ndlovu (2019) further state that 47% of leaves in savanna vegetation are made up of carbon. While Ma *et al.* (2018) assert that the amount of carbon in savanna herbaceous plants is 45%. Accordingly, this study analysed the goat diet of browsing species as having 47% of carbon, and herbaceous plants as having 45%.

DMI in indigenous goats is 49 g per kg $BW^{0.75}$, which was calculated for all the goats in this study including the amount of carbon found in the feed ***(Eq. 12, Appendix 3)***. The exponent to which body weight should be raised when intakes of animal species are compared across forage qualities, should be between 0.75 and 1.0 (Meissner, 2014). Thus, the body weights of goats were raised to 0.75 exponent in this study. The respective weight of goats of different sex and age are as follow, female kid (14.6 kg); male kid (18.6 kg); ewe (26.5 kg); and ram (40 kg) as found by (Snyman, 2012).

Daily carbon intake per female goat kid, male goat kid, ewe, and ram was arrived at by calculating DMI daily matter intake, daily matter intake in leaves, the amount of carbon in leaves, daily matter intake in grass and the amount of carbon in grass. Daily carbon in female and male kids was combined to give a total of 0.1 kgC from kids; daily carbon consumption in ewe was 0.3 kgC; and rams had a daily carbon consumption of 0.4 kgC. The daily carbon intake per kid, ewe, and ram were combined with the proportional representative of kids, ewe, and rams in the goat population to come up with the daily carbon consumption *(DCCG)* in goats per household ***(Eq. 13, Appendix 3)***.

An adult goat emits 162 kg of carbon per year through carbon dioxide emissions (Vichairattanatragul *et al.,* 2015). This amount came to 44 kg per adult goat per year when the 27% of carbon in carbon dioxide emissions was factored into the equation. The amount of carbon redirected through carbon dioxide emissions was multiplied by the proportional percentage of adult goats in the goat population. Kinsman *et al.* (1995) assert that an adult goat emits 5 kg of methane per year. Methane is made up of 75% of carbon and when applied, this translated to 4 kg of carbon redirected by each adult goat through methane emissions per year. Carbon redirected by each adult goat through methane emissions was multiplied by the proportional percentage of adult goats (82%) in the goat population. As with cattle, it was assumed that 25% of the carbon consumed by goats was returned to the environment as dung (Parsons and Rowarth, 2009). Annual carbon dioxide emissions *(CG_c, kg),* annual methane emissions *(CG_m, kg),* and annual carbon dung *(CG_d, kg)* from goats were then calculated ***(Eq. 14; Eq. 15; Eq. 16, Appendix 3).***

At the end, annual net carbon redirected by goats *(CG_n)* was arrived at by subtracting annual carbon dioxide emissions, annual methane emissions, and annual carbon dung from goats, from annual gross carbon in goats ***(Eq. 17, Appendix 3).*** As with cattle, net goat carbon is the carbon stored as animal biomass that is eventually either eaten or sold by the user households.

2.2.4.4 Maize cultivation

To calculate the carbon redirected from maize production and consumption, only maize grown in fields in the communal lands outside of the homestead yard was considered. Because the maize leaves and stalks are left in the field and are usually ploughed back into the soil or eaten by livestock, the calculation of gross and net carbon redirected focussed on the ears of maize only. Maize produced was measured in kilograms; households described amount of ears of maize collected in wheelbarrows (30 kg), 50 kg maize meal bag, 80 kg maize meal bag, and a pick-up truck load (1 200 kg) (Ragie *et al.*, 2020). The total amount harvested and the volume unit were calculated to provide total maize harvested by each household per year. Maize is cultivated for consumption and in most cases, kernels are removed from the ear and the cob is discarded. The mean carbon content of maize kernels is 450-465 $gCkg^{-1}$ (Ma and Dwyer, 2001) while that of maize cobs is 453 $gCkg^{-1}$ (Wienhold *et al.,* 2011). Because these values are in the same range, a value of 453 $gCkg^{-1}$ was assumed for the whole ear of maize. In addition to the survey data, I did my own field quantification of the relative mass of maize kernels to cobs where twelve ears of maize, stripped of their leaf sheaths, were weighed before removing all of the kernels. The dry mass of each cob and of the kernels removed from it were then measured separately. Total kernel mass was then calculated as a percentage of total mass of the ear of maize, averaging 86%. Using the above values, annual gross carbon redirected in maize production was calculated by multiplying total kilograms of maize ears produced per household by 0.453. Net carbon redirected (in the kernels consumed) was calculated by multiplying the gross carbon mass by 0.86. The cobs are discarded, although seldom in the fields or natural environment beyond the village. The net maize carbon was thus the carbon consumed by humans as maize starch

2.2.5 Ethical considerations

As part of the SUCSES study, ethics clearance was obtained from the University of the Witwatersrand human subject research ethics committee (certificate M10301) (Appendices). Because the study is nested in the AHDSS as indicated in the study design **(2.2.2),** approval was also obtained from the Mpumalanga Province Department of Health. Participation in the study was voluntary, and informed consent was obtained from participants before proceeding with interviews.

2 2.2.5 APPENDICES

2.2.5.1 Appendix 1 - Fuelwood harvesting

$$AFC = (3*x) + (9*x0.65) \quad (2)$$

Where *AFC* represents the annual fuelwood consumption (kg), *x* the amount of fuelwood per month (kg) in the cool months (May, June, July); 0.65 the proportion of fuelwood consumption in hot months (August-April) relative to cool months, 3 and 9 being the number of cool and hot months, respectively.

To determine annual gross fuelwood carbon *(CF_g)* redirected by a household (kg), annual fuelwood consumption (kg) was halved because the carbon content of wood is approximately 50% (Eq 4) (Niedertscheider, 2011; Bartels, 2014).

$$CF_g = AFC*0.5 \quad (3)$$

$$AFCE = AFC*0.434 \quad (4)$$

Where AFCE represents the annual fuelwood carbon emissions (kg), *AFC* the annual fuelwood consumption (kg). Subsequently, the annual net fuelwood carbon *(CF_n)* was arrived at by subtracting firewood carbon emissions from gross fuelwood carbon harvested.

$$CF_n = AGCF - AFCE \quad (5)$$

2.2.5.2 Appendix 2 - Cattle Ownership

$$DMIc = 80.5*(M^{0.75}/1\,000) *0.45 \quad (6)$$

Where the M refers to the metabolic weight of cattle (in grams). Metabolic weight refers to livestock body weight raised to the exponent 0.75 as stated earlier. This was divided by 1 000 to get carbon in kilograms. The 0.45 taken as stated earlier is the percentage proportion of carbon in herbaceous plants of the savanna biome. Subsequently, to apportion how carbon is redirected according to the sex, weight, and growth stage of cattle per household per day, the following values was obtained after calculation: 1.7 kg/calf + 2.9 kg/cow + 3.1/bull per household per day. These quantities were further multiplied by the number of cattle and then the proportional percentage of each cattle group, to determine first daily gross carbon, then annual gross carbon from cattle per household.

$$DCCC= (1.7* N_1 *0.21) + (2.9* N_2 *0.6) + (3.1* N_3 *0.19) \quad (7)$$

Where N_1 is the number of calves, N_2 the number of cows and N_3 the number of bulls.

$$CC_c = N*0.79*420 \quad (8)$$

Where N is the total number of cattle

$$CC_m = N_C*0.79*26 \quad (9)$$

$$CCd = Nc*0.79*0.25 \quad (10)$$

Where N_C is the total number of cattle

$$CC_n = CC_g\text{-}CC_c\text{-}CC_m\text{-}CC_d \quad (11)$$

Net carbon from cattle *(CC_n, kg)* was then arrived at by subtracting carbon from carbon dioxide emissions, carbon from methane emissions, and annual cattle dung carbon *(ACDC),* from annual gross carbon redirection from cattle *(Eq. 11).*

2.2.5.3 Appendix 3 - Goat ownership

$$DMIc= 49*BW^{0.75} \quad (12)$$

Where BW refers to the body weight of goats. The exponent to which body weight should be raised when intakes of animal species are compared across forage qualities, should be between 0.75 and 1.0 (Meissner, 2014). Thus, the body weights of goats were raised to 0.75 exponent in this study. The respective weight of goats of different sex and age are as follow, female kid (14.6 kg); male kid (18.6 kg); ewe (26.5 kg); and ram (40 kg) as found by (Snyman, 2012).

$$DCCG = (0.1*N_1*0.18) + (0.3*N_2*0.64) + (0.4*N_3*0.18). \quad (13)$$

Where N_1 the number of kids, N_2 the number of ewe and N_3 the number of rams. To that end, annual gross carbon consumption in goats *(CG_g, kg)* per household was obtained through this calculation by multiplying the daily consumption by 365 days of year.

$$CG_c = NG*0.82*44 \quad (14)$$

$$CG_m= NG*0.82*4 \quad (15)$$

$$CG_d= GACC*0.25 \quad (16)$$

N_G is the number of goats

$$CG_n=CG_g-CG_c-CG_m-CG_d \quad (17)$$

CHAPTER 3

HOUSEHOLD REDIRECTION OF CARBON FROM THE LOCAL ECOSYSTEM BY FUELWOOD HARVESTING, LIVESTOCK FARMING AND CROP PRODUCTION

ABSTRACT

The removal of biomass by rural households through land-based livelihood activities leads to the redirection of carbon from the terrestrial pool and enrichment of the atmospheric pool. There is currently insufficient data on the redirection of the carbon cycle through these activities at the household level in rural savanna socio-ecological systems. This study addresses this knowledge gap by quantifying the mass of carbon redirected annually from the local ecosystem by fuelwood harvesting, livestock foraging, and maize crop production at the household level. The study used the SUCSES household panel data set of 590 households repeated annually over a period from 2010 to 2014 in rural South Africa. The prevalence of fuelwood harvesting, livestock farming, and producing maize, as well as the annual mass of fuelwood used and maize produced, and cattle and goats owned per household were calculated. These were used to calculate the mean gross and net mass of carbon redirected by households per livelihood activity per year. Statistical comparisons were made between years using Kruskal Wallis Test. Fuelwood was the most prevalent land-based livelihood activity, followed by maize crop production and then livestock farming. However, most carbon redirected per household per year came from cattle, both among user-households and when averaged across all households, with the highest gross consumption of 10 972 kgC±1 297 per user-household in 2014. Fuelwood harvested was the second highest at 1 183 kgC ±1 995 in 2012. Mean total gross carbon (including crops) was highest in 2014 with 2 510 kgC±282, while mean total net carbon was 783.79 kgC±108.77 in the same year per household. Mean total gross carbon (excluding crops) was also highest in 2014 with 2 406 kgC±276 and mean total net carbon was 694.10 kgC±103.93 in the same year per household. Gross and net annual carbon varied significantly between years for all activities, although there were few strong directional trends. The results contribute to the scientific knowledge on the use of natural resources in the savanna socio-ecological systems of southern Africa

associated with the mainland-based activities (fuelwood use, livestock farming, and maize crop production) that support rural livelihoods and the resultant gross and net carbon patterns.

3.1 INTRODUCTION

Communal lands in southern Africa support the majority of rural households in the region; many of these people live below the poverty line (Dovie *et al.,* 2004). In South Africa, these communal lands make an important contribution to the livelihoods and well-being of about 13 million people in the former apartheid homelands (Shackleton *et al*., 2007). Natural rangelands under communal tenure support rural livelihoods by providing a variety of goods and services, including the production of natural resources such as forage for livestock and fuelwood for household domestic energy, as well as soil and pollination services when vegetation is cleared for crop production (Shackleton *et al.*, 2007; Palmer and Bennett, 2013). Through the use of these natural resources, Net Primary Production (NPP) is appropriated (Fetzel *et al.*, 2012). Thus, analysing NPP appropriation patterns at the household scale has the potential to improve the understanding of the social and environmental consequences of changing rural livelihoods (Pritchard *et al.*, 2018). To date, most HANPP data are at continental and national levels (Niedertscheider *et al.,* 2012; Haberl *et al.,* 2014). This study focuses on quantification of HANPP of key livelihood activities at a household level in a rural setting.

Fuelwood is one of the major uses of savanna woodlands as the dominant source of energy and therefore a livelihood activity in marginalised communities (Dovie e*t al.,* 2004). The collection of fuelwood is preferentially of dead and dry branches but when demand increases and begins to exceed the supply of deadwood resources, live woody stems and branches are cut for fuelwood (Matsika *et al.,* 2013). Although there is a general perception that fuelwood demand rates have not yet surpassed supply rates, there are still concerns about the sustainability of fuelwood harvesting coupled with a lack of accurate models to better predict fuelwood supply and demand trajectories (Twine and Holdo, 2016). The weakness of these models is attributed to the under-estimation of the adaptive capacity of natural-source dependent communities and the regenerative capacity of woodlands (Mograbi *et al.*, 2017). The assumption is that with increasing growth rates and re-sprouting of the savanna vegetation resulting from CO_2 fertilisation, woody biomass is likely to be stable for the foreseeable future (Twine and Holdo, 2016). Be that as it may, the harvesting and thereby the collection and use of fuelwood is part of biomass harvested from the ecosystem, and contribute to, among other factors, reduced carbon storage and release of CO_2 to the atmosphere (Fetzel *et al.*, 2012), and thus redirecting the carbon cycle at the household level.

Another land-based activity that redirects the carbon cycle in these socio-ecological systems at the household level is livestock farming. Livestock farming has been a key element in the pre-colonial economies of African people in southern Africa and has remained so throughout and after the colonial and apartheid eras (Andrew *et al.,* 2003). Cattle and goats are the main livestock kept by rural households in Bushbuckridge (Ragie *et al.*, 2020). The processes of grazing and browsing by livestock redirect the carbon cycle through the removal of plant leaf biomass where carbon is absorbed, some of which is returned to the soil as manure and to the atmosphere as CO_2 through heterotrophic respiration and methane through enteric fermentation (Asner and Archer, 2014). In South Africa, livestock produces nearly 27% of the national methane gas total, primarily through enteric methane emissions from ruminants (Du Toit and Cumming, 1999). Thus, there is a general perception that livestock is a major contributor to global warming (Scholtz *et al.,* 2013). On the other hand, moderate grazing is said to have the potential to stimulate Above-ground Net Primary Production (ANPP), leading to grazing compensation and increased richness and diversity (Archibald and Hempson, 2016). However, as populations grow, and per capita incomes rise, it is predicted that demand for livestock products will rise in the next decades, and this will put more pressure on land and resources (Teillard *et al.*, 2016), and thus more NPP will be appropriated.

In addition to resource harvesting and livestock farming, rural households also grow crops as another land-based activity. Food crop production has been an important livelihood activity for South African households in homelands, particularly those located in the eastern half of the country where cultivation is rain-fed, associated with a conducive climate (Andrew *et al.,* 2003). Maize is the staple crop in southern Africa (Niedertscheider, 2011). Maize crop production redirects carbon initially through the clearing of vegetation to make way for growing of crops and subsequently the removal of NPP through crop harvesting. Crops are grown in fields outside the village and in home gardens (Hebinck *et al.,* 2018). The latter are the focus of this study. Although many people in the communal areas cultivate crops, the number of households involved in field cropping and the area of land under field cropping is diminishing in many parts of South Africa (Shackleton *et al.*, 2019). Between 2000 and 2004, the proportion of households that practiced agriculture as a main source of food declined from 33% to 6%, while those who used it as an extra source of food increased from 54% to 88% (Baiphethi and Jacobs, 2009). Crop production redirects carbon through land clearing (this is not the focus for this study), and through the removal of crop produce. The reduction in crop production resulting from households' discontinuation of cultivation and abandonment of fields is referred to as cropland abandonment (Lindeskog *et al.*, 2013). In general, a decline in cropland has been noticed in southern Africa relative to the rest of Africa and this decline is associated with considerable productivity losses (Fetzel *et al*., 2016).

All in all, the removal of biomass for fuel, livestock forage, and the removal of vegetation to make room for cultivation of crops, are among anthropogenic activities that lead to the depletion of terrestrial carbon pool and enrichment of the atmospheric pool (Lal, 2004). There is currently insufficient knowledge of the redirection of the carbon cycle through the aforementioned land-based activities at the household level in rural savanna socio-ecological systems. Thus, improved knowledge of carbon fluxes at the household level provide important information to help determine the preferred land management options for an area with respect to carbon sequestration (Gingrich *et al.*, 2015). Land-use associated with the land-based activities under this study, may lead to degraded ecosystem states that will not be able to provide key ecosystem services in the future (Scheiter *et al.*, 2019). This study quantified annual gross and net household carbon removal from the local ecosystem using detailed data on fuelwood harvesting, livestock farming and crop production. The former two redirect carbon from the native savanna vegetation. This is in contrast with carbon redirected from rangelands that have been transformed into crop land. This makes a valuable contribution to understanding ecosystem carbon fluxes and pools at the household level. In turn, this is important to predict the responses to climate change and for choosing climate adaptation measures which are crucial to southern African terrestrial ecosystems that are strongly affected by human activities (Berger *et al.*, 2019).

3.2 METHODS

Data on fuelwood harvesting, livestock ownership, and maize production, and the annual net and gross carbon redirected by these at household level from 2010 to 2014, were analysed in this chapter. Details of the general methods were described in Chapter 2. However, this section focuses on the methods specific to this chapter.

The prevalence of fuelwood use, ownership of cattle and goats, and maize production, among households were expressed in percentages. Mean annual mass (kg) of fuelwood and maize, and mean numbers of cattle and goats were calculated per household. Descriptive statistics for carbon redirected by each land-based livelihood category under this study per year were calculated for both user households only and all households. Frequency distributions of annual consumption of fuelwood and annual maize production, and numbers of cattle and goats were assessed using histograms.

Mean ± SE and median gross and net annual carbon redirected per household by fuelwood use, livestock foraging, and maize production were calculated per user household and averaged across all households per year. Annual summed total gross and net carbon per household (including and excluding crop production) was also calculated. Statistical comparisons were made between years using Kruskal-Wallis test, as the data were not normally distributed. Kruskal-Wallis Test allows comparisons to be made of scores on a continuous variable for three or more groups as a non-parametric alternative to a one-way between groups analysis of variance (Pallant, 2013). Thus, statistical tests were done using Kruskal-Wallis test to determine if there were differences between years for gross and net fuelwood carbon, gross and net cattle and goat carbon, and gross and net maize carbon. The output of these tests have the following characteristics: Chi-square value, the degree of freedom (df), and the significance level. All analyses were conducted using the Software Package for Social Sciences (SPSS).

3.3 RESULTS

3.3.1 Overview of land-based livelihood activities

Fuelwood use was the most prevalent land-based livelihood activity, with more than 90% of households engaged in fuelwood use from 2010 to2014 (**Figure 3.1**). Prevalence of fuelwood use increased slightly over the five years, but frequency of use declined, such that by 2014, 26% of households were using fuelwood occasionally (less often than once a month) while only 59% were using it more than once a week (**Table 3.1**). Ownership of cattle and goats among households was consistently low during the same period, with an average of only 12% owning cattle and 11% owning goats. Goat ownership fluctuated moderately between years while a slight increase in cattle ownership was evident over the five years. A mean of 33% of households were involved in maize cultivation in fields outside the village from 2010 to 2014 with slightly more cultivating in 2010 and 2011, and only 29% cultivating in 2012 (**Figure 3.1**).

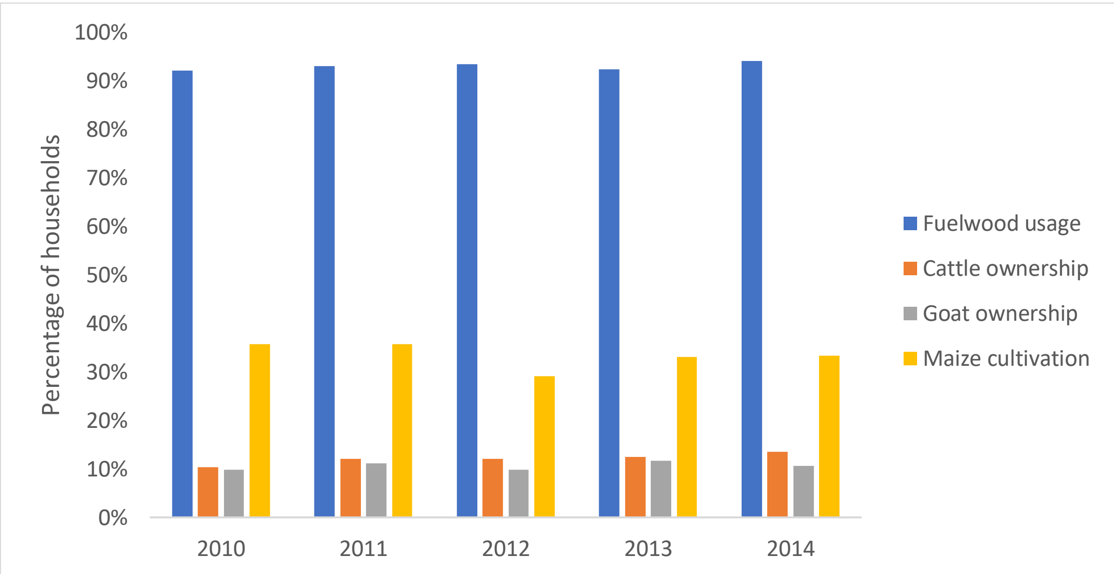


Figure 3.1: Prevalence of use/ownership by households (all households), 2010 - 2014

Table 3.1: Fuelwood frequency of use per week/month

Year	<1x/Month		1x/Month-1x/Week1		>1x/week	
	Frequency	Percentage	Frequency	Percentage	Frequency	Percentage
2010	82	14.00%	89	15.19%	373	63.65%
2011	95	18.41%	77	14.92%	344	66.67%
2012	133	25.43%	77	14.72%	313	59.85%
2013	86	17.48%	79	16.06%	327	66.46%
2014	130	26.42%	71	14.43%	291	59.15%

Mean annual fuelwood consumed per user household peaked in 2012 (2 366 kg ± 106.22) and was lowest in 2014 (2 041 kg ± 99.84) (**Table 3.2**).

Table 3.2: Mean ± SE kg of fuelwood and maize consumed, and number of cattle and goats owned per user-household and averaged across all households per year (2010-2014)

Source	Households	2010	2011	2012	2013	2014
Fuelwood	**User-households**	2 120±10071	2 188±86.46	2 366±106.22	2 098±94.25	2 041±99.84
	All households	1 942±95.81	1 954±83.31	2 189±101.81	1 098±89.62	1 900±95.66
Cattle	**User-households**	10.03±1.15	10.44±1.59	10.23±1.69	10.86±.51	11.19±1.60
	All households	1.02±0.17	1.21±0.23	1.22±0.24	1.33±0.24	1.47±0.27
Goats	**User-households**	5.36±0.57	5.18±0.55	5.38±0.51	5.67±0.55	5.46±0.55
	All households	0.49±0.08	0.58±0.09	0.53±0.09	0.65±0.10	0.57±0.09
Maize	**User-households**	507.46±91.45	676.63±123.00	444.92±85.90	686.52±99.16	757.66±100.13
	All households	177.06±26.86	246.57±38.63	136.20±21.55	279.77±32.92	284.88±33.92

Averaged across all-households, mean annual fuelwood was still highest in 2012 (2 189 kg±101.81) and lowest in 2014 (1 900 kg±95.66). The frequency distribution of mass of harvested wood was similar across all years, with most household using less than 1 000 kg per year (**Figure 3.2**).

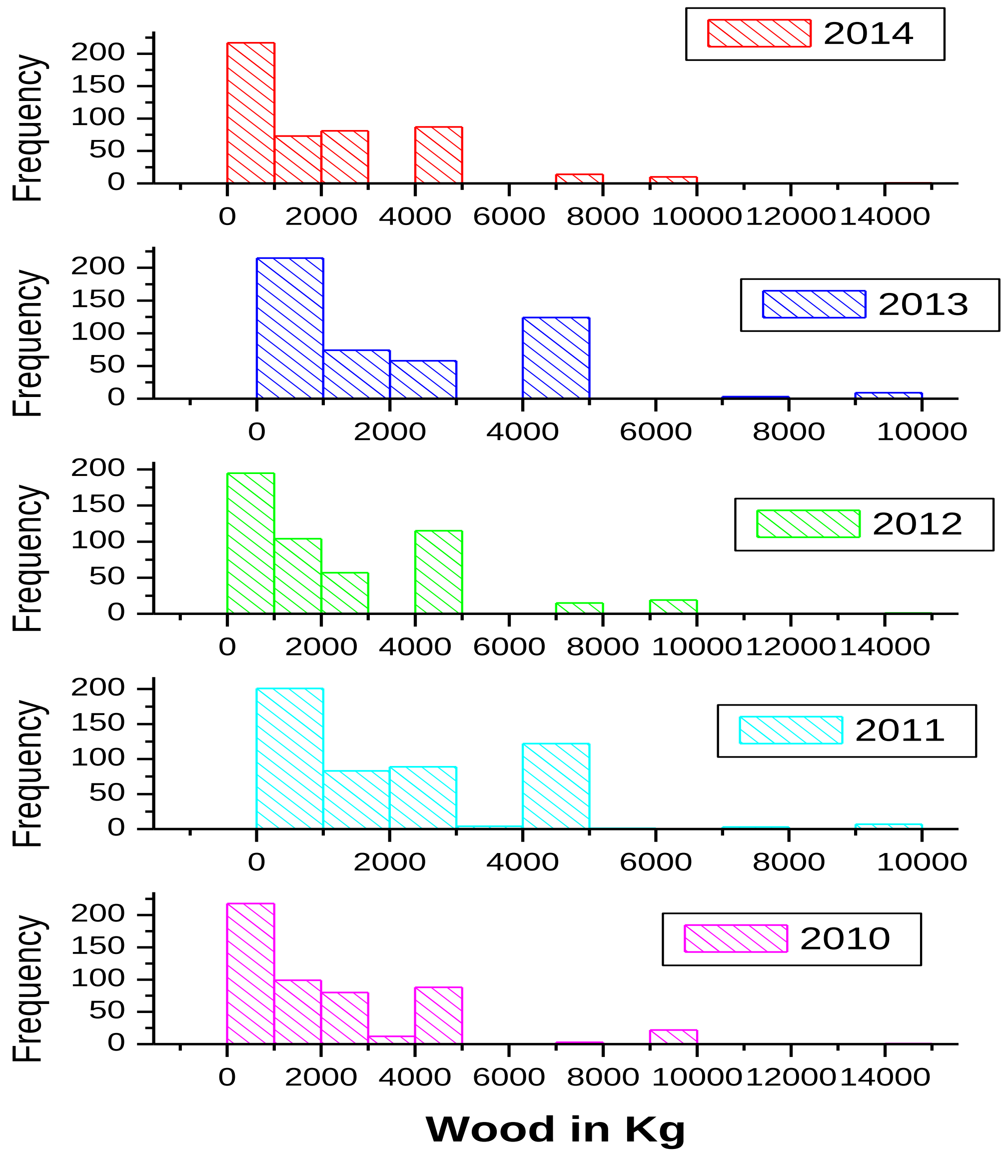


Figure 3.2: Frequency distribution of harvested wood in kg

Averaged across all years, user households owned a mean of 10 cattle and 5 goats, and this varied little per year. Across all years and all households, households owned on average less than 2 cattle per year (Table 3.3). The frequency distribution indicates that from 2010 to 2014, the majority of user households owned under 10 cattle, with few owning more than 10 and very few owning over 20 cattle per year (**Figure 3.3**)

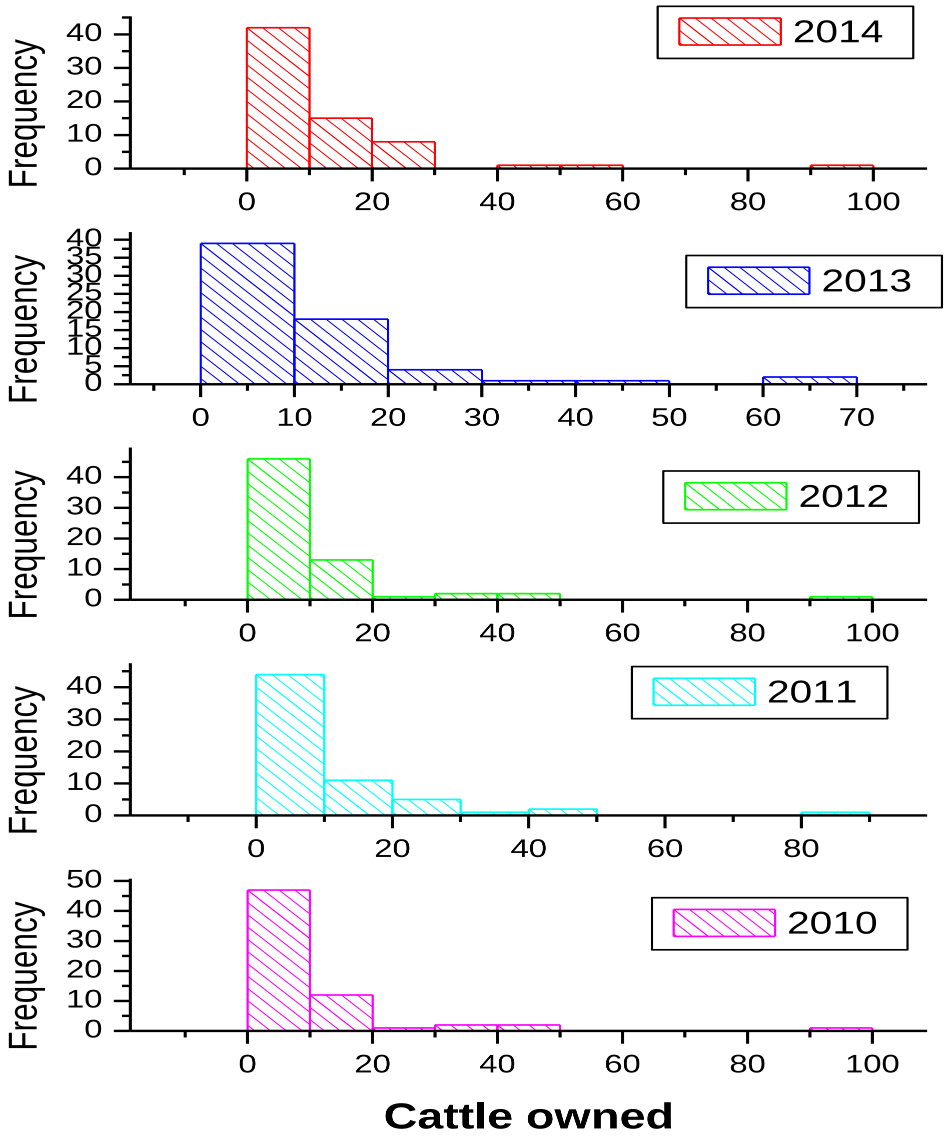


Figure 3.3: Frequency distribution of number of cattle owned

The frequency distribution of goat ownership followed a similar trend across all years (**Figure 3.4**).

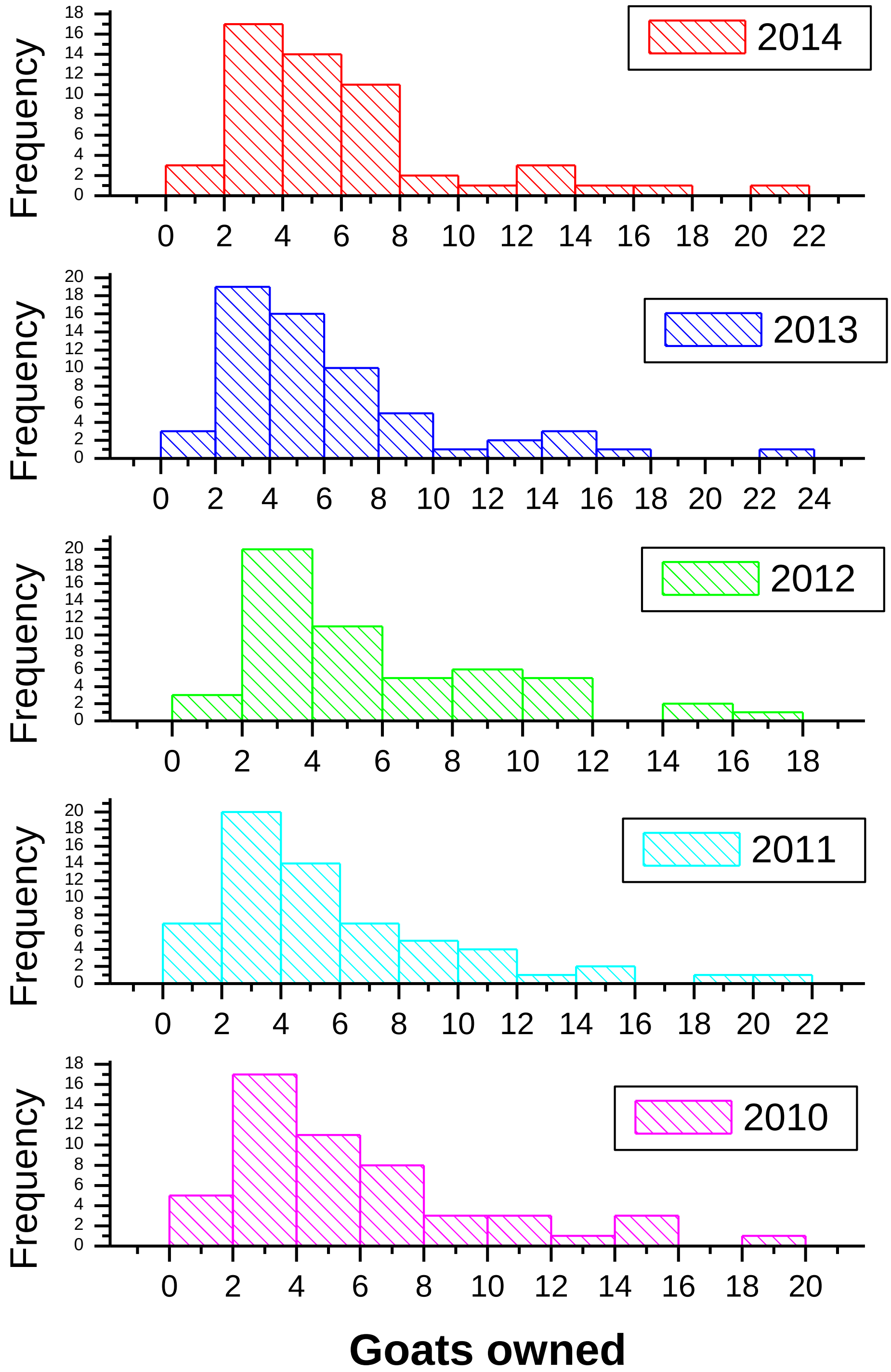


Figure 3.4: Frequency distribution of goats owned

Mean annual maize production per user household was 615 kg from 2010 to2014, ranging between 444.92 kg ± 85.90 in 2012 and 757.66 kg ± 100.13 in 2014 **(Table 3.3).** Averaged across all years, and all households, mean annual maize production was 221.29kg. In general, the distribution of maize production followed a similar trend across all years, with most user households producing less than 500 kg per year (**Figure 3.5**).

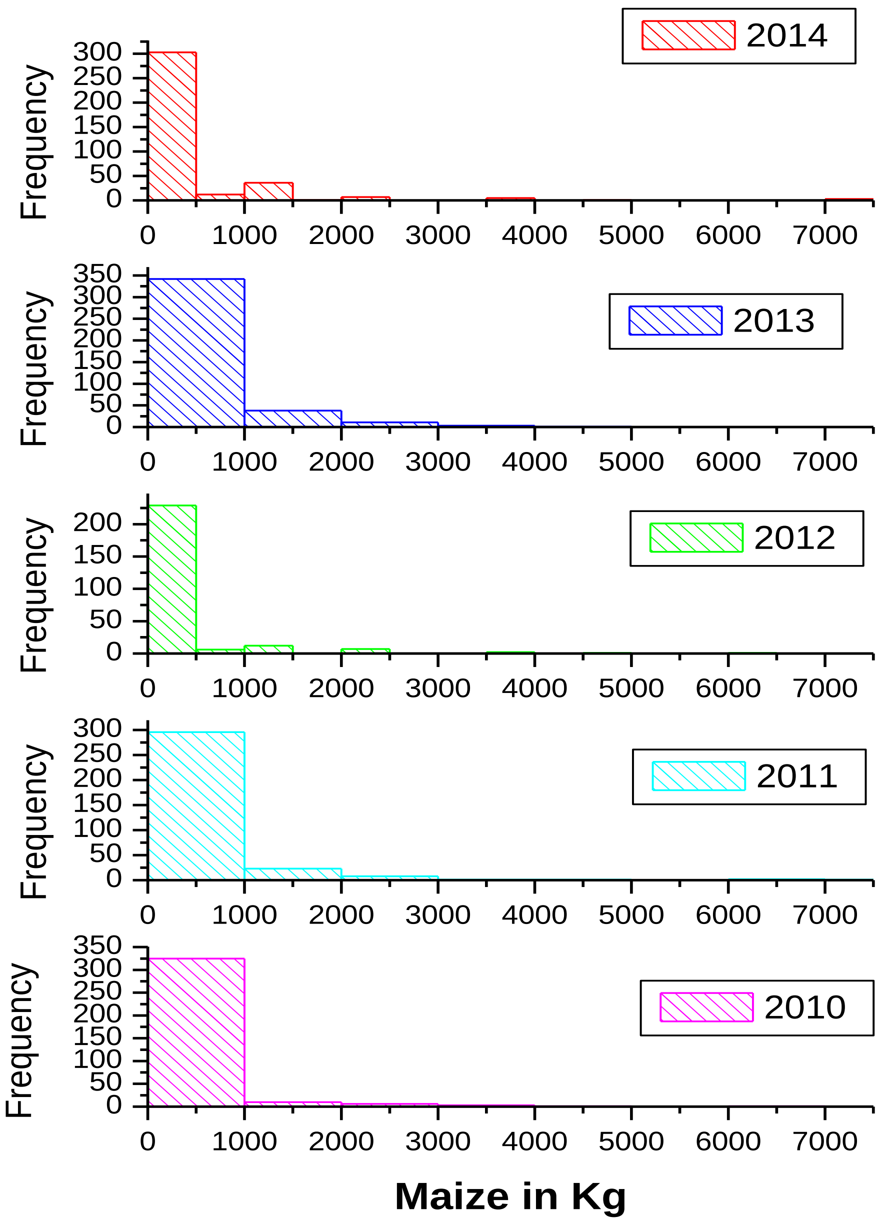


Figure 3.5: Frequency distribution of maize production in kg

3.3.2 Carbon redirection per use category

Most gross carbon redirected per user household per year came from cattle with 2014 having the highest consumption of 10 972 kgC ± 1 297 **(Table 3.4)**. Fuelwood harvested was the second highest at 1 183 kg ± 1 195 in 2012. Maize and goats redirected the least gross amount with the highest being in 2011 and 2013, respectively. Similarly, cattle redirected most of the net carbon with the highest being 4 286 kgC ± 5 068 in 2014; while the highest net carbon redirected from fuelwood was in 2012 with 156.19 kgC ± 157.70; and 84.94 kgC ± 64.10 from goats in 2013. Due to the skewed distribution of livestock ownership, fuelwood usage and maize production, the median values for gross and net carbon redirection for these uses were lower than the means **(Table 3.4).** However, the general patterns were the same, except that carbon redirection by maize production was lower than that by goats. Gross and net annual carbon varied significantly between years for cattle ($KW\chi^2 = 258.10$, $p<0.001$; $KW\chi^2 = 293.28$, $p<0.001$) and fuelwood ($KW\chi^2 = 2\ 281.80$, $p<0.001$; $KW\chi^2 = 2\ 189.06$, $p<0.001$), as did gross and net carbon from maize production ($KW\chi^2 = 24.08$, $p<0.001$; $KW\chi^2 = 24.08$, $p<0.001$). There were no clear directional trends in the variation in these values, although carbon redirection in the form of fuelwood was lowest in the last two years of the study. However, carbon redirection by goats was highly consistent between years, and did not vary significantly between 2010 and 2014.

Table 3.3: Mean ±SE and median annual gross and net carbon per user household (KgC/household/year), 2010 - 2014

Year	Stats	Fuelwood		Cattle		Goats		Crops	
		Gross	Net	Gross	Net	Gross	Net	Gross	Net
2010	Mean	1 060±50.36	139.98±6.65	9 838±1 132	3 843±441.99	224.43±23.90	80.35±8.56	229.88±41.43	197.70±35.63
	Median	588.53	77.69	6 863	2 681	167.32	59.90	77.92	33.63
	Min	16	2	980	383	42	15	2	2
	Max	7 062	932	36 274	14 169	795	285	4 361	3 750
2011	Mean	1 059±43.28	139.81±5.71	10 233±1	3 997±609.92	216.57±23.00	77.53±8.23	306.51±55.72	263.60±47.92
	Median	700.92	92.52	6 863	2 681	77.53±64.82	59.90	77.92	67.01
	Min	16	2	980	64	42	15	1	1
	Max	4 708	621	82 353	32 168	837	299	5 451	4 689
2012	Mean	1 183±53.11	156.16±7.01	10 030±1	3	223.09±21.41	79.87±7.66	201.49±38.91	173.28±33.46
	Median	700.92	92.52	5 882	2 298	167.32	59.90	38.96	33.51
	Min	32	4	980	383	42	15	1	1
	Max	7 062	932	88 235	34 466	711	255	2 726	2 344
2013	Mean	1 049±47.13	138.48±6.22	10 649±1	4 159±579.86	237.26±22.93	84.94±8.21	310.99±44.92	267.45±38.63
	Median	526.69	69.39	5 882	2 298	167.32	59.90	77.92	67.01
	Min	32	4	980	383	42	15	1	1
	Max	4 708	621	65 868	25 658	962	344	5 451	4 689
2014	Mean	1 021±49.92	134.73±6.59	10 972±1	4 286± 614.54	225.12±22.86	80.59±8.18	343.22±45.31	295.17±38.96
	Median	525.69	69.39	6 863	2 681	80.59	59.90	116.87	100.51
	Min	32	4	980	383	42	15	1	1
	Max	7 062	932	88 235	34 466	837	299	3 271	2 813

Similar to gross and net carbon redirected by user households, mean gross carbon averaged across all households followed the same trend with cattle having redirected the highest, followed by fuelwood, crops, and goats. Mean gross and net carbon redirected by cattle was highest in 2014 with 1 293 kgC ± 5 667 and 505.07 kgC ± 2 214, respectively; all the other years followed a similar trend. There is a small difference in gross and net carbon values between cattle and fuelwood, as the next highest redirected mean gross carbon came from fuelwood with the highest in 2012 being 1 095 kgC ± 1 191. Fuelwood mean net carbon values consistently increased with a small margin from 2010 to2014. Maize crops and goats redirected the least mean gross and net carbon, with maize values relatively higher than goats **(Table 3.4)**. The median values are in all uses lower than mean values but mostly similar from one year to the next in all uses. Gross and net annual carbon differed significantly between years for fuelwood (KWχ^2 = 37.38, p<0.001; KWχ^2 = 37.38, p<0.001). Gross and net annual carbon also varied for maize production (KWX^2 = 19.29, p<0.001; KWX^2= 19.29, p<0.001) between years. Gross and net carbon for cattle and goats did not vary significantly from 2010 to 2014.

Table 3.4: Mean ±SE and median annual gross and net carbon per household (KgC/household/year) averaged across all households, 2010 - 2014

Year	Stats	Fuelwood		Cattle		Goats		Crops	
		Gross	Net	Gross	Net	Gross	Net	Gross	Net
	Mean	971.44±47.74	128.23±6.30	997.53±168.53	389.65±65.83	20.40±3.45	7.30±1.24	63.10±12.13	54.26±10.43
2010	Median	525.69	69.39	0	0	0	0	0	0
	Min	0	0	0	0	0	0	0	0
2010	Max	7 062	932	36 274	14 169	795	285	4 361	3 751
	Mean	976.94±41.65	128.96±5.50	1	461.76±88.59	24.24±3.87	8.68±1.38	90.18±17.40	77.56±14.97
2011	Median	582.99	76.96	0	0	0	0	0	0
	Min	0	0	0	0	0	0	0	0
2011	Max	4 708	621	82 353	32 168	837	299	5 452	4 689
	Mean	1	144.48±6.72	1	465.56±93.70	22.02±3.54	7.88±1.27	43.83±39.16	37.70±7.87
2012	Median	525.69	69.39	0	0	0	0	0	0
	Min	0	0	0	0	0	0	0	0
2012	Max	7 062	932	88 235	34 466	711	225	2 726	2 344
	Mean	952.49±76	125.73±5.91	1	508.20±91.90	27.20±4.19	9.74±1.50	92.36±14.67	79.43±12.62
2013	Median	513.30	67.76	0	0	0	0	0	0
	Min	0	0	0	0	0	0	0	0
2013	Max	4 708	621	65 686	25 658	962	344	5 452	4 689
	Mean	948.06±47.78	125.14±6.31	1	560.44±101.97	23.81±3.87	8.52±1.39	104.29±15.38	89.69±12.23
2014	Median	513.30	67.76	0	0	0	0.00	0	0
	Min	0	0	0	0	0	0	0	0
2014	Max	7 062	932	88 235	34 466	837	299	3 271	2 813

Household carbon backflows were dominated by fuelwood use, followed by cattle and then goats. Fuelwood greenhouse gas emissions were highest in 2012 with a mean value of 950.08 C±1 033. The lowest was in 2014 with 822.92C±945.62. With regard to cattle carbon backflows, the highest was in 2014 with 485.58C±2 015. Carbon backflows from goats were substantially low across all years in comparison to the other two categories. Carbon backflows from goats ranged from 8.00C±32.38 in 2010 to 10.66C±37.90 in 2013 across all years. As expected, between the two livestock measurements, cattle had the highest dung carbon values. The cattle values which increased steadily ranged from 249.38C±1 008 in 2010 to 358.69C±1 488 in 2014. On the other hand, goat dung carbon was lowest in 2010 with 5.10C±20.65 and highest in 2014 with 5.51C±20.68. Goat carbon backflows had the smallest difference between GHG emissions and dung carbon **(Table 3.5).**

Table 3.5: Mean ±SE carbon backflows to nature (kg) averaged across all households

Year	Fuelwood GHG	Cattle GHG	Goat GHG	Cattle dung	Goat dung
2010	843.21±991.08	337.60±1 364	8.00±32.38	249.38±1 008	5.10±20.65
2011	847.99±851.02	400.08±1 807	9.50±35.74	295.53±1 335	6.06±22.76
2012	950.08±1 033	403.38±1 899	8.63±32.42	297.97±1 403	5.51±20.68
2013	826.76±896.14	440.32±1 837	10.66±37.90	325.26±1 357	6.80±24.17
2014	822.92±945.62	485.58±2 015	9.33±34.60	358.69±1 488	5.95±22.07

3.3.3 Total combined carbon redirected per household, 2010 – 2014

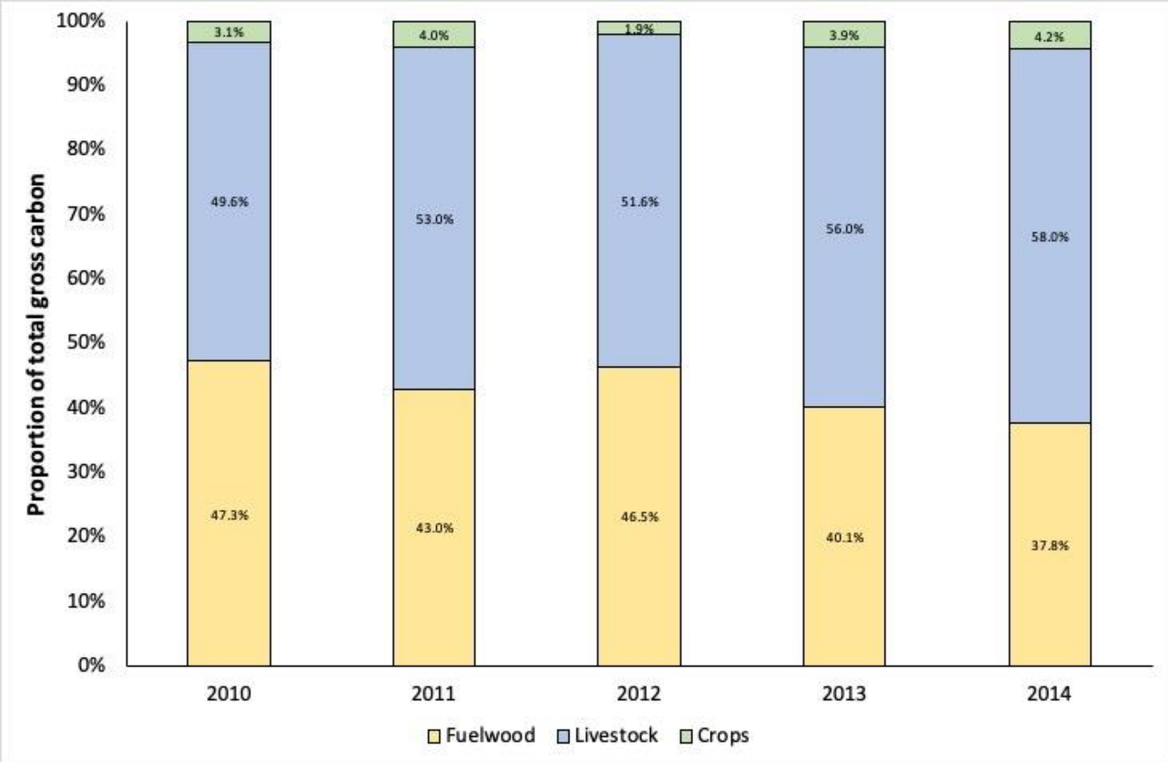
From 2010 to2014, mean total gross carbon per household (including crops) averaged 2 311 kgC/household/year, ranging from roughly 2 000 in 2010 to 2 500 kgC in 2014 **(Table 3.6).** The median values were all lower than mean values across all years. However, the trend remained the same. Total gross carbon redirected from native vegetation (i.e. excluding crops) showed a similar trend to total gross carbon with crops, averaging 2 233 kgC/household/year, 2010 still having the lowest mean value (1 989 kgC ± 178) and 2014 the highest (2 406 kgC ± 276) **(Table 3.6).** Total net carbon (including crops) averaged 684 kgC/household/year, ranging from 579.44 kgC ± 68.38 in 2010 to 783.79 kgC ± 108.77 in 2014. Total net carbon excluding crops ranged between 525.18 kgC ± 66.70 in 2010 and 694.10 kgC ± 103.93 in 2014 and averaged 616 kgC/household/year **(Table 3.6).** Total gross and net carbon did not vary significantly between years.

Table 3.6: Mean SE, median, min and max, total gross and net carbon (with and without crops) across all households, 2010 - 2014

Source	Stats	2010	2011	2012	2013	2014
Gross: Fuelwood + Livestock + crops	Mean	2 052±179	2 273±243	2 352±251	2 372±244	2 510±282
	Median	179.26	876.15	700.92	700.92	700.92
	Min	0	0	0	0	0
	Max	36 362	89 904	91 214	66 040	96 933
Gross: Fuelwood + Livestock	Mean	1 989±178	2 183±236	2 308±249	2 280±241	2 406±276
	Median	588.53	700.92	700.92	700.92	612.76
	Min	0	0	0	0	0
	Max	36 362	84 986	89 649	66 037	95 297
Net: Fuelwood + Livestock + crops	Mean	579.44±68.38	676.94.39±96.96	655.63±96.80	723.10±95.42	783.79±108.77
	Median	106.10	130.02	115.65	138.52	155.37
	Min	0	0		0	0
	Max	14 181	36 529	35 813	25 704	36 805
Net: Fuelwood + Livestock	Mean	525.18±66.70	599.39±89.79	617.93±94.71	643.67±92.54	694.10±103.93
	Median	92.52	97.08	92.52	92.52	92.52
	Min	0	0		0	0
	Max	14 181	32 778	34 875	25 704	35 398

3.3.4 Proportional contribution of the different uses to total gross and net carbon (with and without crops), 2010 – 2014

Averaged across all years, for all activities, livestock contributed the most (54%) to total gross carbon across all households. This was followed by fuelwood (43%) and then maize crop production which contributed 3% **(Figure 3.6a).** Most total gross carbon from livestock was attributed to cattle. For total net carbon, the proportion followed the same trend as that for gross with livestock still the highest but with a much higher proportion (71%), fuelwood with 19%, and maize crop production still contributed the least with 10% **(Figure 3.6b)**. The total contribution for gross and net carbon from indigenous vegetation only i.e. from fuelwood and livestock activities, livestock contributed the most to total gross and net wit 56% and 79% respectively, while the rest, 44% and 21% belonged to fuelwood **(Figure 3.7a, b).**



a)

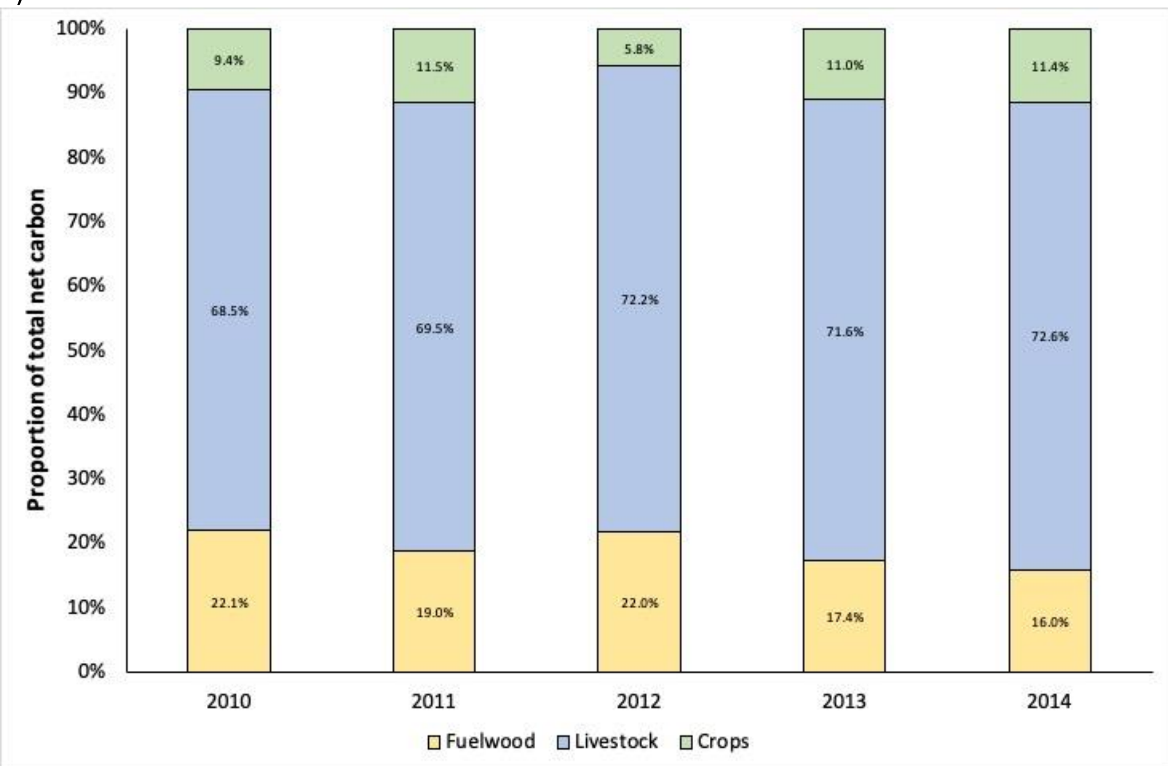
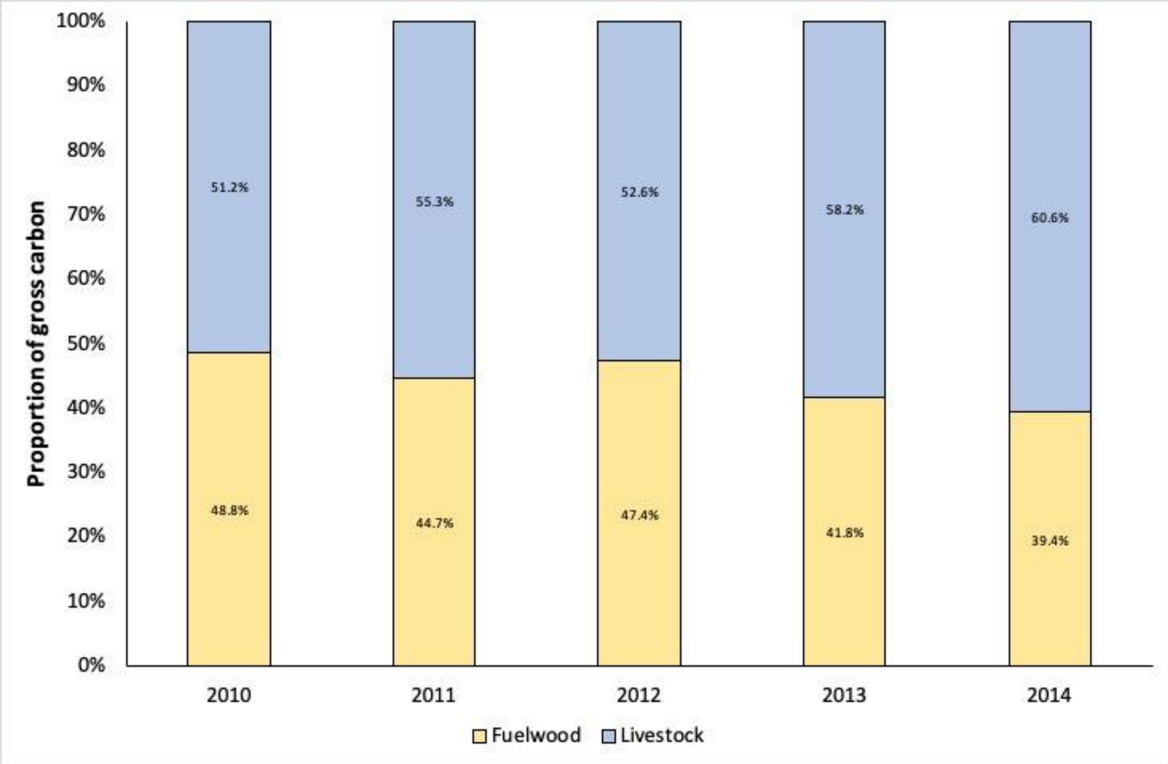


Figure 3.6: Proportional contribution of fuelwood, livestock and crops (maize) to total a) gross and b) net carbon redirection by households between 2010 and 2014



b)

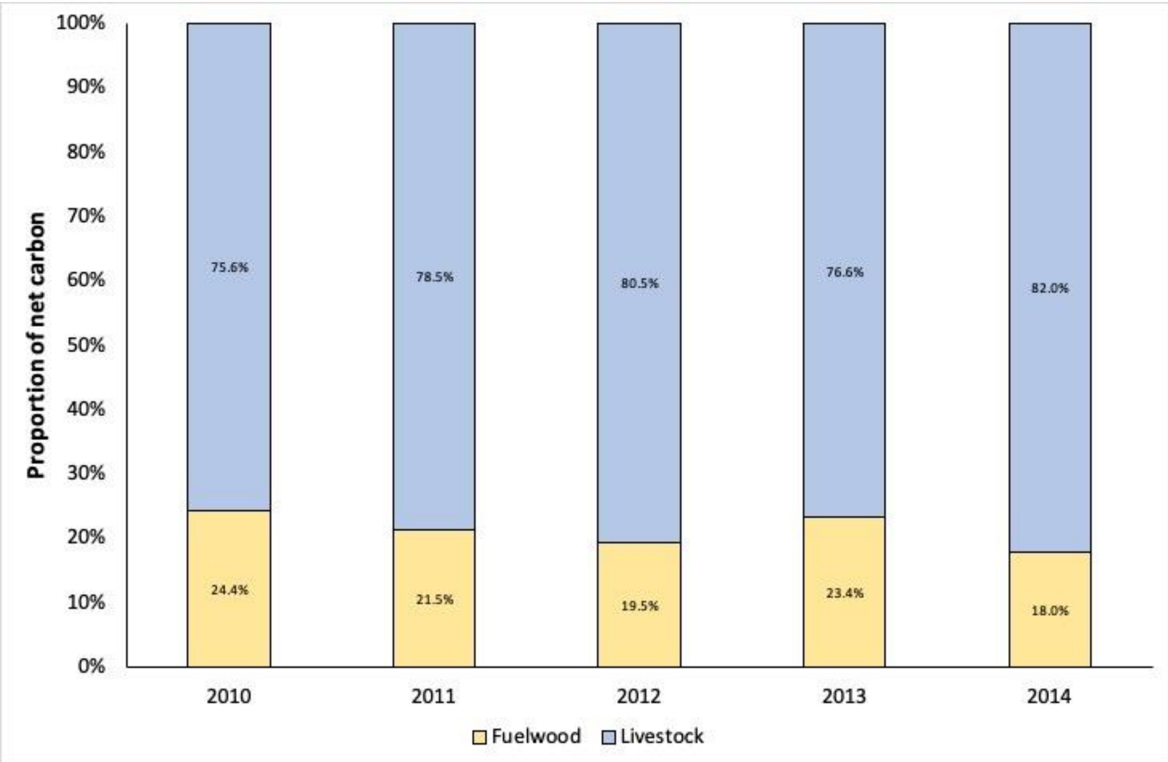


Figure 3.7: Proportional contribution of fuelwood and livestock to total a) gross and b) net carbon redirected by households between 2010 and 2014

3.4 DISCUSSION

This chapter's objective was to quantify annual gross and net household carbon redirection from the local environment in a rural communal socio-ecological system using detailed data on household land-based livelihood activities. For reasons outlined in Chapter 1, the focal land-based livelihood activities considered in these analyses were fuelwood harvesting, cattle and goat ownership, and maize production in fields excluding home gardens. This section first considers the prevalence of these livelihood activities and magnitude of their use per household (kg of fuelwood used, number of cattle and goats owned, and kg of maize produced). This forms the backdrop to the discussion of gross and net household carbon redirection per livelihood activity and in total, including the relative contribution of each of these livelihood activities to total carbon redirection. The fuelwood use, livestock ownership and maize crop production data from this longitudinal study will be helpful on models that predict trends and changes in land-based activities. In addition, the study offers insight on the influence of rural households on the carbon cycle. The household is the most important unit of production and consumption in these communities, that involves the control of and access to assets, labour and income (Dovie *et al.,* 2005). All in all, the study provides an understanding of land system trajectories and mechanism changes through fuelwood harvesting, livestock ownership and maize crop production.

3.4.1 Land-based activities use and ownership

The quantity of production or consumption per land-based livelihood activity is key to determining the carbon redirected per activity per user-household, while the prevalence of engaging in each activity determines the carbon values when averaged across all households, and influences the community-level impact on the carbon cycle (see Chapter 4). This study reveals that fuelwood harvesting was the most prevalent activity among households, followed by maize cultivation in fields **(Figure 3.1).** In contrast, the ownership of cattle and goats was consistently low among households.

3.4.1.1 Fuelwood use

In this study, fuelwood was used by the majority of households (average of 93%) sampled from nine rural villages in Bushbuckridge, South Africa over the study period **(Figure 3.1).** This is comparable to data from older studies from the same region, which indicate fuelwood as the main source of energy among most rural households (>90%), especially for cooking and heating (Dovie *et al.,* 2005; Madubansi and Shackleton, 2007; Matsika *et al.,* 2013). This prevalence of use is also comparable with other rural parts of the country, such as 85% of households in sites in Limpopo and KwaZulu-Natal provinces (Shackleton *et al.,* 2004); more than 95% of households in the Kat River valley in the Mpofu district of the former Ciskei homeland in the Eastern Cape (Shackleton and Shackleton, 2006). The percentage of households using fuelwood was similar in 2010, 2011, and 2013. It increased in 2012 and it was slightly higher in 2014 as compared to the rest of the years.

Although 2014 had the highest prevalence of use, the kilograms of fuelwood used per household was the lowest in the said year. This is because the percentage of households using fuelwood more than once a week declined and the percentage of households using fuelwood less than once a month increased in 2014. This could be attributed to ESKOM (Electricity Supply Comissions) blackouts which were experienced all over South Africa as from 2014. In light of this, the South African printed media indicate that the South African power grid came under severe constraints during the 2013/2014 summer maintenance programme and ESKOM implemented load shedding in March 2014, for the first time since 2008 (NEWS 24, 2014). Thus, although dependence on fuelwood as the dominant household energy source might be gradually declining, occasional use as a coping strategy in response to irregular electricity supply is still common. This study reveals that from 2010 to 2014 on average, households consumed 2 163 kg of fuelwood per user-household per year, which is less than what was reported in other communal areas of South Africa. In Giyani and Venda, Limpopo Province, South Africa, it was found that a household of 7-8 people used an average of 2 847 kg of fuelwood for cooking one meal per annum in both areas (Makhado *et al.*, 2014). In the Kat River Valley of the Eastern Cape, it was found that households used fuelwood per annum according to the wealth status of the households where wealthy households used 3 212 kg, intermediate 3 650 kg, and poor households used 4 198 kg (Shackleton and Shackleton, 2006). In Thorndale, Bushbuckridge, each household used 4 343 kg per annum (Dovie *et al.,* 2004).

The lower average fuelwood consumed over the years as compared to other areas could be attributed to a decline in dependence on fuelwood as the only or dominant household energy supply for cooking and heating water. This may be driven by a decline in fuelwood availability and increasing access to electricity in the area, with more households using electricity or a mixture of energy sources. Nearly two decades earlier, Thorndale households in Bushbuckridge on average used 4 343 kg of fuelwood annually (Dovie *et al.,* 2004). Also, comparisons of the woodland conditions of two villages in Bushbuckridge between 1992 and 2009 indicate that the total standing wood stock of both villages declined over the respective years (Matsika *et al.,* 2013). Although woodland degradation extent is highly dependent on the social context of an area (Matsika *et al.,* 2013), the afore-mentioned two examples are an indication that the area of Bushbuckridge might have gone through the process of woodland degradation thereby causing fuelwood scarcity and subsequently leading to the lower average consumption of fuelwood from 2010 to 2014 as per this study's findings.

Another reason for a decline in fuelwood consumption could be that Bushbuckridge, like many rural communities in southern Africa might be going through what Dovie *et al.,* (2004) refers to as a fuelwood 'crisis'. The fuelwood 'crisis' is defined as a shortage of fuelwood supply to meet households' energy needs and is evident as an ever increasing distance travelled by households to obtain and harvest suitable wood. The 'crisis' might have caused an energy transition mainly informed by household income in Bushbuckridge. Household income informed their energy transition in the sense that un-electrified households moved from the collection of wood to purchasing of wood, while electrified households switched to more extensive use (Madubansi and Shackleton, 2006). Although this seems to suggest that electrified households switch extensively to electricity and abandon the use of fuelwood; this is refuted by Madubansi and Shackleton (2007) who established that despite the availability of electricity, up to 95% of households continued to use fuelwood in Bushbuckridge. The continued use of fuelwood despite the availability of electricity is attributed to the relatively high cost of electricity and the need to purchase and maintain technologies such as stoves among other reasons (Matsika *et al.,* 2013). The same has also been observed elsewhere in southern Africa where Zimbabwean rural households continued to use fuelwood for their major thermal needs in the presence of electricity (Vermeulen *et al.,* 2000).

Although this study established a general low consumption of fuelwood in Bushbuckridge, the prevalence of use **(Figure 3.1)** among households is still high. This indicates that the South African government post-Apartheid rural electrification programme has not had a significant impact on the reduction of fuelwood use, and thus on carbon redirected from its use. This echoes the findings of Madubansi and Shackleton (2007) who did not find much difference in fuelwood use between 1991 and 2002 in the same region. Thus, without changes in the local economy substantially, rural South Africa might remain dependent on fuelwood use for the foreseeable future (Matsika *et al.,* 2013). This is not only unique to rural South Africa, but similar results have been observed in other southern African countries such as Malawi, Namibia, and Zimbabwe (Makhado *et al.*, 2009).

It has been established that fuelwood collection has already resulted in substantial changes in the composition and structure of savanna in many parts of South Africa (Berger *et al.*, 2019). It has also been found that fuelwood usage from natural vegetation in South Africa is not likely to decrease (Dovie *et al.,* 2004). What this means for the South African and indeed southern African savanna ecosystem is that rural households will continue to demand more NPP through fuelwood use and this will ultimately lead to the release of CO_2, the removal of CO and non-hydro carbons to the atmosphere through fuelwood burning. This, in itself is a disturbance to the carbon cycle. Fuelwood depletion is one of the causes of reduced biomass production of natural ecosystems (Niedertscheider *et al.,* 2012). If biomass production is jeopardised, rural livelihoods whose survival depend on biomass productivity will be negatively affected.

These results build on existing knowledge of fuelwood use and its importance as the main source of energy among rural households in South Africa. Although there have been numerous studies on fuelwood use among South African rural households and the rest of the sub-continent, this study goes beyond the use patterns and analysed NPP patterns associated with this activity. In addition, the southern African savanna systems have been going through social and ecological changes that it is important to keep abreast of these developments that could have an impact on the millions of people this ecosystem serves. Thus, this study fills such a gap by giving updated data on the patterns of fuelwood use among rural households that has taken place in recent years. These data would be useful for fuelwood supply and demand models to project future fuelwood use and NPP patterns. Madubansi and Shackleton (2007) indicate that there is a need to develop a predictive knowledge with regard to patterns of fuelwood use change over time given especially the fact that the socio-economic and environmental aspects of the rural areas are changing. While fuelwood is a renewable resource, population growth, development activities, and over-utilisation provide a challenge to the sustainability of fuelwood resources (Vasicek and Gaugris, 2014). Thus, fuelwood supply and demand models and policies aimed at finding a solution to fuelwood scarcity should consider the afore-mentioned factors that are a challenge to the sustainability of fuelwood resources.

3.4.1.2 Livestock ownership

This study reveals that on average of 12% of the households owned cattle (average of 10 animals) and 10% of the households owned goats (average of 5 animals) over the study period **(Figure 3.1).** The average percentage of ownership and the number of cattle and goats owned from 2010 to 2014 did not vary substantially between years. These levels of livestock ownership are lower than reported in other studies. A study conducted in the small and remote Bushbuckridge village of Thorndale revealed that 34% owned cattle only while 49% owned goats only, and another 17% owned both (Dovie *et al.,* 2006). In two villages of the Limpopo Province, 58% and 65% of households owned livestock; while in a KwaZulu-Natal village, 87% had livestock (Shackleton *et al.*, 2002). In a rural Eastern Cape study, 75% of households owned goats, while 62% of households owned cattle (Du-pont *et al.*, 2020). The general outline of cattle and goat ownership among South African rural households seems to suggest a high variability in livestock ownership, probably reflective of a combination of local environmental conditions, socio economic status and availability of alternative livelihood options. For example, financial reasons were attributed to most households owning goats than cattle in Thorndale, indicating that most people could not afford large stock such as cattle (Dovie *et al.,* 2005). The variation in cattle and goat ownership among rural households in South Africa is confirmed by Andrew *et al.* (2003) who observed that the percentage of those owning cattle ranged from a mere 10% in densely populated former Lebowa homeland to 75% in some deep rural areas of KwaZulu-Natal.

The low ownership of livestock is also in line with what Blair *et al.* (2018) observed across South African communal rangelands that a substantial decline in the proportion of households owning cattle has been observed. In particular, cattle-owning households reduced from around 71% in 1948 to 30% proportionally in 2000 in the former Ciskei area (Andrew *et al.,* 2003). A lack of finances has been reported in the villages of Guquka and Koloni of the Eastern Cape Province as the reason for a decline in cattle ownership. On the other hand, drought was said to have been responsible for a decline in livestock ownership in Bushbuckridge (Giannecchini *et al.*, 2007). Should the trend of low ownership of livestock as well as the low number of livestock among rural households in South Africa and southern Africa continues, this will see improved rangelands as less NPP is demanded through grazing and browsing. This will also increase productivity of the savanna biomass in communal rangelands. This is corroborated by (Asner and Archer, 2014) who found a difference in ANPP between a grazed and un-grazed land.

The lower prevalence of livestock ownership and livestock numbers contribute an insight into how the dynamics of this land-based activity could be changing among rural households in South Africa and what this could mean for the current and future NPP patterns associated with this activity. Few livestock also mean less GHG (Green House Gases) associated with livestock farming. Overall, it is predicted that because population growth and rising per capita incomes, higher demands for livestock products is expected to rise in the next decade and this will put more pressure on land and resources (Teillard *et al.*, 2016). It would be of ecological importance for future research to look into livestock products demand among rural households and what that would mean for GHG emissions associated with increasing livestock numbers.

3.4.1.3 Crop production

In this study, about 33% of households practiced maize crop production in fields beyond the homestead food garden. Findings from previous studies indicate a disparity in crop production among rural South African households. In Thorndale, 96% of households cultivated and harvested at least one crop, including maize (Dovie *et al.,* 2005). In Athol, Bushbuckridge, 87% of households harvested crops from home gardens while 38% harvested them concurrently from fields and home gardens (Giannecchini *et al.*, 2007). In Cutwini in the Eastern Cape, 92% of households used farming lands (Haag and Hadju, 2014). These findings indicate that in communal areas of South Africa, households either cultivate in home gardens or arable fields or both, although a shift from cultivating in fields to home gardens has been observed (Blair *et al.,* 2018).

The relatively low participation of households in maize crop production in fields beyond the homestead is possibly attributed to the following reasons. One, most households are producing their maize in home gardens (Table 3.1). This is also confirmed by Haag and Hadju (2014) who found a shift to cultivation of crops in home gardens as opposed to arable fields in the Eastern Cape study, which was necessitated by the migration of men who migrated as labour migrants and left women and children who found smaller gardens easier to fence and watch over. Secondly, the majority of rural households in South Africa supplement their cultivated crops with cash-based income resulting in their livelihoods not solely based on agriculture (Baiphethi and Jacobs, 2009). Lastly, a progressive decline in the area of active fields and an increase in the area of disused fields, has been observed in the former homelands (Shackleton *et al.*, 2019). This could be the reason why even, there was slight decline on percentage of households cultivating maize in fields over the five years spanned for this study.

This study's findings indicate signs of cropland abandonment which has been observed elsewhere in rural South Africa such as in the Eastern Cape, Free State, and Kwa-Zulu Natal, corroborated by different authors (Baiphethi and Jacobs, 2009; Blair *et al.,* 2018; Shackleton *et al.*, 2019). Although a reduction in crop production leads to food insecurity among rural households, it also means that less vegetation is cleared to make way for cultivated fields and therefore less demand of NPP by rural households. Re-vegetation of the abandoned fields on the other hand contributes to carbon sequestration over time (Shackleton *et al.*, 2019).

Although a decline in maize production has taken place in rural South Africa as per this study's findings, this does not necessarily mean that this land-based activity will cease to exist in the near future. The cultivation of maize crops is likely to continue (probably on a smaller scale) because the importance of agricultural activities such as this is not only in their actual contribution to livelihood needs, but also in their role as complementary, back-up strategy, a crucial part of a rural culture and a way of life (Haag and Hadju, 2014). Among rural households, farming is not only about food production. It also makes an important contribution to land-based livelihoods of rural households by improving their capacity for provide for themselves, provision of non-food goods, monetary and non-monetary services, as a buffer from shocks, and a sense of place, identity and well-being among other benefits (Blair *et al.,* 2018). While crop production generally increases the ecosystem NPP through the growth of crops (in this case maize), the fact that the natural vegetation still needs to be cleared to make way for cultivation, still affects the availability of NPP. Also, the clearing of vegetation reduces high potential NPP and replaces it with low NPP since the lifespan of natural vegetation is longer than that of cultivated crops (Abdi *et al.*, 2014).

The results from maize crop production build on existing knowledge of the state of crop production among rural households in southern Africa, with an emphasis on the changing patterns of crop production. This study provides an insight on how crop production is no longer the main source of food among rural South African households. While in most of southern Africa, rural households still derive most of their food from crop production; with the government social grants, remittances from urban areas and a relatively better economy, most rural households in South Africa are possibly relying more on cash-based food. This also puts South Africa at a less rural position as compared to other countries in southern Africa and rural livelihood analysis policies need to take this into consideration.

3.4.2 Gross and net carbon redirection and the proportional contribution of each activity to gross and net carbon redirection at the household level

This section looks at the gross and net carbon patterns at the household level, for both user households and all households. Net carbon entails the carbon removed after accounting for carbon that is returned to the environment in gaseous form (carbon dioxide; methane) and in solid form as dung. A few studies have looked at carbon patterns associated with land-based activities at local levels, such as Pritchard *et al.* (2018) in Zimbabwe, and Bartels *et al.* (2016) in Tanzania, but, few have focused their analysis at the household level, and most of them only considered biomass removal by anthropogenic activities, without factoring in backflows to the environment i.e. have not quantified net appropriation of NPP. As such, this study makes a significant contribution to the discussion of land-based livelihood activities and how they influence carbon patterns at household levels in southern African savannas.

As stated in the previous sub-section (3.4.1), this study found that fuelwood usage and maize production had the highest prevalence of use among all household land-based activities. However, the high prevalence of use did not translate into the highest carbon consumption among households. Instead, the highest gross and net carbon redirection among both user-households and averaged across all households was through cattle. Thus, across all households, the most total gross and net carbon with and without crops was redirected by livestock from 2010 to 2014. Thus, although relatively uncommon, cattle owners have a disproportionate impact on carbon dynamics in this savanna socio-ecological system. Through grazing and browsing, changes occur to the productivity of vegetation and cover, and species abundance and life forms affect the ecosystem's carbon cycle (Houghton, 2015).

The removal of biomass through grazing and browsing has the potential to change ecosystem processes such as erosion, disturbance types and frequency, species invasion, and the structural and biochemical characteristics of soils, and all these in some way affect the carbon cycle (Asner and Archer, 2014). Once the vegetation is digested by livestock through their feed intake, CO_2 is released to the atmosphere through respiration, methane is released to the atmosphere through enteric fermentation and manure, and carbon is returned to the environment through livestock dung (Equations 6-11, Appendix 2 and 3). Methane, with its global warming potential 23 times that of CO_2 is potentially more detrimental to the carbon cycle than CO_2. However, the atmospheric lifetime of methane is approximately 9.6 years, while that of CO_2 is in the order of one to two centuries (Sonnemann and Grygalashvyly, 2014).

The second highest carbon consumption was redirected through fuelwood use among user households and averages across all households. Although fuelwood use is different from livestock farming as land-based activities, they can be compared in the sense that both remove biomass from the environment and can be compared to contribute to the understanding of the dynamics involved in land-based livelihood activities at the household level and their relative impact on the redirection of carbon. Thus, relatively, fuelwood redirects less carbon substantially as compared to livestock farming, although the prevalence of use among households is higher for the former.

Carbon consumed at the household level through maize crop production and goat ownership were the least of all the land-based activities, with goat ownership being the lowest of all. However, maize crop production contributed the least to total gross and net carbon redirection. The amount of maize harvested was on average 353 kg per household per year; this translated to 345 kg gross carbon. The lowest amount of carbon redirected through goat ownership could be attributable to the fact that goats are relatively smaller in size and hence their emissions as compared to cattle body size. In addition, when energy requirement is expressed on a $LW^{0.75}$ (live weight) basis, cattle require more feed as compared with small ruminants such as goats (Nizar *et al.,* 2013).

When averaged across all households, fuelwood use had the largest difference between gross and net carbon redirected, followed by cattle ownership and goat ownership, respectively. This is explained by the total carbon emissions associated with fuelwood use, with only ash remaining, as compared to total emissions from livestock. Thus, although the amount of GHG emissions from burning wood is lower than that released by cattle at household level, they are higher as a proportion of carbon removed from the environment.

When it comes to user households, gross and net carbon redirected through cattle ownership had the largest difference, followed by fuelwood use and goat ownership, respectively. As this is for user households only, this is indicative of the greenhouse gas emissions associated with an individual livestock (cattle or goat), and therefore their relative contribution to the amount of carbon redirected at the household level through land-based activities.

Among user households and across all households, gross and net annual carbon redirected varied significantly between years for fuelwood and maize production. For cattle, the gross and net annual carbon redirected only varied significantly among user households. The significant variation between years in gross and net carbon redirected through cattle ownership and maize production could have been caused by variation in rainfall between years. Rainfall is highly variable in the study region, and in South Africa generally (Wessels *et al.*, 2013) . As such, if variation in rainfall occurred during the study years, this could have resulted in plant productivity variation in terms of maize crops productivity. For example, the lower prevalence of maize cultivation and lower maize production in 2012 was associated with a 2011/2012 growing season that received rainfall 30% below the long-term mean.

Carbon is redirected by cattle and goats through the removal of biomass in the form of grazing and browsing. Although not the focus of this study, livestock also impact on the carbon cycle in other indirect ways such as trampling which causes topsoil compaction and in the end this degrades its physical quality, decreases its hydraulic conductivity and lowers plant coverage and this results in greater magnitude of runoff (Ndangalasi *et al.,* 2007). It has been established that many South African semi-arid grazing systems (including communal rangelands) have become degraded as a result of a history of chronic heavy livestock grazing (O'Connor, 2015). As such, heavily grazed rangelands exhibit symptoms of progressive degradation (Du Toit and Cumming, 1999).

In general, degradation has been found to occur under sustained and prolonged high grazing intensities, where perennial grass abundance decreases and woody plant species become abundant leading to a decrease in productivity and biodiversity of the system in the process called bush encroachment (Lohmann *et al.*, 2012). Bush encroachment, which is estimated to have an extent of 10-20 million hectares in South Africa, is considered one of the most extensive forms of degradation in rangelands in arid and semi-arid regions (Lukomska *et al.,* 2010; Stafford *et al.*, 2017). This is because it decreases the diversity of species and ground layer productivity and thus reduces feed availability for grazers such as cattle (Eriksen and Watson, 2009). Grazing was identified as one of the principal causes of carbon loss from most rangelands (Reid *et al.*, 2004). Degraded soils occur because of the removal of plants by grazing which reduces leaf and root biomass, and ultimately this leads to reduced litter input and shifts in soil bacterial communities and soil C processes (Zhou *et al.*, 2018). However, Parsons and Rowarth (2009) assert that an increase in the stocking rate of livestock will reduce all carbon fluxes. This is likely to be the case in some communal areas of South Africa, while it will differ in others because, this study found the prevalence of cattle ownership among these rural communities to vary from one communal rangeland to the next.

On the other hand, fuelwood harvesting is believed to have a complex interrelationship with deforestation, which in turn is known to exacerbate conditions that could produce global warming, such as the release of CO_2 into the atmosphere (Link *et al.,* 2012). However, it was found that deforestation resulting primarily from fuelwood harvesting has been exaggerated (Twine and Holdo, 2016). If fuelwood is used unsustainably, it could lead to continuation of rural communities impoverishment and long-term woodland degradation (Wessels *et al.*, 2013). However, if managed wisely and harvested within sustainable limits however, fuelwood can continue to meet the energy, construction and other needs of the rural poor (Williams and Shackleton, 2002). There is therefore increasing concern that deforestation and degradation resulting in the loss of mature trees has the potential to result in the transformation of the woodlands into scrublands or grasslands, with the associated decline in biodiversity and biomass, and increase in carbon emissions (Ribeiro *et al.*, 2013). This is because substantial amount of carbon is stored in woodland and thus large trees are a valuable sink of carbon. Given the fact that unsustainable use of fuelwood has been observed in the Bushbuckridge region, a suggestion has been made for coppice regrowth to be investigated as a method to manage the sustainable use of fuelwood resources (Kaschula *et al.,* 2005). It has been established that coppicing is significant in meeting high fuelwood demand in savanna systems (Twine and Holdo, 2016). Unless the socio-economic aspects of rural households in South Africa drastically change, fuelwood harvesting will continue to redirect carbon from the savanna socio-ecological system of South Africa and the rest of sub-Saharan Africa.

Crop production is one of the anthropogenic activities that lead to soil degradation with attendant emission of CO_2 and other greenhouse gases (Lal, 2004). In addition, the removal of vegetation into cropland releases substantial amounts of CO_2 and also reduces the carbon sink potential (Lindeskog *et al.*, 2013). This is demonstrated in a study in Zimbabwe where it was found that rapid decline of organic carbon was evident in the initial years of cultivation on smallholdings at all sites; a greater loss of organic carbon was also observed in coarse-textured soils in South Africa (Zingore *et al.*, 2005). It is further indicated that improving agriculture on smallholdings could enhance food security and the life of the rural poor, as well sequestering more carbon in the soil (Zingore *et al.*, 2005). Of all the livelihood land-based activities under this study, maize crop production appears to have less impact on the redirection of carbon and will continue to do so at the household level. This is made even more possible by a projected decline of crop production among rural households in South

Africa and in some countries in sub-Saharan Africa through the process of cropland abandonment as established by this study.

Data on fuelwood use, livestock ownership and maize crop production and associated gross and net carbon fills an important knowledge gap identified by Berger *et al.* (2019) and Ciais *et al.*, (2011), of the southern African carbon budget and its projected changes that are uncertain, as well as lacking knowledge of CO_2 fluxes for savanna areas under human land-use. Through the analysis of gross and net carbon patterns of the land-based activities at the household level, this study gives an insight on NPP patterns through a bottom-up approach as this study first analysed data at the household level before it was up-scaled at the village level. As a result of this, a knowledge gap which (Williams *et al.*, 2007) identified of the need for continent-wide observations supporting both bottom-up and top-down methods of estimating carbon sources and sinks, is filled. Many studies have already looked at fuelwood use, livestock farming and maize crop production at the household level but very few have looked at the NPP patterns through gross and net carbon associated with these activities, which are important for climate change mitigation policies. Hebinck *et al.* (2018) assert that the African landscape needs to be read in ways that are different than is commonly done in the academic literature and policy documents and initiatives.

Although GHG emissions from fuelwood are the highest in comparison to the other two livelihood activities. The burning of biomass fuels such as fuelwood may be neutral if the CO_2 emitted is reabsorbed in the following growing season by tree growth and resprouting, if fuelwood is harvested at sustainable levels(Stoten *et al.,* 2016). In the case of Bushbuckridge, sustainable harvesting might be a challenge as signs of fuelwood scarcity has already been experienced (Dovie *et al.,* 2004).

Thus, the balance reabsorption indicated above might be impossible. With regard to GHG emissions from livestock, irrespective of the amount emitted, this should be a concern. This is because, as ruminants, one of the gases emitted, methane (CH_4) accounts for 17-37% of global anthropogenic methane (CH_4) (Brouček, 2015).

Data on carbon backflows associated with land-based livelihood activities at the household level are crucial in the understanding of the carbon cycle dynamics because GHG are major sources of atmospheric pollution. Thus, if the impact of the use of fuelwood and livestock on local environments is to be measured, and possibly give an impression of these emissions as sources of atmospheric pollution (Brocard and Eva, 1998), estimates such as these at the household level are important. If the local environment is to be sustainably maintained, all activities (such as fuelwood harvesting and livestock farming GHG emissions) with the potential to destabilise ecosystems need to be analysed.

3.5 CONCLUSION

The results of this study contribute to the scientific knowledge on the redirection of carbon in the savanna socio-ecological systems of southern Africa associated with the main land-based activities (fuelwood use, livestock farming, and maize crop production) that support rural livelihoods and the resultant gross and net carbon patterns. This also includes carbon backflows from fuelwood harvesting and livestock farming, a component not usually considered in HANPP studies. With fuelwood harvesting having the highest prevalence of use, this appears to suggest that the South African government post-Apartheid rural electrification programme has not had a significant impact on the reduction of fuelwood use. In light of this, the redirection of carbon by fuelwood harvesting will continue for some foreseeable future and will thus continue to influence the savanna carbon cycle. Nevertheless, this study established that fuelwood use does not redirect as much carbon as livestock farming despite its high prevalence. The results also established a low prevalence of livestock ownership as well as livestock numbers, indicating a possible change in rural economic dynamics as far as livestock husbandry is concerned. Despite the low prevalence, livestock farming redirected the most carbon among all the activities under this study. This indicates the potential impact that livestock has on the carbon cycle in comparison to other activities, despite low prevalence of livestock ownership at a household level. The findings of this study found a low participation of most households in maize crop production outside of the village. As a supposed source of food for rural households, this indicates that most households are becoming more dependent on cash-based economy supported mainly by the government social grant and urban remittances, thus likely diminishing the role of subsistence crop production on the carbon cycle in such systems. A limitation of this study is that it did not factor in rural households' shifting preferences towards consumer-based lifestyles. Future studies should include consideration of the redirection of the carbon cycle through these consumer-based activities at the household level.

CHAPTER 4

STATISTICAL RELATIONSHIPS BETWEEN HOUSEHOLD CARBON REDIRECTION AND HOUSEHOLD SOCIO-ECONOMIC AND DEMOGRAPHIC CHARACTERISTICS.

ABSTRACT

The livelihoods of rural communities in Africa depend on land-based activities such as agriculture and harvesting of natural resources. Variables such as household size, gender, age and gender of the head of household, and household wealth have been shown to influence household engagement in these land-based livelihood activities, which in turn, are likely to influence household Net Primary Productivity (NPP) footprints. However, data on the direct influence of household characteristics on carbon redirection through their land-based activities is lacking. To address this gap, this study analysed statistical relationships between household carbon redirection and household socio-economic and demographic relationships. Associations between selected household socio-economic and demographic characteristics and a) the likelihood of a household engaging fuelwood use, cattle and goat ownership, and maize production, and b) the net mass of carbon redirected from the local environment per household annually by these activities were investigated using multiple logistic and linear regression models. Statistically significant relationships emerged from the results. For example: the likelihood of a household using fuelwood increased significantly with household size and the proportion of female members in the household. The likelihood of a household owning cattle increased significantly with the age of the household head. The likelihood of maize crop production increased significantly with household size, proportional number of females in a household and age of the head of a household. Net carbon redirected per household by fuelwood use increased significantly with household size, proportion of female members and age of the household head. Net carbon redirected by cattle per household increased significantly with age of household head and household wealth. These results improve the understanding of the factors driving the use of natural resources and associated net carbon redirection by households in southern African savannas such as gender or age of the head of a household and give insight into potential carbon trajectories in these socio-

ecological systems under changing socio-economic and demographic conditions. For instance, as socio-economic dynamics change such as changes in household size or the age of the head of a household, so will carbon off-take from these environments.

4.1 INTRODUCTION

Rural communities in the developing world use a variety of non-timber forest products (NTFPs) that contribute to livelihoods through provisioning for household domestic needs, income generation, and as a safety net in times of crisis (Shackleton *et al.*, 2002). Although the use of NTFPs is widespread, the extent of use, the quantities used and the value derived vary spatially, temporally and depending on various household characteristics (Paumgarten and Shackleton, 2011). In any given community, there is significant socio-economic differentiation arising from a number of factors such as levels of employment, education, and age (Shackleton *et al.,* 2001). Thus, the dependence on NTFPs by rural households for their livelihoods varies according to a set of demographic factors and socio-economic conditions (Hussain *et al.*, 2019). There is a limited number of in-depth quantitative studies in southern Africa that have explored the relationship between NTFP use and selected socio-economic characteristics of households (Cavendish, 2002; Dovie *et al.,* 2004; Shackleton and Shackleton, 2006). None of these studies have considered how livelihood strategies and socio-economic characteristics influence the redirection of the carbon cycle at the household level (Pritchard *et al.*, 2018). Socio-economic factors known to have an effect on natural resources use among rural households include education, cultural factors, distance to obtain the source, employment, household size, gender, age and gender of the head of the household, and wealth status (Cavendish, 2002; Timko *et al.,* 2010; Karimu, 2015). Shackleton *et al.*, (2019) indicate that the socio-economic factors are more important than environmental, and these drivers and their effects are site-specific and are strongly influenced by the social and historical context. These are therefore likely determinants of the manner and extent to which individual households redirect carbon from the local environment in rural African savanna socio-ecological systems. Given the importance of households in resource consumption, focusing on households is important to reducing environmental impacts (Bradbury *et al.,* 2014).

Household size has been identified as one of the household socio-economic factors that influence land-based livelihood activities among rural households. Accordingly, larger families rely on woodland resources to increase their income or meet their basic needs (Adams and El Tayeb, 2014). This is especially so when households lack other income generation options such as formal employment (Garekae *et al.,* 2017). Also, the more members a household has, demand for natural and the harvesting capacity becomes high too (Thondhlana and Shackleton, 2012). In addition, larger households clear more woodland because they have more workers and because they have more mouths to feed (Mamo *et al.,* 2007). For example, a study found that for a unit influence of household size, households were about twice as likely to harvest mopane worms (Garekae *et al.,* 2017).

Gender is also one of the factors known to play a key role in the degree to which rural Africans depend on NTFPs as women's and men's rights, responsibilities, and expectations with regard to natural resources are generally culturally determined (Timko *et al.,* 2010). As such, collection and use of natural resources is strongly linked to the sex of the individual concerned (Cavendish, 2002). Females' extensive participation in land-based activities rather than paid work points to issues of power in the household and gender inequality in the control of key resources (Dovie *et al.,* 2005). For example, the economic fortune of males in an Ethiopian society comes partly from the socio-cultural dominance of men, which gives them more opportunities for owning key productive resources such as land and engaging in more lucrative activities than women (Vedeld *et al.*, 2007). Also, Bennett *et al.* (2013) indicate that many women remain marginalised and disadvantaged in many ways such as power relations and access to resources, and thus this leads to gender differences in terms of natural resources use.

Gender of the household head is another socio-economic factor that has bearing on the use of natural resources. For example, Cavendish (2002) indicate that in Zimbabwe, remittances dominate the income accounts among female-headed households and thus these households are "cash-rich" and collect fewer natural resources. However, this might only be unique in some instances such as the one in Zimbabwe. This is because Mamo *et al.* (2007) indicate that female-headed households are found in woodland-based low return cash activities in male-dominated rural settings, who are unable to make a significant living from agriculture as a result of the absence of male labour for activities such as ploughing. Similarly, male-headed households are less likely to be found in woodland dominated activities because they have more economic options than their female counterparts (Babulo *et al.*, 2008). All in all, households headed by women are often disproportionately represented in the poorer sectors of rural communities, and thus NTFPs often contribute significantly more to total household income than is the case for households headed by men (Shackleton and Shackleton, 2006).

As far as age of the household head is concerned, it is indicated that older individuals for instance are unable to conduct certain economic activities which demand considerable effort and thus eventually turn to activities that involve less physical labour (Cavendish, 2002). On the other hand, older people are more knowledgeable in various woodland resources, and may therefore utilise more medicine plants and wild foods than their younger counterparts (Mamo *et al.,* 2007). Mbiba *et al.* (2019) found that in Bushbuckridge, the quantities of natural resources used by housed was positively associated with age of the household head. Concerning agriculture, Swarts and Aliber (2013) also indicate that the youth are less likely to pursue agriculture because of a lack of access to, or control over, productive assets such as land.

The way households use NTFP resources depends on their wealth levels (Luckert *et al.,* 2000; Cavendish, 2003). An increase in the financial status of a household does not always result in a decrease in the use and quantity of natural resources as it has been proven otherwise by (Cocks, 2008). If anything, Mamo *et al.* (2007) establish that better endowment of assets allow households to exploit more woodland resources. An example is indicated by Thondhlana and Shackleton (2012) of wealthy households in some communities who hunt wild animals for commercialisation due to political connections without punishment from the local authorities and thereby using more resources than poorer households. However, wealthier households buy significantly more products than their poorer counterparts, while the intermediate households fall between these two classes (Shackleton and Shackleton, 2006). Thus, due to few economic opportunities, poorer households are often involved in more opportunistic, low-skill, and low return activities with few barriers of entry such as trading in wild fruits, vegetables, and other products such as traditional beer (Shackleton and Shackleton, 2004). As such, wild resources contribute an average 40% of total household income for poorer households, while 29% for wealthy households in a communal area in Zimbabwe (Cavendish 2000). Garekae *et al.,* (2017) and Lepetu *et al.,* (2009) also indicate that households with larger wealth assets are less dependent on woodland resources. Shackleton and Shackleton (2006) assert that there is no difference in the proportion of households that use NTFPs, nor the total number of NTFPs used per household as far as household wealth is concerned. However, the difference is in the way households of different wealth commercialise natural resources; a difference less pronounced around domestic consumption (Shackleton and Shackleton, 2006). Thus, proportionally, poorer households sell one or more NTFPs and across households, they sell a greater number of NTFPs per household in comparison to their wealthy counterparts as this is their only source of income (Shackleton and Shackleton, 2006).

Socio-economic factors that influence household use of natural resources are contextual (Mamo *et al.,* 2007), meaning that their influence on the use of natural resources differs relatively from one rural setting to another. There is a knowledge gap in the understanding of the nature and drivers of decision-making by households whose livelihoods are dependent to a great extent on natural resources (Thornton *et al.*, 2007). This study aims to determine statistical relationships between household socio-economic and demographic characteristics and household carbon redirection through fuelwood use, livestock farming and maize crop production. The household socio-economic and demographic characteristics are the 'drivers of decision-making' that Thornton *et al.* (2007) refers to above. The first sub-objective looks at the likelihood of fuelwood use, ownership of livestock and maize production as influenced by household characteristics, while the second sub-objective focuses on the influence of household characteristics on household net carbon per source and total net carbon across all sources. Using five household socio-economic independent variables that were possible to compute from available household data, and have been identified in the literature as being predictors of resource use, the study tested the following hypotheses: Hypothesis 1 - larger households redirect more carbon via fuelwood, livestock, and maize crop production, and more carbon in total than smaller households; Hypothesis 2 - female-headed households redirect more carbon via fuelwood and maize crop production, but less through livestock, than male-headed households; Hypothesis 3 - households with a higher proportional number of females redirect more carbon through fuelwood and maize crop production, and less through livestock and less carbon in total, compared to those with fewer females; Hypothesis 4 - households headed by older people redirect more carbon via fuelwood, livestock, and maize crop production, and more carbon in total than households headed by younger people; and Hypothesis 5 - wealthier households redirect less carbon via fuelwood, but more through livestock and maize crop production and redirect more carbon in total than poorer households.

4.2 METHODS

Data from Chapter 3 on household engagement in livelihood activities and net carbon redirection through fuelwood harvesting, cattle and goat farming, and maize production were used to explore relationships between these livelihood strategies and household socio-economic and demographic characteristics using statistical models. Multiple logistic regression models were used to determine the likelihood of households' engagement in fuelwood harvesting, livestock ownership and maize crop production. Logistic regression is used to analyse associations between a binary dependent variable and continuous or binary predictor variables (Nima, 2018). Thus, these regression analyses were done to determine the likelihood of households' engagement in fuelwood harvesting, livestock ownership and maize crop production. In this case, the likelihood of households' engagement was the binary variable dependent on a set of binary independent (predictor) variables (numbers of members in a household, household size, proportional of household members that are female, age of the household head, gender of the household head, and household wealth.

Multiple linear regression models were used to determine the influence of household socio-economic characteristics on the use of fuelwood, livestock ownership, and maize production. A multiple linear regression analysis is carried out to predict the values of a continuous dependent variable, given a set of predictable variables (Hasan, 2020). The models contained five household socio-economic independent variables namely: number of members in a household (household size), proportional of household members that are female, age of the household head, gender of the household head, and household wealth. Fuelwood net carbon, cattle and goat net carbon, and maize net carbon were the continuous dependent variables. In the absence of any prior-knowledge of the linearity of the relationships between dependent and predictor variables, linear regression models were the most appropriate, especially for multivariate models. In general, a multivariate regression (be it linear or logistic) model estimates more than one outcome based on a set of predictions (Anderson and Fu, 2016), which was the basis for using multiple linear and logistic regressions to get the outcomes that were obtained for this study. However, logistic regression is used on a binary dependent variable while linear regression is used on a continuous dependent variable and that necessitated both models. Logistic regression is similar to multivariate linear regression in that both create a model to describe the impact of multiple predictors on a single response variable; however, in logistic regression, the outcome variable must be categorical (Worster, Fan, and Ismaila, 2007).

Household wealth has been quantified in various ways, such as by the number of modern appliances, traditional assets owned such as livestock, in terms of income, or the ability to pay school fees, the size and style of house, or employment (Twine *et al.*, 2003; Shackleton and Paumgarten, 2011; Sartorius *et al.*, 2014). Scoones (2017) points out biases imposed by the design of the questionnaire and the influence of the researcher, as well as the inadequate reflections of poverty indicators as some of the weaknesses of the stratification of houses according to wealth difference. Although Adams and Evans (1997) have recognised the strength of the method as its adaptability to local circumstances, they have also indicated the weakness of the approach as it is unable to identify or quantify differences in specific dimensions of household wealth. Thus, Adams and Evans (1997) advised that the approach should never be standardised. Scoones (2017) further emphasised that wealth is best defined when the individuals surveyed can decide what wealth means to them. For example, in this study among rural households in Zimbabwe, the local participants in the survey ranked a household headed by a widow as poor although the household possessed a number of assets and a reliable source of remittance income.

Be that as it may, this study derived households' wealth status indexed by total number of assets owned by households. These assets were electrical/gas stove, refrigerator, television, video player, satellite dish, radio, fixed telephone lines, cellular phone, sewing machine, plough, car, tractor, motor bike, bicycle, and donkey cart. Livestock were not included in the wealth index to avoid circularity in analyses of the relationships between wealth and these livelihood activities since livestock net carbon is already treated as a dependent variable in the models discussed above. Due to reasons such as seasonal variability in earnings, multiple and diverse informal activities, high rates of self-employment among low and middle-income rural settings, household assets index has proven to be a better proxy for a household's longrun wealth as compared to information on income or expenditures (Kabudula *et al.,* 2017). It is against this background that this study used asset ownership as a means of indexing wealth. Despite the short-comings of various methods of determining a household wealth status. Descriptive statistics of independent variables and statistical relationships between independent variables were determined. The association between household variables and the likelihood of a household engaging in land-use practice (using fuelwood, farming with cattle or goats, or cropping with maize) was investigated using multiple logistic regression models, while controlling for year of study. The influence of the same household variables on household net carbon redirection per livelihood activity while controlling for year of study, was then explored using multiple linear regression models. Net carbon redirection per land use is directly related to the mass of fuelwood consumed, number of livestock owned, and mass of maize produced. Therefore, given that net carbon was the ultimate variable of interest, first analysing the relationship between these metrics and household socio-economic and demographic characteristics would have resulted in unnecessary redundancy in the results. Similarly, the gross and net carbon redirected per activity were perfectly correlated, so it would have also been redundant to analyse for both gross and net carbon redirected. The study also tested relationships between independent variables. All analyses were performed in Statistical Package for Social Science software (SPSS).

4.3 RESULTS

4.3.1 Description of independent variables

This study's findings indicate that on average, each household had between 7 and 8 household members from 2010 – 2014 **(Table 4.1).** Between 51% and 52% of household members were female. On average, between 42% and 44% of households were headed by women from 2010 – 2014. Household heads were on average between the age of 51 and 56 years old. Because this is a cohort study, the average age of the head gradually increased over the five- year study period. Lastly, the mean total number of assets per household was 5-6. The trends were similar across all villages.

Table 4.1: Mean ±SE of independent variables per year, 2010 - 2014

Variables	2010	2011	2012	2013	2014
Members	7.71±0.17	7.64±0.17	7.41±0.17	7.71±0.17	7.59±0.17
Prop Female	0.52±0.01	0.52±0.01	0.51±0.01	0.51±0.01	0.51±0.01
Female Head	0.42±0.02	0.43±0.02	0.43±0.02	0.42±0.02	0.44±0.02
Head Age	51.84±0.61	53.40±0.61	53.67±0.62	55.39±0.62	56.05±0.60
Assets	5.17±0.08	5.43±0.07	5.78±0.07	5.56±0.08	5.53±0.08±

A significant positive relationship was found between household size and the proportional number of females in a household. Likewise, household size and the age of the head of household; as well as the proportional number of females in a household and female-headed households had significant positive relationships. Other significant positive relationships were identified between female-headed households and the age of households; as well as between the age of the household head and household wealth. Significant negative relationships were found between female-headed households and wealthy households; and between the proportional number of females in a household and the age of the household head **(Table 4.2)**. Collinearity of independent variables can be problematic for fitting regression models if too high. Therefore, multi-collinearity in the matrix of these independent variables was assessed using the *coldiag2* command in Stata 16. The resultant conditional number was 8.14; well below the suggested threshold of 30, meaning that the degree of collinearity between variables was unlikely to be problematic in the regression models that follow (Carsten *et al.,* 2012).

Table 4.2: Co-efficient of correlation between independent variables (pooled across years)

Variables	Members	Prop. Female	Female Head	Head Age	Assets
Member	1	0.037	-0.017	0.291**	0.183**
Prop Female	0.037	1	0.283**	-0.088**	-0.039*
Female Head	-0.017	0.283**	1	0.157**	-0.169**
Head Age	0.291**	-0.088**	0.157**	1	0.108**
Assets	0.183**	-0.039*	-0.169**	0.108**	1

*p<0.05, **p <0.01.

4.3.2 The likelihood of fuelwood use, livestock ownership and maize production as influenced by household characteristics

The likelihood of a household using fuelwood increased significantly with household size and the proportion of female members in the household. However, it was negatively associated with female-headed households and with wealth status **(Table 4.3).** There was no significant association with age of the household head. There was no significant difference between years either.

Table 4.3: Logistic regression analysis of the likelihood of fuelwood use, 2010 – 2014 (2010 is the reference year)

Variables	Coefficient	Std. Error	Odds ratio	Wald	P value
Members	0.144	0.027	1.155	27.730	**0.001**
Prop Female	1.078	0.415	2.939	6.744	**0.009**
Female Head	-0.375	0.174	0.687	4.637	**0.031**
Head Age	0.010	0.006	1.010	2.626	0.105
Assets	-0.215	0.047	0.806	21.357	**0.001**
Year 2011	0.103	0.115	1.108	0.801	0.371
Year 2012	0.147	0.079	1.158	3.417	0.065
Year 2013	0.076	0.060	1.079	1.606	0.205
Year 2014	0.096	0.050	1.101	3.699	0.054
Constant	1.688	0.439	5.407	14.783	0.001

Model X^2 = 221.52 p<0. 001
Pseudo R^2 = 0. 159
Log Likelihood = 1 607.17

The likelihood of a household owning cattle increased significantly with the age of the household head. It was negatively associated with female-headed households **(Table 4.4).** The household size and the proportional number of females in the household had no significant impact on the likelihood of a household owning cattle. There were no significant differences between years.

Table 4.4: Logistic regression analysis of the likelihood of cattle ownership, 2010 – 2014 (2010 is a reference year)

Variables	Coefficient	Std. Error	Odds ratio	Wald	P value
Members	-0.015	0.016	0.985	0.935	0.333
Prop Female	-0.333	0.379	0.717	0.774	0.379
Female Head	-0.279	0.141	0.757	3.879	**0.049**
Head Age	0.041	0.005	1.042	77.041	**0.001**
Assets	0.363	0.039	1.037	86.880	0.713
Year 2011	0.037	0.100	1.037	0.135	0.713
Year 2012	-0.018	0.067	0.982	0.073	0.787
Year 2013	-0.003	0.051	0.997	0.004	0.949
Year 2014	0.012	0.040	1.012	0.096	0.757
Constant	-6.080	0.421	0.002	208.913	0.001

Model X^2 = 237.225 $p<0.001$
Pseudo R^2 = 0. 159
Log Likelihood = 1 775.677

The likelihood of the ownership of goats increased significantly with household size, the age of the household head, and household wealth. However, the likelihood of owning goats was negatively associated with the proportional number of females in a household **(Table 4.5).** The gender of the head of a household had no significant influence. There were no significant differences between years either.

Table 4.5: Logistic regression analysis of the likelihood of goat ownership, 2010 – 2014 (2010 is reference year)

Variables	Coefficient	Std. Error	Odds ratio	Wald	P value
Members	0.099	0.015	1.104	45.357	**0.001**
Prop Female	-1.313	0.407	0.269	10.399	**0.001**
Female Head	-0.081	0.142	0.922	0.324	0.569
Head Age	0.016	0.005	1.016	10.917	**0.001**
Assets	0.126	0.039	1.134	10.671	**0.001**
Year 2011	0.053	0.100	1.055	0.283	0.595
Year 2012	-0.024	0.069	0.976	0.122	0.727
Year 2013	0.017	0.051	1.018	0.117	0.732
Year 2014	-0.003	0.041	0.997	0.006	0.937
Constant	-3.904	0.402	0.020	94.332	0.001

Model X^2 = 120.910 $p<0.001$
Pseudo R^2 = 0. 088
Log Likelihood = 1 720.802

Lastly, the likelihood of maize crop production increased significantly with household size, proportional number of females in a household and age of the head of a household **(Table 4.6)**. Gender of household head and household wealth had no significant influence. There were no significant differences between years too.

Table 4.6: Logistic regression analysis of the likelihood of maize crop production, 2010 – 2014 (2010 is reference year)

Variables	Coefficient	Std. Error	Odds ratio	Wald	P value
Members	0.064	0.027	1.066	5.685	**0.017**
Prop Female	1.854	0.432	6.385	18.423	**0.001**
Female Head	-0.044	0.181	0.957	0.059	0.809
Head Age	0.034	0.007	1.035	26.488	**0.001**
Assets	0.029	0.047	1.029	0.378	0.539
Year 2011	-0.188	0.136	0.828	1.904	0.168
Year 2012	-0.101	0.082	0.904	1.511	0.219
Year 2013	-0.037	0.066	0.964	0.316	0.574
Year 2014	-0.100	0.090	0.905	1.228	0.268
Constant	0.072	0.555	1.075	0.017	0.869

Model X^2 = 75.458 p<0. 001
Pseudo R^2 = 0. 74
Log Likelihood = 1 195.75

4.3.3 The influence of household characteristics on household net carbon redirection per livelihood activity and in total

Net carbon redirected per household by fuelwood use increased significantly with household size, proportion of female members and age of the household head, but was negatively associated with a female head and with household wealth **(Table 4.7).** Carbon values increased by 6.83 kg with each additional household member, by 47.4 kg with every increment in the proportion of household members that were female, and by 1.3 kg with every additional year of age of head of the household. Having a female head was associated with a decrease of 18.2 kg net carbon relative to male-headed households, as well as with a decrease of 3.9 kg with every additional asset owned. The only significant year effect was in 2012, in which fuelwood carbon redirection was, on average, 6.3 kg higher than in 2010, all else held equal.

Table 4.7: Linear regression analysis of fuelwood net carbon redirection, 2010 – 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	6.83	0.716	0.185	9.358	**0.001**
Prop Female	47.37	14.923	0.059	3.002	**0.002**
Female Head	-18.19	5.983	-0.062	-3.040	**0.002**
Head Age	1.34	0.207	0.129	6.470	**0.001**
Assets	-3.97	1.598	-0.049	-2.487	**0.013**
Year 2011	0.16	4.205	0.001	0.038	0.969
Year 2012	6.29	2.831	0.053	2.223	**0.026**
Year 2013	-0.74	2.154	-0.008	-0.345	0.730
Year 2014	-1.24	1.718	-0.017	-0.722	0.471
Constant	10.60	16.157		0.656	0.512

Model R^2 = 0.64
P = <0. 001

Net carbon redirected per household by cattle increased significantly with age of household head and household wealth **(Table 4.8).** However, it was negatively associated with household size and expectedly, with proportional number of females in a household. With each additional year of age of the head, carbon values increased by 18.7 kg and by 231.4 kg with each additional asset owned. Carbon values decreased by 24.5 kg with each additional household member. Likewise, there was a decrease of 720.7 kg with every increment in the proportion of household members that were female. The gender of a household head had no significant influence. There were no significant differences between years either.

Table 4.8: Linear regression analysis of cattle net carbon redirection, 2010 – 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	-24.83	10.531	-0.046	-2.358	**0.018**
Prop Female	-720.68	223.415	-0.065	-3.266	**0.001**
Female Head	-110.36	86.335	-0.026	-1.278	0.201
Head Age	18.69	2.984	0.125	6.263	**0.001**
Assets	231.39	23.060	0.197	10.034	**0.001**
Year 2011	-7.75	60.681	-0.003	-0.128	0.898
Year 2012	-37.47	40.857	-0.022	-0.917	0.359
Year 2013	-9.66	31.089	-0.007	-0.311	0.756
Year 2014	-0.40	24.798	0.000	0.016	0.987
Constant	-1 157.73	233.146		-4.966	0.001

Model R^2 = 0.64
P<0. 001

Net carbon redirected per household by goats increased significantly with household size and household wealth, but it was negatively associated with the proportional number of females in a household **(Table 4.9).** Net goat carbon increased by 1.3 kg with each additional member in a household and by 1.4 kg with each additional asset owned. On the other hand, carbon values decreased by 9.5 kg with each increment in the proportion of female members of a household. The gender of household head, and the age of household head had no significant influence. The values were equal between the years.

Table 4.9: Linear regression analysis of goat net carbon redirection, 2010 - 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	1.31	0.159	0.164	8.201	**0.001**
Prop Female	-9.52	3.382	-0.057	-0.281	**0.005**
Female Head	-1.02	1.307	-0.016	-0.799	0.436
Head Age	0.02	0.045	0.009	0.438	0.661
Assets	1.36	0.349	0.077	3.902	**0.001**
Year 2011	0.52	0.919	0.013	0.567	0.571
Year 2012	-0.02	0.619	-0.001	-0.028	0.978
Year 2013	0.27	0.471	0.013	0.564	0.573
Year 2014	0.12	0.375	0.008	0.325	0.511
Constant	-5.33	3.530		-1.511	0.745

Model R^2 = 0.43
P<0. 001

Net carbon redirected per household by maize production increased significantly with household size, age of the head of household, and household wealth. It was however negatively associated with a female-head **(Table 4.10**). Net maize carbon increased by 4.7 kg with each additional member in a household, by 3 kg with each additional year of age of the head, and with 6.4 kg with each additional asset owned. Having a female head was associated with a decrease of 48.3 kg net carbon in comparison to male-headed households. The only significant year effect was in 2011, in which fuelwood carbon redirection was, on average, 19.9 kg higher than in 2010, all else held equal.

Table 4.10: Linear regression analysis of maize net carbon redirection, 2010 - 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	4.689	1.453	0.064	3.226	**0.001**
Prop Female	21.035	30.791	0.014	0.683	0.495
Female Head	-48.313	11.913	-0.084	-4.055	**0.001**
Head Age	2.908	0.412	0.143	7.065	**0.001**
Assets	6.432	3.172	0.040	2.028	**0.043**
Year 2011	19.967	9.704	0.056	2.058	**0.040**
Year 2012	-10.614	5.528	-0.043	-1.920	0.055
Year 2013	0.419	4.171	0.002	0.100	0.920
Year 2014	8.144	5.832	0.041	1.396	0.163
Constant	-173.621	39.228		-4.426	0.001

Model R^2 = 0.041
P = <0. 001

Total net carbon per household *including maize* decreased with the proportional members of the household that are female and with households that are headed by females **(Table 4.11).** Total net carbon decreased with 664.4 kg with each additional increment in the proportion of female members of a household. Likewise, having a female head was associated with a decrease of 178.8 kg net carbon in comparison to households headed by males. However, total net carbon increased with the age of the household head and household wealth. Total net carbon increased by 22.8 kg with every additional year of age of the household head. Similarly, carbon values increased with 234.3 kg with every additional asset owned by households. Year (compared to baseline at 2010) had no influence on total net carbon.

Table 4.11: Linear regression analysis of total net carbon redirection (including crops), 2010 - 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	-11.704	11.902	-0.021	-1.055	0.291
Prop Female	-664.418	234.977	-0.057	-2.828	**0.005**
Female Head	-178.814	90.914	-0.040	-1.967	**0.049**
Head Age	22.836	3.141	0.145	7.270	**0.001**
Assets	234.283	24.207	0.189	9.678	**0.001**
Year 2011	0.376	63.830	0.000	0.006	0.995
Year 2012	-40.096	42.986	-0.022	-0.933	0.351
Year 2013	-8.151	32.759	-0.006	-0.249	0.804
Year 2014	2.515	26.088	0.002	0.096	0.923
Constant	-1294.360	244.952		-5.284	0.001

Model R^2 = 0. 69
P<0. 001

Similar to the scenario above, total net carbon per household *excluding maize* decreased with the proportional members of the household that are female **(Table 4.12).** Total net carbon decreased by 644.1 kg with each additional increment in proportion of female household members. However, total net carbon increased with the age of the household head and household wealth. Carbon values increased by 18.9 kg with every additional year of age of the household head. Likewise, total net carbon increased by 199.2 kg with every additional asset owned by households. Year (compared to baseline at 2010) had no influence on total net carbon.

Table 4.12: Linear regression analysis of total net carbon redirection (excluding crops), 2010 - 2014 (2010 is reference year)

Variables	Unstandardized Coefficient	Std. Error	Standardised Coefficient	T	P Value
Members	-15.73	10.355	-0.030	-1.519	0.129
Prop Female	-644.17	215.969	-0.059	-2.983	**0.003**
Female Head	-146.63	84.108	-0.035	-1.743	0.081
Head Age	19.00	2.884	0.129	6.585	**0.001**
Assets	199.16	19.804	0.194	10.056	**0.001**
Year 2011	-7.51	120.627	-0.001	-0.062	0.950
Year 2012	-75.44	121.673	-0.014	-0.620	0.535
Year 2013	11.09	120.762	0.002	0.092	0.927
Year 2014	50.91	119.702	0.010	0.425	0.671
Constant	-963.21	218.724		-4.399	0.001

Model R^2 = 0. 64
P<0. 001

4.4 DISCUSSION

4.4.1 The likelihood of fuelwood use, ownership of livestock, and maize crop production as influenced by household characteristics

The likelihood of fuelwood use, ownership of livestock, and maize crop production as influenced by household characteristics is discussed here. This is important because it focuses on the factors determining the likelihood of a household influencing the carbon cycle through these land-based activities. Through the longitudinal survey data, exploration of any changes that might have taken place over the study period (2010 to 2014) with regard to fuelwood harvesting, livestock farming, and maize crop production and the key household socio-economic drivers of household dependence on these was analysed.

This study found that the likelihood of a household using fuelwood increased significantly with household size, the proportional number of females in the household, and decreased significantly with female-headed households **(Table 4.3).** The positive relationship between household size and fuelwood use is consistent with studies in Nigeria and Zimbabwe (Cavendish, 2002; Buba *et al.,* 2017). This is attributed to larger families having adequate labour to allocate across gathering activities such as fuelwood harvesting and subsequently high levels of fuelwood use (Garekae *et al.,* 2017). The responsibility of gathering fuelwood in most developing countries lies in the hands of women and children (Makhado *et al.*, 2009; Karimu, 2015). This may explain the positive relationship between the proportional number of females in a household and the likelihood of fuelwood use. In addition, women in general have few financial opportunities as compared to their male counterparts who usually have an option of migrating to urban areas in search of employment opportunities making them less reliant on natural resources such as fuelwood (Babulo *et al.*, 2008).

The negative association between female-headed households and fuelwood use is puzzling given the above. Since fuelwood scarcity has already occurred in the Bushbuckridge area (Twine, 2005), it is possible that households either invest their limited financial resources into buying fuelwood, cook less often, and might have incorporated electricity into their household energy mix as coping strategies (Matsika *et al.,* 2013). Given their financial standing in society, it is also a possibility that women have no access to assets such as donkey-carts to collect wood from far. Statistical analysis between independent variables have also found a negative relationship between female-headed household and household wealth, indicating that in general households headed by females tend to also be poorer households with fewer financial resources to support their livelihoods. The negative association between fuelwood use and household wealth is consistent with Paumgarten and Shackleton (2011) who assert that the poorest rural households get multiple benefits such as fuelwood from the goods and services available in their immediate environments. Also, wealthier households would use fuelwood less because they are more inclined to more modern but costlier energy alternatives such as the use of electricity as opposed to the use of fuelwood (Madubansi and Shackleton, 2007).

This study found that the likelihood of a household owning cattle and goats increased significantly with age of the household head, while the likelihood of owning goats increased with household wealth **(Table 4.4 and 4.5).** The positive relationship between livestock ownership and older heads of households can be explained in the context of a typical sub-Saharan African rural set up where it is mostly older generation that remains in the rural areas while the youth migrate to urban centres for non-farm employment opportunities. A study in the Eastern Cape revealed that the youth's aspiration for a better life other than living a rural lifestyle, has caused a shift from an agrarian lifestyle (Blair *et al.,* 2018). The limited participation in livestock farming by younger people could also be attributed to the little incentive that young people feel is offered from the livestock farming activity and this ultimately discourages them from participating (Bennett *et al.*, 2013).

Shackleton *et al.* (2005) found that about 60% of rural households in the former homelands own goats, and only about 30% own cattle. This could explain why the likelihood of owning goats increased with household wealth as it appears that goat ownership tends to be higher than cattle ownership in rural areas. It is also interesting that cattle ownership was not correlated with the ownership of modern assets, and perhaps households would rather own modern assets instead of cattle. This is an indication that as cultural dynamics are changing, it is possible that rural households do not value cattle as much as they did in the past, and perhaps because goats perform the same cultural duties such as rituals as cattle do. Also, some farmers might prefer to invest in goats as opposed to cattle as goats are efficient foragers because they are grazers and browsers feeders, and they are more resilient to drought than cattle (Giannecchini *et al.*, 2007). The study also found a negative relationship between households headed by females and cattle ownership, and between the proportional number of females in a household and goat ownership. These relationships are explained in the same context because they both involve women and their role in livestock farming. The statistical analysis between independent variables indicate a negative relationship between female-headed households and household wealth. This implies that the majority of poorer households are headed by women and ultimately would not be in a position to purchase livestock.

The study also found that the likelihood of maize crop production increased significantly with household size, proportional number of females in a household and age of the head of a household **(Table 4.6).** The likelihood of a maize crop production increasing significantly with household size could be attributed to the ability of larger households to allocate labour to various household activities such as maize crop production (Mamo *et al.,* 2007). With the proportional number of females in a household, a study in the Eastern Cape found that women are the ones mainly responsible for household food production (Aliber and Hart, 2009). The likelihood of maize crop production being positively influenced by age of the head of a household could be explained by the fact that smallholder farming such as crop production is dominated by older women mainly because they are the custodians of farming knowledge (Ubisi *et al.*, 2017). However, this is only applicable if the older women are the ones heading the households.

This study provides an exploration of the relationship between household socio-economic characteristics and land-based activities at the household as opposed at the national levels. This offers explicit analysis of rural livelihood strategies and their effect on the carbon cycle as seen through the use of these land-based activities which are relatively accurate because national data are not always accurate.

4.4.2 The influence of household characteristics on household net carbon per source and total net carbon across all sources

This section's results area discussed under five hypotheses informed by the literature on the influence of household socio-economic characteristics on the use of fuelwood, livestock farming and maize crop production and subsequently net carbon associated with these land-based activities. The results are thus discussed under each hypothesis. Specific literature on the influence of household socio-economic characteristics on redirection of carbon is lacking, hence the lack of such comparative literature in the discussion below. This part of the study is informed by a need identified by Luckert *et al.* (2000) of the analysis of a relationship between household characteristics such as household wealth and the use and reliance on NTFPs which is required for understanding and modelling capabilities for rural areas such as the one under this study in southern Africa.

Hypothesis 1: Larger households redirect more carbon via fuelwood, livestock, maize crop production, and more carbon in total than smaller households

Net carbon redirected by households from fuelwood use increased significantly with household size which supported the hypothesis. This is because larger households typically use more fuelwood (Cavendish, 2002; Mamo *et al.,* 2007; Thondhlana and Shackleton, 2012). As such, a study in Uganda found that household size increased fuelwood demand by 49% as a result of increased quantity and frequency of cooking in a household associated with a large household size as well as increased labourers who would be available for fuelwood collection (Egeru, 2014). Larger households are able to clear more forest for fuelwood as well as for cropland, and ultimately use more fuelwood and cultivate crops since they have sufficient labour and more mouths to feed (Mamo *et al.,* 2007). However, a negative relationship was also found between household size and NTFPs dependency in Botswana which was attributed to different demographic profiles specifically because the average households in this particular study consisted of less than 6 people as compared to the studies stated above (Garekae *et al.,* 2017). The negative relationship is indicative of the fact that if a household has few members, it uses a small quantity of fuelwood, more so if most of the household members are male. According to this study's findings, larger households tend to have a higher number of females. The large quantity of wood collected by larger households and larger land cleared for cultivation would mean that more net carbon is redirected in comparison to smaller households.

With regards to net carbon redirected by livestock, the hypothesis is partly supported by this study's findings which indicate that net carbon redirection from goats increased with household size but decreased for cattle. The issue of financial affordability possibly responsible for the likelihood of households farming more with goats as opposed to cattle can still be applied as one of the reasons responsible for the positive relationship between goat net carbon and household size. This part consolidates the previous section of the explanations involved in the likelihood of larger households owning goats rather than cattle. Larger households are able to divert part of their labour to off-farm activities in an effort to earn extra income (Mugi-ngenga *et al.*, 2016). Part of that extra income could be allocated to the purchase of goats. Also, larger households have an advantage when it comes to labour because they are able to allocate part of their labour to other activities such as looking after goats (Mugi-ngenga *et al.*, 2016). The negative relationship between net carbon cattle and household size could also be because large-sized households mostly consist of women **(Table 4.9),** and financially, women are not as advantaged as men are as they have few opportunities to increase their income and therefore would not necessarily afford to buy cattle. As such, a study in Namaqualand, South Africa indicate that although women engage in a range of agricultural activities, a few of them are willing to challenge the patriarchal system that favours men when it comes to land allocation, and thus a few of them engage in independent livestock farming (Kleinbooi and Lahiff, 2007). This study's findings also established a positive relationship between net carbon from maize production and household size, which also supports the hypothesis. As previously stated, larger households are able to allocate their labour accordingly and that could also include crop production. In addition, larger households have got more mouths to feed and thus crop production would be necessary to ensure food is secured in the household.

What these results imply is that although larger households have the potential to redirect more carbon from the ecosystem through fuelwood and maize crop production, the influence of household size on livestock carbon redirection is dampened somewhat by the opposite relationships for cattle and goat ownership. Also, the impact of fuelwood and maize crop production on the carbon cycle is less than that of livestock because fuelwood gross and net carbon values are proportionately much lower than those of livestock. On an aggregate basis, larger households redirect more carbon through these land-based activities as this study has shown and this supports the hypothesis.

Hypothesis 2: Female-headed households redirect more carbon via fuelwood, but less through livestock and maize crop production and thus less total carbon, than male-headed households.

This study's findings did not support this hypothesis concerning fuelwood. This differs from studies elsewhere in South Africa and southern Africa but is consistent with the results of this study in the previous section, thus the same reasons apply. In the Eastern Cape, households headed by women often relied more on NTFPs than male-headed households (Shackleton and Shackleton, 2006). This means they derive much more benefits from their immediate environment such as using greater amount of fuelwood as they cannot afford other sources of energy such as gas or electricity. Also, in Zimbabwe, female-headed households generally derived greater total shares of income from the sales of natural resources such as wild fruit and thatching grass (Cavendish, 2002). Although the Zimbabwean example does not strictly address the use of fuelwood, it does give perspective in understanding the relationship between households headed by females and natural resources use.

Negative relationships between female-headed households and net carbon from livestock and maize and were observed, which support this hypothesis. Typically, rural women have few financial opportunities than men as alluded to in the previous section (Vedeld *et al.*, 2007). However, that might not be the only reason why female-headed households are not involved in livestock farming as compared to their male counterparts. In general, there appears to be a distinction between female-headed households and male-headed households and their role in livestock farming. On average, male heads tend to be younger than female heads of households and more likely to be primary income-earners, while female heads tend to conform to the conventional view of the head of the household as the key decision-maker (Posel, 2020). As such, the ability of a household to purchase and keep livestock might also extend to who the decision maker is and if they are in favour of livestock farming. Generally, women might be more concerned about the upkeep of the household needs and purchasing of livestock might not be one of the needs. Posel (2020) further adds that women assume responsibility for both spheres of resources allocation, even when they are not the primary income-earners, and thus the authority is more fully vested in them. With regard to maize crop production and households headed by females, this can be linked to their lack of participation in livestock farming. This leads to less access to draught power and manure which are derived from livestock especially cattle. This hinders their ability to partake in crop production. In Zimbabwe, Cavendish (2002) found that female-headed households receive remittances allowing them to purchase food and depend less on cultivation for food supply. Livestock farming proportionally emit more carbon relative to fuelwood harvesting. Considering the fact that most households headed by females are not involved in livestock farming, and more in fuelwood harvesting, this puts female-headed households in a position to redirect less carbon in total in comparison to their male counterparts, and this supports the hypothesis

Hypothesis 3: Households with a proportionally higher number of females redirect more carbon through fuelwood and maize crop production, and less through livestock, less carbon in total than households with fewer female members.

Net carbon redirected by households from fuelwood use increased significantly with the proportion of female members in a household, thus supporting the hypothesis. This relationship is explained through the context of activities such as fuelwood collection among African rural households which is mainly done by female members of the household as stated before (Cavendish, 2002; Makhado *et al.*, 2009; Karimu, 2015). Thus, if a household has a high number of females proportionally, it is also likely to harvest more fuelwood in comparison to a household with few female members. Also, females participate more in land-based activities such as the use of fuelwood rather than paid work because of gender inequality when it comes to controlling key resources (Dovie *et al.,* 2005). Thus, because they remain marginalised and disadvantaged in terms of power relations and access to resources, they use fuelwood more as their options such as using electricity instead of fuelwood, are limited (Bennett *et al.*, 2013). In addition, as per this section's statistical analyses, the findings reveal that most households headed by women are poor. On the other hand, a study found that men were associated with selective harvesting of forest resources such as fuelwood since they harvested those for selling, and also because they have access to assets such as animal driven carts, they extract and subsequently use more resources than their female counterparts (Mamo *et al.,* 2007).

A negative relationship was found between net cattle and goat carbon and the proportional number of females in a household, also supporting the hypothesis. Females are responsible for much of the household activities such as cultivation of the fields, collecting fuelwood, and the general upkeep of the household (Mugi-ngenga *et al.*, 2016), and might thus have less time for cattle and goat farming. This finding agrees with Dovie, Witkowski and Shackleton, (2005)'s Bushbuckridge study where it was observed that males participated mostly in the maintenance of livestock and females participated mostly in crop production further supporting the hypothesis. A study in Namaqualand, South Africa indicate that although women engage in a range of agricultural activities, a few of them are willing to challenge the patriarchal system that favours men when it comes to land allocation, and thus a few of them engage in independent livestock farming (Kleinbooi and Lahiff, 2007). Similarly, Bennett *et al.* (2013) revealed that women receive limited support in their efforts to expand their ownership of livestock assets. These findings appear to suggest that the economic disadvantage of females at the household level might influence the carbon cycle negatively as female members of households are generally more reliant on land-based livelihoods as Shackleton *et al.* (2007) also indicate. Similar to the scenario from the previous hypothesis, proportionally, females are less involved in the land-based activity (livestock farming) through which more carbon is redirected in total than the other two land-based livelihood activities. As such, these results support the hypothesis.

Hypothesis 4: Households headed by older people redirect more carbon via fuelwood, livestock, and maize crop production, and more carbon in total than households headed by younger people

Net carbon redirected by households increased significantly with age of the household head for all three livelihood activities, supporting the hypothesis. Older members of households tend to be more traditional in their values, preferences and aspirations. For example, older heads of households in Thulamela Municipality of Limpopo Province attributed the use of large quantities of fuelwood to the cooking activity as they believe that food prepared with fuelwood tastes better than cooked with electricity (Uhunamure *et al.,* 2017). On the other hand, Thondhlana and Shackleton (2012) found that households with older heads were small, usually just consisting of a husband and wife and sometimes a grandchild, and thus had low natural resources needs as energy needs are compensated and catered for through government old-age grants. In addition, households with older heads are only able to use fuelwood if the household consists of enough young people to collect the fuelwood because physically older people are unable to do so (Garekae *et al.,* 2017). However, older people in South Africa, especially those that have reached pension age, receive government grants (Thondhlana and Shackleton, 2012), and even if they are not able to collect fuelwood themselves, they are able to purchase fuelwood.

The older heads of households positively influence net cattle carbon possibly because livestock ownership and consequently access to the communal rangelands is dominated by older men, often being a barrier to younger people becoming involved (Bennett *et al.*, 2013). The correlation analyses findings indicate a positive relationship between household head age and household wealth status (Table 4.9). That means, households headed by older people are in most cases wealthy and thus able to afford livestock. Also, traditionally, it is the older generation that see value in keeping livestock as opposed to the younger generation in communal areas as stated before. As such, livestock in rural South Africa are a social relations markers and of cultural and ritual identity, but central to their usefulness is that they have multiple meanings and uses (Ainslie, 2013). These are values that are more meaningful to the older generation, rather than the younger ones, and this further explains the positive relationship.

With regard to maize net carbon and head age, these results could be explained by the fact that households headed by an older person is likely to be larger and might have many more adult labour relative to a household headed by a younger person. However, the statistical analyses between head age and proportional number of females in a household (who are known to be mainly responsible for crop production), and between head age and household size are both negative. As such, a study in the Eastern Cape revealed that the youth's aspiration for a better life than the marginal means of living a rural, smallholder farmer have driven a migration away from an agrarian lifestyle (Blair *et al.,* 2018). Overall, these findings indicate that households headed by older people have the potential to redirect more carbon because older people of rural communities appear to be in tune with the traditional land-based activities as compared to the youth. The findings also thus support the hypothesis. Since households headed by older people appear to be involved in all land-based livelihood activities under this study, their redirection of total carbon is thus greater than households headed by relatively younger people. Thus, these results support the hypothesis.

Hypothesis 5: Wealthier households redirect less carbon via fuelwood, but more through livestock, maize crop production, and more carbon in total than poorer households.

Net carbon redirected through fuelwood use decreased with household wealth, as hypothesised. Paumgarten and Shackleton (2011) observed that proportionally poor households utilise NTFPs more frequently and more greatly, and rely more on them than their wealthy counterparts. However, other studies found opposite results. Mamo *et al*. (2007) observed that total household income and wealth is often found to have a non-linear relationship with NTFP resource extraction, and this would affect fuelwood use. Also, empirical evidence from Zimbabwe indicate that richer households use greater quantities of natural resources in absolute terms while the poorer households are more dependent on these resources for daily needs (Cavendish, 2002). Elsewhere, a study in Peru also found that demand for natural resources grows with income but that the poor depend more on natural resources for their livelihoods as their options are more limited than the wealthy (Escobal and Aldana, 2003). As such, in Uganda, a study revealed that rural households with a higher income demanded about 31% less fuelwood because such households mainly used charcoal as the alternative to fuelwood (Egeru, 2014). These studies seem to suggest that although wealthier households are able to derive large quantities of resources from the environment, the poorer households will continue to depend on the environment more. Thus, Dovie, Witkowski and Shackleton (2005) found that in Bushbuckridge, households with higher cash income used large amounts of woodland resources and had the means to obtain a greater share of fuelwood as they have resources to their disposal such as pick-up vehicles that enable them to collect more fuelwood. In addition, well-off San and Mier households of the South African Kalahari showed a higher income shares from natural resources and livestock than medium and poor households (Thondhlana and Shackleton, 2012).

Net carbon values increased with household wealth through cattle and goat ownership and maize crop production, thus supporting the hypothesis. Two studies from the Eastern Cape in South Africa found that well-off households owned a significant number of livestock such as cattle and goats (Chirau, 2018). As an example, a taxi owner from the Eastern Cape owned between 60 and 90 cattle (Hebinck *et al.,* 2018). In the same Province in South Africa, it was observed that less-poor households reported more livestock than the poor and very poor households (Du-pont *et al.*, 2020). This suggests that a household that is financially equipped has the ability to purchase livestock and this could explain the positive relationship between livestock net carbon and household wealth. However, Pica-ciamarra *et al.* (2011) indicate that it is difficult to generalise whether poorer or richer households are more likely to keep livestock because households with different levels of income have incentives to keep livestock because of a wide spectrum of benefits associated with livestock. These incentives therefore differ from one household to the other, whether they are wealthy or not. The ownership of livestock by wealthy households enables them to practice crop production because livestock provide them with draught power and manure which are vital for maize crop production (Dovie *et al.,* 2005). It would also be safe to assume that wealthier households have extra income that can be diverted to buying seeds and all materials necessary for crop production. Also, a study in Thorndale, Bushbuckridge found that households with greater cash incomes tended to invest more in crop production (Giannecchini *et al.*, 2007). Thus, with more assets at their disposal, wealthy households are able to clear more land for cultivation, invest in labour for cultivation and ultimately redirect more carbon than less-wealthy households. The results on household wealth and carbon demand respond to a concern raised by Pritchard *et al.* (2018) of whether the pattern of 'elite capture' of environmental goods is replicated in NPP appropriation or not. These results indicate that wealthier households do not demand NPP directly as compared to their poorer counterparts, in this case high demand through livestock and maize crop production and less through fuelwood. Because wealthier households have the means to own more livestock, and produce crops, they have a greater chance to redirect more carbon in total compared to the poorer households. These results support the hypothesis.

4.4.3 Implications

With weakening institutional control of access to resources on communal land, high unemployment rates and people's perceptions of their rights and responsibilities (Twine, 2005), there is likely to be a combination of household characteristics that would continue to have an influence on the use of natural resources and subsequently on the carbon cycle. For example, predictions are indicating that due to urbanisation and industrialisation in addition to other socio-economic factors, household sizes in developing countries such as South Africa are decreasing (Bradbury *et al.,* 2014). This would mean less pressure on natural resources such as fuelwood, and perhaps even less participation in livestock and crop farming at a household level, which would also result in less carbon redirected from rural ecosystems. Gender roles and their influence on natural resources could also change. The changing nature of household income will lead to gender role switching, with many women and children turning to new activities (Goebel *et al.*, 2000). The improvement in household income could see women participating greatly in livestock farming for instance, something that is predominantly done by men currently; this will probably take place at a slower pace. It is not only changing household income that influences gender roles to change. Resource scarcity has also been identified as a cause of role-switching for instance in the case of fuelwood where in the face of scarcity, it has been observed that wealthier households switch to the use of animal-drawn carts rather than head-loading, and thus males become the wood collectors (Goebel *et al.*, 2000). It is also highly possible that since households' livelihoods depend more on cash income, from formal and informal economic activities, and the increasing shortage of near wood resources (Giannecchini *et al.*, 2007), the sale of fuelwood by rural South African households will increase. The declining fuelwood resources means rural households will continue to appropriate NPP, while the decline in livestock farming would result in reduced NPP.

4.5 CONCLUSION

The results of these analyses indicate that larger households, households with a high proportion of females, and households headed by females are likely to use fuelwood. Larger households and households with a high proportion of females are also likely to practice maize production. Likewise, households headed by relatively older people are likely to own both cattle and goats and practice maize production. While wealthier households are likely to own goats. Larger households increase net carbon through fuelwood use, goat ownership, and practice maize cultivation. While households with a high proportion of females in a household increase net carbon through fuelwood use. Likewise, households headed by older people increase net carbon at household level through fuelwood use, cattle and goat ownership, and maize production. Wealthy households also increase net carbon via cattle and goat ownership, as well as through maize crop production. Reflecting on these findings, carbon mitigation interventions at household levels in socio-ecological settings should focus on these variables. The results of these analyses demonstrate the importance of household socio-economic factors as drivers of resource use and thus on the influence of rural households on the carbon cycle. These findings are centred within the livelihood approach which aims to highlight the different elements that shape people's livelihoods as well as the redirection of the carbon cycle in savanna ecosystems, the factors that influence them, and the linkages between these various factors as analysed in this study (Babulo *et al.*, 2008). Through these analyses, the findings offer a glimpse of the status of rangelands under common management in southern Africa and how they continue to experience transformation through the influence of household socio-economic factors on land-based strategies. These changes have an influence on NPP patterns. This discussion addresses a knowledge gap identified by Niedertscheider (2011) of the need for empirical data on the complex interactions and feedbacks driving the land system. This is essential for improving understanding of trajectories of changes in land system and their underlying mechanisms and constraints, as well as their implication to sustainable development. Understanding these interactions is important for modelling and predicting future carbon redirection trajectories in the context of changing socio-demographic factors. They should thus be taken into consideration in communal land-based livelihood sustainability and climate change policies as they have the prospective to change NPP footprints. Considering the fact that southern African terrestrial ecosystems are strongly affected by human activities (Berger *et al.*, 2019), these data are valuable as they add to the existing knowledge of savanna carbon stocks and how they are affected by human activities, which are important for predicting climate change responses and ultimately for choosing appropriate climate change adoption measures.

African rural households are diverse and complex. While this study has shown that household socio-economic and demographic factors certainly have an influence on the redirection of net carbon through fuelwood harvesting, livestock farming and maize crop production; it could not analyse all household socio-economic factors. Also, rural settings differ and it is possible that the factors affecting net carbon redirection in rural South Africa might be different from those in other African countries. Further enquiry is thus needed to identify those factors, and how they influence the redirection of net carbon.

CHAPTER 5

LOCAL CARBON DEMAND AND SUPPLY AT VILLAGE AND LANDSCAPE LEVELS

ABSTRACT

Human Appropriation of Net Primary Production (HANPP) originated as a global scale indicator of the extent to which human activities affect flows of trophic energy in ecosystems, with few studies investigating HANPP at the local level. This study determined local carbon demand from the surrounding environment from land-based livelihood activities as a proportion of local Net Primary Production (NPP) at village and landscape levels by upscaling from the household level in the Agincourt Health and Demographic Surveillance System (AHDSS) study site in Bushbuckridge, South Africa. Gross and net carbon redirected from the environment were calculated for each of nine rural villages in 2014 using data from the SUCSES study, which was nested in the AHDSS, using two methods (*summed model* and *multiplied mean*). The accuracy of the two methods were compared relative to the known household carbon values for the sample of households in the SUCSES study. Annual gross and net carbon demand from 2010 to 2014 were then calculated for the AHDSS landscape encompassing 420 km^{-2} and 20 villages using the *multiplied mean* method, which was deemed easier to use and satisfactory trade-off between accuracy and household data required at a landscape level. Carbon backflows to nature for the livelihood activities, such as in emissions, were also calculated at village and landscape scales using the *multiplied mean* method. The MODIS (Moderate Resolution Imaging Spectroradiometer) NPP data product was used to calculate total available carbon within 1.5 km of each of the nine SUCSES villages and across the entire AHDSS landscape. Total gross and net carbon (including and excluding crops) redirected by humans increased steadily 2010 to 2014, averaging 11.5% and 11.3% total gross (excluding crops) and total net (excluding crops) 3.4% and 3.1% as a proportion of NPP from the two methods at the village level. Humans redirected 13.7% and 3.9% total gross and net (including crops), and 13.2% and 3.7% (excluding crops), as a proportion of the total NPP in the landscape from 2010-2014. The proportion of NPP redirected in this lived-in landscape

increased steadily over the five-year study period. This study makes a significant contribution as it analysed NPP patterns at the village and landscape levels and thus adds a new dimension to the HANPP studies which have mostly been concentrating on HANPP patterns at national and regional scales. The study used a bottom-up approach that used data collected at the household level to upscale to village and landscape levels which reduces the margins of error and offers new insights on local level carbon dynamics which increases our understanding of how human interaction with the landscape affects NPP over-time.

5.1 INTRODUCTION

The connection between humans and the environment in the drylands of Africa forms a complex, interlinked system that provides ecosystem services (Abdi *et al.*, 2014). Traditional savanna resource management systems such as southern African ecosystems are increasingly being modified and replaced, and thereby undergoing substantial socio-ecological changes (Eriksen and Watson, 2009; Berger *et al.*, 2019). These changes reshape landscapes and may trigger environmental risks such as greenhouse gas emissions, land degradation and the loss of biodiversity (Tao *et al.*, 2011). The biomass productivity changes are reflected in the appropriation of net primary productivity (NPP) by human activities such as fuelwood harvesting, livestock grazing and crop production (Pritchard *et al.*, 2018). The flows of biomass are linked to the global biogeochemical cycle of carbon and to the flow of trophic energy in ecosystems (Haberl *et al.*, 2007). The conversion of the landscape by humans typically reduces NPP, which is the uptake of carbon by plants and other autotrophs minus energy lost via respiration, metabolism and maintenance (Andersen and Quinn, 2020). The human use of biomass over the next decades is projected to increase due to future population growth, changes in human diet, and a growing demand for biomass used for energy provision and fibre (Haberl *et al.*, 2007). Global biomass demand used as feed for livestock is currently the largest component of socioeconomic biomass demand with an amount of 7 Pg DM/yr, while for fuelwood it amounts to between 1.0 and 1.8 Pg DM/yr (Krausmann et al. 2009). For a better understanding, one kg dry matter biomass roughly equals 0.5 kg of carbon (Temper, 2016).

HANPP is related to important global sustainability issues including, among others, widespread malnourishment of a large proportion of the world population, the continuing conversion of valuable ecosystems to infrastructure, cropland or grazing land, and all these have dire consequences for human-induced alterations of biogeochemical cycles (Krausmann *et al.*, 2012). Owing to these developments and their implications for the NPP of land ecosystems, the current global HANPP average level is 25% (Haberl *et al.,* 2014). However, HANPP varies by land use, such as row crop harvest which contributes nearly 50% of the global total HANPP, grazing on rangelands which contributes nearly 29%, and timber harvest which contributes almost 11% (Haberl *et al.*, 2007). Studies of HANPP at the global and regional levels have gained considerable attention due to the interpretation of HANPP as a measure of human domination of ecosystems and thus indicate that HANPP may be a strong indicator of pressures on biodiversity (Krausmann *et al.*, 2012). HANPP integrates two aspects of human impacts on annual biomass flows in ecosystems (NPP) which are the amount of biomass harvested per year ($HANPP_{harv}$) and changes in the annual NPP resulting from land use and land-use change ($HANPP_{luc}$) (Fetzel *et al.,* 2016). $HANPP_{harv}$, which is the focus of this study, entails harvested biomass in a year which comprises crop biomass, wood harvest, and harvest of grazing biomass (Niedertscheider *et al.*, 2016). It also includes 'used' and 'unused' components which entail biomass actually used and biomass that is destroyed during harvest but remains in the ecosystem referred to as 'backflows to nature' (Krausmann *et al.*, 2012). HANPP analyses provide valuable information on the extent of anthropogenic impact on ecosystems (Fetzel *et al.*, 2012). Since NPP is an indicator of incoming energy to the biosphere and a measure of net CO_2 assimilation, the attention of the scientific community has been drawn towards research into terrestrial NPP because this provides a basis for assessing the status of a wide range of ecological processes (Pan *et al.*, 2017).

The trajectory of Africa's HANPP differs from the global trend because it grew by almost 44% between 1980 and 2005, which considerably exceeds the global average of 13 % (Fetzel *et al.,* 2016). Thus, a steeper increase in HANPP associated with increasing socio-economic demand for biomass has been observed in Africa than on any other continent over the last century (Fetzel *et al.,* 2016; Pritchard *et al.*, 2018). As such, the human appropriation of the NPP in densely populated regions of Africa is currently as high as in Europe (Ciais *et al.*, 2011). Thus, because Africa is known for its widespread poverty, slow economic growth, and agricultural systems, it is important to understand the response of NPP to environmental changes in African ecosystems (Pan *et al.*, 2017). Due to the coarse analysis of HANPP at the global level, African land systems' current and future challenges call for a more detailed analysis of land-use and HANPP patterns at a regional level (Fetzel *et al.,* 2016)

Although it has been established that the African continent is a small sink of atmospheric carbon (Räsänen *et al.,* 2017), land use pressures are expected to increase in Africa in the coming years and the forecasted increase in drought and temperature will lead to a significant decrease in ecosystem carbon stocks in savannas provided there are no human countermeasures (Bombelli *et al.*, 2009). It is therefore important to assess carbon source dynamics for the sustainability of systems such as local agro-ecosystems among others (Manlay *et al.*, 2002). Semi-arid regions are vulnerable to fluctuations in the supply of NPP due to its natural scarcity (Abdi *et al.*, 2014). Thus, to set management priorities, an understanding of the major factors influencing the NPP of savannas is essential (Groen *et al.*, 2011). The ability to estimate primary productivity patterns and predict changes in productivity associated with environmental change is essential to both resource management and global change science (Caylor and Shugart, 2004).

HANPP originated as a global scale indicator, and so far, fewer calculations have been done at the local level (Temper, 2016). Andersen and Quinn (2020) indicate that local case studies could increase our understanding of how human interaction with the landscape affects HANPP over time. HANPP has been quantified at continental, regional, national (mostly in Europe and recently one in South Africa) scales. Only two village-level studies are available for Africa; a case study in Tanzania (Bartels *et al.,* 2017), and another in Zimbabwe (Pritchard *et al.*, 2018). Thus, further local-level case studies are needed to capture the variety of rural African contexts (Pritchard *et al.*, 2018). Applications at smaller scales have important policy implications as they can serve as early alerts by demonstrating increasing vulnerability of local communities to local shortfalls in NPP (Running, 2014). In addition, HANPP calculations have been observed to suffer from constraints with regard to data availability (Temper, 2016). Reflecting the research gaps described above, and avoiding the inaccuracies associated with the use of national statistics, this chapter aims to determine local carbon demand at village and landscape levels by up-scaling from the household level using statistical models and detailed household data for entire villages from a health and demographic surveillance system. The NPP patterns of the land-based livelihood activities investigated in this study are useful in understanding socio-metabolic profiles and carbon flows in a typical sub-Saharan African socio-ecological rural setting. Estimations such as these are important for both policy (emissions inventories) and science (understanding feedbacks in the carbon-climate system) (Houghton *et al.,* 2009). This study applied the HANPP framework to measure biomass flows (in carbon measurements) in the AHDSS (Agincourt Health and Demographic Surveillance System) landscape by assessing the processes of biomass harvesting that involved harvested fuelwood, grazed biomass and harvested crops. The 5-year longitudinal study on the flows of carbon associated with the three land-based activities analysed under this study, allows for drawing a rich picture of household and landscape NPP patterns in southern African savanna socio-ecological systems. This section thus addresses these three questions:

a) What are the strengths and weaknesses of the two methods used to scale up from the household level to the village level?
b) What is the total carbon demand and supply from the local environment at the village level?
c) What is the total carbon demand and supply from the local environment at the landscape level?

5.2 METHODS

Household-level data on gross and net carbon redirected from the local environment from fuelwood use, livestock, and crop production from the SUCSES study were used for upscaling to village and landscape levels in this chapter (see Chapter 2 and Chapter 3 for the household-level data and methods). The analyses entailed the following steps

1) Use and compare two methods for calculating total gross and net carbon redirected collectively by a pool of households using data for the SUCSES sample of 487 household spanning nine villages for 2014.
2) Calculate total gross and net carbon redirected per SUCSES village in 2014 using the two upscaling methods for the nine SUCSES villages.
3) Calculate available NPP in 2014 within a 1.5 km buffer around each of the SUCSES villages using MODIS NPP data.
4) Express village-level gross and net carbon redirection as a percent of available village NPP.
5) Upscale annual carbon redirection to the landscape level (20 villages embedded in 421 km^2 of communal lands of the AHDSS) for 2010-2014.
6) Calculate total annual NNP at the landscape level 2010-2014 using MODIS NPP data.
7) Express annual gross and net carbon redirected at a landscape level as a proportion of total landscape NPP.

The two methods used and compared to scale up to village level for the nine SUCSES villages were as follows:

a) *Summed model* method: household-level carbon data from the SUCSES study and selected household variables available for all households in these villages from the AHDSS were used to derive statistical models to predict household-level carbon values from household characterises for all households in these villages, which were then summed to get village totals.
b) *Multiplied mean* method: mean household carbon values (Chapter 3) were multiplied by the number of households per village to get village totals

The total household gross and net carbon models (excluding crops) were determined for the year 2014 by running multiple regression analyses that involved total gross and net carbon (excluding crops) as dependent variables and cattle and goat ownership (binary), cook using fire (binary), ownership of a stove (binary), total assets owned, total number of household members, and proportion of household members that are female as independent variables. These are household variables that were available for all households in the SUCSES villages from the AHDSS database and likely to influence household carbon demand (see Chapter 4). Models with various combinations of the independent variables were compared for predicting both gross and net carbon. The Akaike Information Criterion (AIC) was used to select the best model for total gross carbon and total net carbon. AIC is a statistical measure used for the comparative evaluation among a series of models, such that the model with the lowest AIC value is the best trade-off between goodness of fit and simplicity of the model (Profillidis and Botzoris, 2019). The modelled data were analysed using SPSS (Software Package for Social Sciences). The best models using AIC were as follows:

Gross Carbon (excl. crops) = $8\,522*C_o+1\,550*G_o+1\,059*C_f-23*P_f+1\,777$

Net Carbon (excl. crops) = $3\,269*C_o+531*G_o+301*C_f-9*P_f+546$

where C_o refers to cattle ownership, while G_o is goat ownership, C_f is cook using fire, and P_f is the proportion of household members that are female, and 1 777 and 546 are the respective model constants. The model equations were then used to calculate total gross and net carbon (excluding crops) in tonnes for each of the households in the sample. Before upscaling to the village level, the *summed model* and *multiplied mean* total gross and net carbon values calculated for the pool of SUCSES households (n=487) were compared to the summed actual values for this collection of households to determine the accuracy of the two approaches for calculating total gross and net carbon redirected by the pool of households relative to the actual known values. The difference percentage between the totals from these two approaches and the actual totals were calculated.

Total village-level gross and net carbon values (including and excluding crops) were then calculated for the SUCSES villages in 2014 using the *summed model* and the *multiplied mean* approaches. For the former, values were calculated for each household in each of the nine villages using the derived model equation above and household variables available for each of the households in the villages from the AHDSS database, and then summed per village. For the latter, the mean carbon values from Chapter 3 were multiplied by the number of households in each village in 2014. The percentage difference between the two approaches was also calculated. Total village-level carbon backflows to nature – greenhouse gas (GHG) carbon emissions (from livestock and burning fuelwood) and carbon in livestock dung – were calculated per SUCSES village in 2014 by multiplying the mean values from Chapter 3 by number of households per village. All total gross and net carbon values (excluding crops), as well as fuelwood and livestock carbon emissions were expressed in tonnes of carbon.

MODIS (Moderate Resolution Imaging Spectro-radiometer) NPP data was used to calculate total available NPP per SUCSES village. MODIS began to provide information for the estimation of global primary production at a 1 km and 500 m resolution at 8-day intervals, which is known as MOD17 as part of the MODIS land products (Justice *et al.*, 2002). MOD17 is a satellite-driven data set continuously monitoring global vegetation productivity composite GPP, net photosynthesis (PsnNet), and annual total GPP and NPP at 1-km resolution over 109,782,756 km^2 of vegetated land surface (Zhao *et al.,* 2006) . This consistent data set benefits our understanding of the global carbon cycle and is useful in natural resource management (Running *et al.*, 2004).

To calculate NPP available per village, 1.5 km buffers were generated around each of the nine SUCSES village polygons, and these were superimposed over the MODIS NPP (500 m resolution) rastar image for the study site in QGIS 2.8 software (**Figure 5.1**). This distance was selected as the village NPP use zone because evidence from the study area shows that most resource harvesting occurs within 1.5 km from villages (Wessels *et al.*, 2013). Mean NPP within each village buffer was then calculated using the QGIS rastar zonal statistics function. The MODIS NPP pixel values had to be transformed by a factor of 0.0001 to arrive at NPP values expressed as mean kg carbon (C) m^{-2}. The area of each buffer was calculated in m^2 using the QGIS area attribute function, and the mean kgC m^{-2} per village was then multiplied by the area to get total kg of carbon in the village buffer. This value was divided by 1 000 to get tonnes of carbon available per village. Total village gross and net carbon values were then expressed as a percent of these available village carbon values.

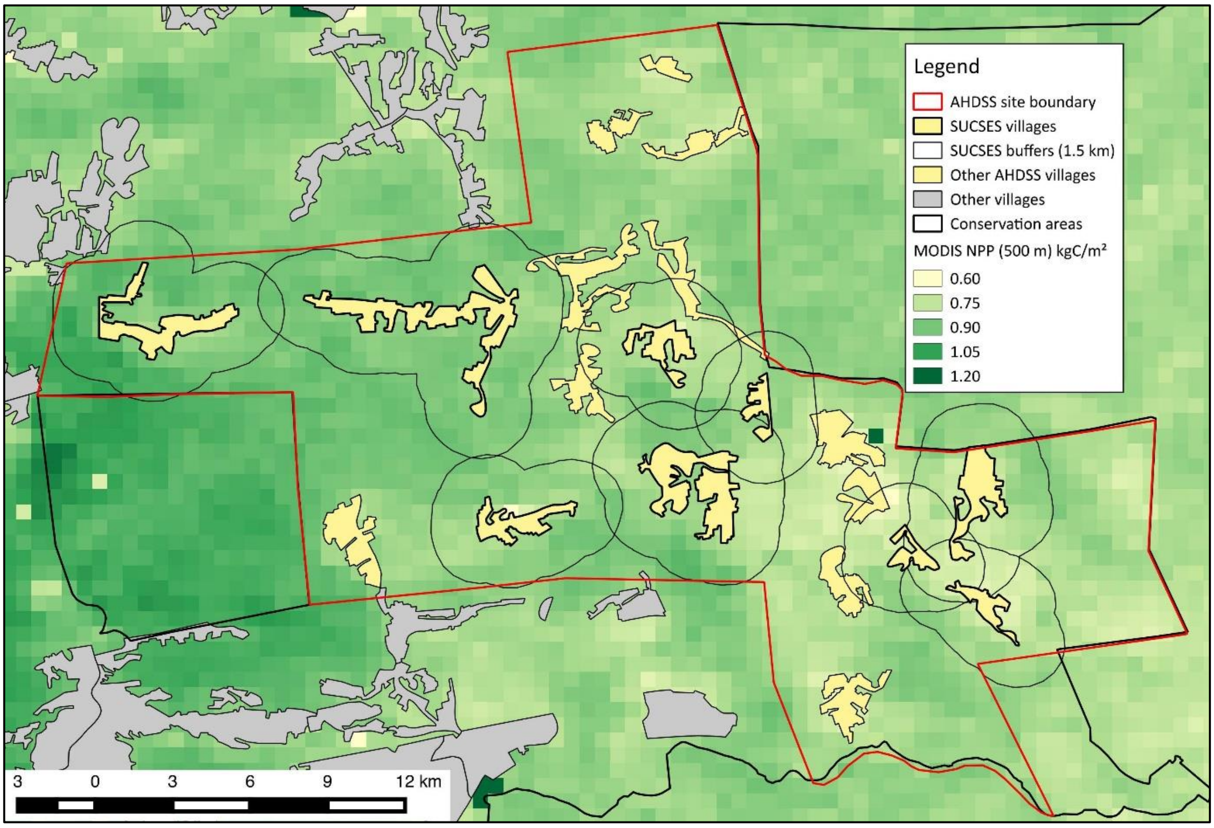


Figure 5.1: NPP (500 m resolution) within 1.5 km buffers around the nine SUCSES villages in 2014

Only the *multiplied mean* approach used to calculate total gross and net carbon, as well as backflows, for the AHDSS landscape, as the researcher did not have access to household level data for all 18 999-21 537 households from 2021-2014 and the *multiplied mean* approach was deemed a satisfactory trade-off between accuracy and household data required. Total gross and net carbon (including and excluding crops) removed from the local environment, as well as the various carbon backflows to nature, were calculated for the AHDSS landscape for 2010-2014 by multiplying the mean annual values from Chapter 3 by the total number of households in the 20 villages in the landscape.

Total NPP available annually in the AHDSS landscape from 2010 to 2014 was calculated using the annual MODIS NPP (500 m) data product for the site for these years. The polygon demarcating the boundary of the 421 km^2 AHDSS landscape was superimposed over the MODIS NPP rastar image for each of the study years (see **Figure 5.1** for 2014). This boundary followed the outer cadastral boundaries of the village communal lands for the 20 villages in this landscape. Using the same technique as described above for village use zone buffer polygons, mean kgC m^{-2} was calculated for the landscape polygon per year. Because each NPP rastar pixel is 250 000 m^2 in area, the mean NPP per m^2 was multiplied by this number to get mean kg C per pixel for the landscape per year. This was multiplied by four to get kgC km^{-2}, since each pixel is 0.25 km^2. Finally, this value was multiplied by 421 (km^2) and divided by 1 000 to get total tonnes carbon for the landscape. Human demand for carbon from the landscape, expressed as both total gross and net carbon (including and excluding crops) redirected by households, was then evaluated as a percentage of the total NPP in the AHDSS landscape annually from 2010 to 2014.

5.3 RESULTS

5.3.1 Two methods for upscaling from household level

Gross carbon calculated by the *summed model* method was very close (0.7% higher) to the total actual value for the pooled 487 SUCSES households, while for net carbon, it was 5.5% higher. The total *multiplied mean* gross carbon was 10.5% lower than the actual total gross carbon and 5.1% lower for total net carbon **(Table 5.1).** For both methods, the total net carbon was ~30% of the total gross carbon value.

Table 5.1: Total gross and net carbon excluding crops (in tonnes) for the SUCSES sample (n=590), 2014

Variable	Total summed actual values	Total summed model values	Total multiplied mean values	Difference between total summed model & actual total	Difference between total multiplied mean & actual total
Gross carbon	1 216	1 224	1 087	0.7%	-10.5%
Net carbon	351	370	333	5.5%	-5.1%

5.3.2 Village-level carbon demand and supply

Mean village level total gross carbon was 2 334±2 847 tC using the *summed model* method and 2 175±1 133 tC using the *multiplied mean* method (**Table 5.2**) The village-level gross carbon values using the *summed model* method were, on average, 8.6% higher than the *multiplied mean* values, although for two villages (Kildare and Lillydale B) the multiplied mean totals were higher.

Table 5.2: Total gross carbon (in tonnes) per village (SUCSES villages) in 2014, excluding crops

Village name	Number of households	Total: *summed model* method	Total: *multiplied mean* method	% Difference
Agincourt	1 196	3 859	2 901	33%
Cunningmore B	752	1 537	1 498	3%
Huntington	741	1 916	1 668	15%
Ireagh A	746	1 694	1 514	12%
Ireagh B	472	1 218	985	24%
Justicia	1 452	2 934	3 231	10%
Kildare	2 035	3 625	4 182	-13%
Lillydale B	481	900	1 206	-25%
Xanthia	893	2 299	1 932	19%
Mean±SD	**974±508**	**2 220±1 486**	**2 124±1 073**	**8.6%±18.12**

The mean total net carbon using the *summed model* method was 700±1 079 tC, and for the *multiplied mean* method, it was 666±347 tC **(Table 5.3).** The village-level net carbon values using the *summed model* method were 14.8% higher than the *multiplied mean* values on average, although the totals for Lillydale B and Justicia villages were lower.

Table 5.3: Total net carbon (in tonnes) per villages (SUCSES villages) in 2014, excluding crops

Village name	**Number of households**	**Total: *summed model* method**	**Total: *multiplied mean* method**	**% Difference**
Agincourt	1 196	1 215	889	37%
Cunningmore B	752	471	459	2.6%
Huntington	741	590	511	15%
Ireagh A	746	514	464	11%
Ireagh B	472	376	302	25%
Justicia	1 452	832	990	-16%
Kildare	2 035	1 058	602	76%
Lillydale B	481	240	369	-35%
Xanthia	893	700	592	18%
Mean±SD	**974±508**	**666±319**	**579±229**	**14.8%31.51**

Fuelwood carbon emissions were the highest backflow, with the mean per village of 801.78±417.75 tC, followed by cattle carbon greenhouse gas (GHG) emissions with 502.67±261.82 tC, cattle dung carbon with 349.55 tC, and the least carbon backflows came from goats with 9 tC as GHG backflows and 5.11 tC as dung carbon, respectively **(Table 5.4)**.

Table 5.4: Fuelwood and livestock carbon backflows to nature (in tonnes) per village (SUCSES villages) in 2014 (*multiplied mean* method only).

Village Name	Fuelwood GHG	Cattle GHG	Goats GHG	Cattle dung	Goats dung
Agincourt	984	617	11	429	7
Cunningmore	619	388	7	270	4
Huntington	610	382	7	266	4
Ireagh A	614	385	7	268	4
Ireagh B	388	244	4	169	4
Justicia	1 195	749	14	521	3
Kildare	1 675	1 050	19	730	12
Lillydale	396	248	4	173	3
Xanthia	735	461	8	320	5
Mean±SD	**801±417**	**502±261**	**9.00±4.89**	**349±182**	**5.11±2.85**

Mean total available village NPP per SUCSES village in 2014 was 19 525±8 743 tonnes of carbon (**Table 5.5**). The villages on the western side of the study site (e.g. Xanthia and Agincourt) tended to have higher total NPP. Gross village carbon redirection was 11.5%±3.5 (*summed model*) and 11.3%±4.6 (*multiplied mean*) of NPP within 1.5 km of the village, while mean net village carbon redirection was between 3.4%±1.0 and 3.1%±1.1 for the two methods respectively (**Table 5.5**). Justicia and Kildare had the highest gross carbon demand (16.4%-16-9% *summed model*; 18.6%-18.9% *multiplied mean*) while Lillydale B and Xanthia had the lowest net carbon demand (2.2%-2.5%) using the *summed model* method and Xanthia and Agincourt had the lowest (2.1%-2.3%) using the *multiplied mean* method.

Table 5.5: Total gross and net village carbon redirection (excluding crops) as a proportion of NPP within 1.5 km of the village.

Village name	Area (km^2)	Total NPP (tonnes)	*Summed model* method		*Multiplied mean* method	
			Gross carbon	Net carbon	Gross carbon	Net carbon
Agincourt	43.45	38 324	10.1%	3.2%	7.6%	2.3%
Cunningmore B	21.02	17 724	8.7%	2.7%	8.5%	2.6%
Huntington	17.54	13 411	14.3%	4.4%	12.4%	3.8%
Ireagh A	19.40	15 647	10.8%	3.3%	9.7%	3.0%
Ireagh B	15.72	12 570	9.7%	3.0%	7.8%	2.4%
Justicia	22.29	17 359	16.9%	4.8%	18.6%	5.7%
Kildare	26.67	22 103	16.4%	4.8%	18.9%	2.7%
Lillydale B	14.66	10 847	8.3%	2.2%	11.1%	3.4%
Xanthia	30.05	27 740	8.3%	2.5%	7.0%	2.1%
Mean±SD	**23.42±9.01**	**19 525±8 743**	**11.5%±3.5**	**3.4%±1.0**	**11.3%±4.6**	**3.1%1.1**

5.3.3 Landscape-level carbon demand and supply

Total NPP available in the 421 km^2 AHDSS landscape, averaged across the five years of study, was 346 293±14 721 tC **(Table 5.6**). It was highest in 2013 with 369 553 tC, while the lowest was in 2011 with 332 855 tC. Total NPP in the rest of the years fell between the two extremes. Comparing the spatial patterns of NPP at the start (2010) and end (2014) of the study period (**Figure 5.2**), the western and very eastern parts of the landscape had the highest values, with apparent depletion of NPP particularly around the central and eastern villages. However, no major changes were evident over time.

Mean total gross carbon redirected annually by all households in the landscape was 47 506±5 325 tC including crops and 45 691±5 352 tC excluding crops and there was a steady increase from 2010 to 2014 (**Table 5.6**). Mean total redirected carbon, net of backflows to nature, was 14 013±2 230 including crops and 12 620±1 875 excluding crops. There was a steady increase of a mean of roughly 3 300 tonnes redirected per year for gross carbon and 1 200 tonnes per year for net carbon (including and excluding crops) from 2010 to 2014. Total net carbon redirected also increased over time, although the trend was steadier excluding crops (the value for 2011 including crops was slightly higher than in 2012).

Table 5.6: Total NPP and total gross and net carbon (incl. and excl. crops) for the AHDSS (in tonnes) per year in the AHDSS landscape.

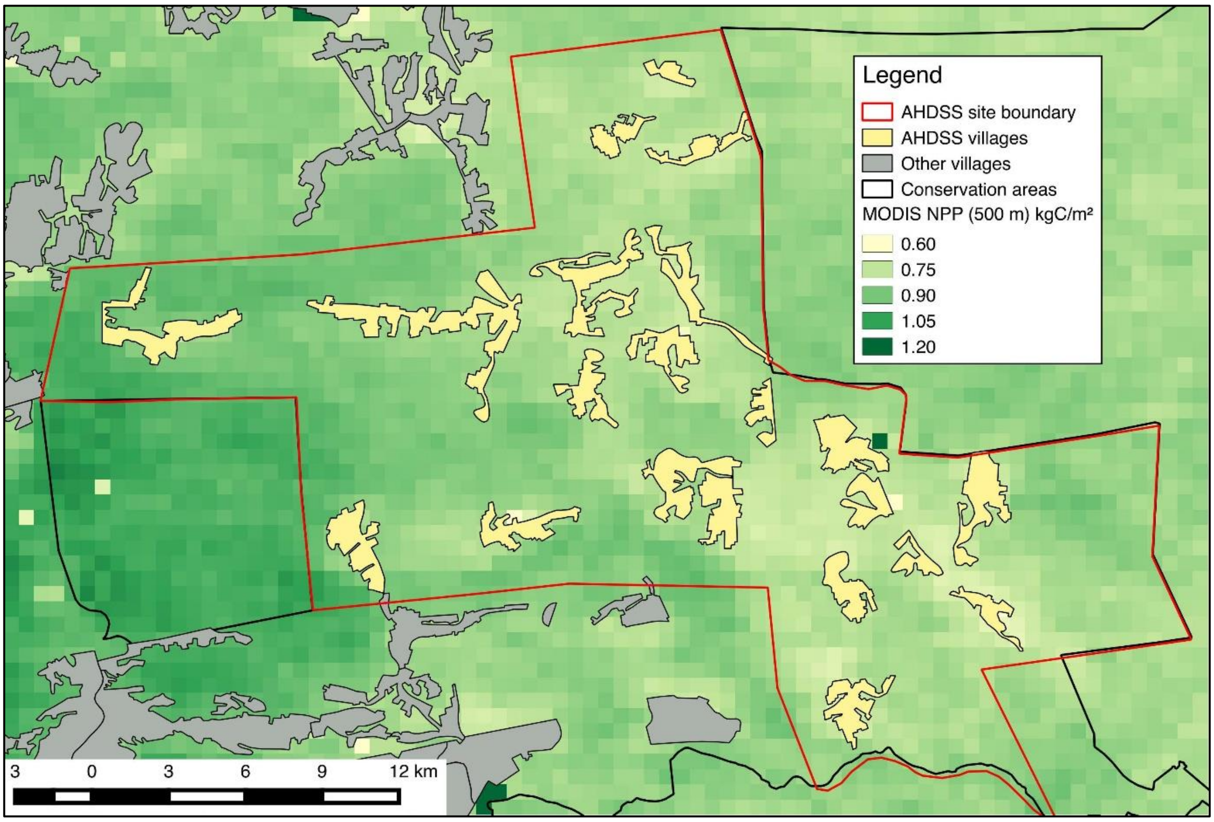
Year	Total NPP	Total gross carbon incl. crops	Total net carbon incl. crops	Total gross carbon excl. crops	Total net carbon excl. crops
2010	346 103	39 980	10 999	37 783	9 973
2011	332 855	45 196	13 462	43 407	11 911
2012	334 447	47 898	13 359	47 002	12 586
2013	369 553	50 400	15 362	48 445	13 684
2014	348 506	54 058	16 885	51 818	14 947
Mean±SD	**346 293±14 721**	**47 506±5 325**	**14 013±2 230**	**45 691±5 352**	**12 620±1 875**

Just like with the 2014 village-level carbon backflows, fuelwood carbon backflows at the landscape were the highest level, followed by cattle, and then goats. Fuelwood carbon backflows were highest in 2012 with 19 348 tC and lowest in 2010 with 16 018 tC. Total cattle GHG backflows and total cattle dung carbon backflows increased gradually from 2010 – 2014. Total cattle GHG backflows were 6 413 tC in 2010 and 9 390 tC in 2014, while total cattle dung carbon backflows were 4 737 tC in 2010 and 7 725 tC in 2014. Contrastingly, total goat GHG backflows and total goat dung backflows did not increase steadily from 2010 – 2014. Instead, the highest was in 2013 for both with 227 tC and 144 tC respectively, while the lowest was in 2010 with 152 tC and 97 tC (**Table 5.7)**.

Table 5.7: Carbon backflows to nature (in tonnes) per year in the AHDSS landscape.

Year	Fuelwood GHG	Cattle GHG	Goats GHG	Cattle dung	Goats dung
2010	16 018	9 802	152	4 737	97
2011	16 861	10 260	189	5 876	120
2012	19 348	10 508	176	6 068	112
2013	17 567	10 964	227	6 911	144
2014	17 723	11 113	201	7 725	128
Mean±SD	**17 503±1 232**	**10 529±532**	**189±28**	**6 263±1 126**	**120±18**

A



B

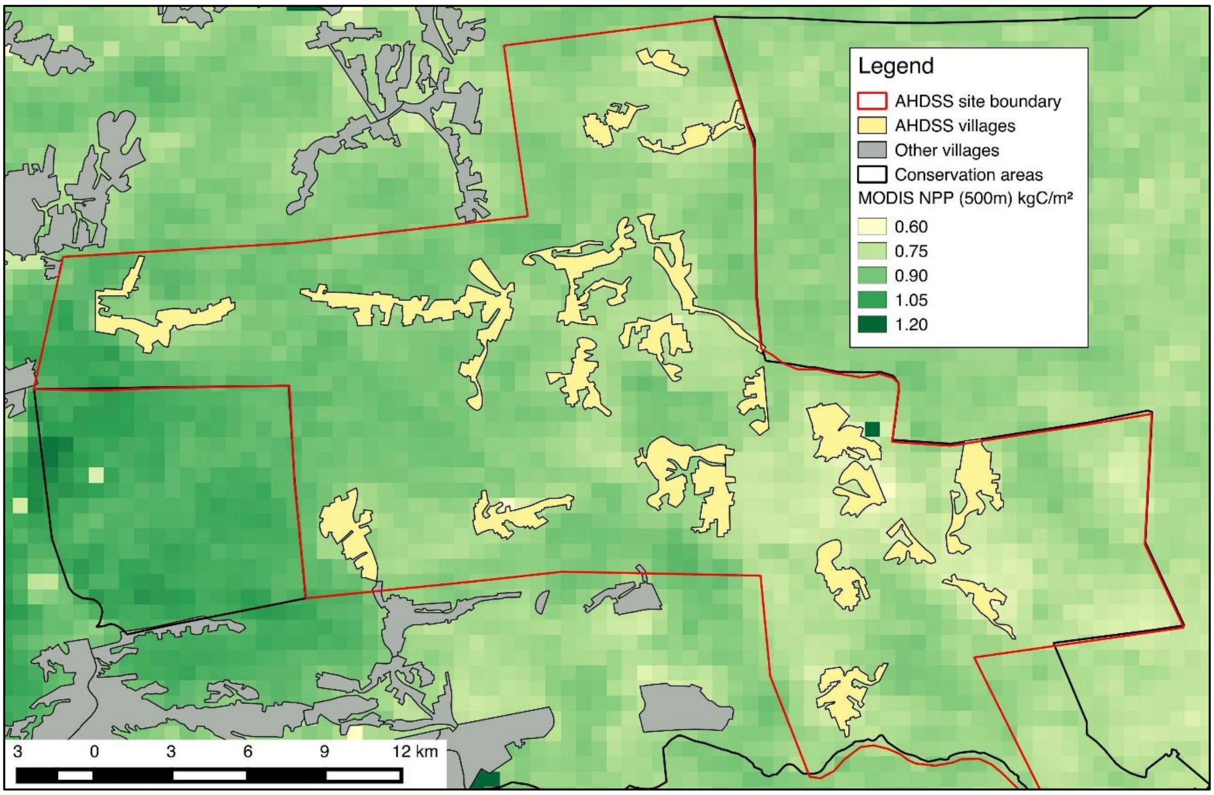


Figure 5.2: NPP (500 m resolution) in the AHDSS landscape in A) 2010 and B) 2014.

The total gross and net carbon redirected from the landscape by humans, including crop harvesting, from 2010 to 2014 averaged 13.7%±1.4 and 3.9%±0.6 of available NPP respectively **(Table 5.8).** Values increased steadily over five years from 11.6% to 15.5% for gross carbon and 3.2% to 4.8% for net carbon. The proportion of NPP redirected by humans through total gross and net carbon removed from the indigenous vegetation only (i.e. excluding crops) was 13.2%±1.5 and 3.7%±0.5, respectively. Gross carbon redirected increased from 10.9% to 14.9% of total NPP and net carbon increased from 2.9% to 4.3% between 2010 and 2014.

Table 5.8: Proportion of total landscape NPP redirected by humans per year in the AHDSS landscape.

Year	Total gross carbon (incl. crops)	Total net carbon (incl. crops)	Total gross carbon (excl. crops)	Total net carbon (excl. crops)
2010	11.6%	3.2%	10.9%	2.9%
2011	13.6%	4.0%	13.0%	3.6%
2012	14.3%	3.4%	14.1%	3.8%
2013	13.6%	4.2%	13.1%	3.7%
2014	15.5%	4.8%	14.9%	4.3%
Mean %±SD	**13.7%±1.4**	**3.9%±0.6**	**13.2%±1.5**	**3.7%±0.5**

5.4 DISCUSSION

5.4.1 Comparing two methods for upscaling from household level

When assessing the accuracy of the two methods for upscaling carbon redirection from the household level, the *summed model* approach was more accurate than the multiplied means method for gross carbon. The former almost exactly predicted actual gross carbon for the sample of 487 households, while the latter under-predicted gross carbon by 10.5%. However, for net carbon, the margin of error was roughly the same for both methods (~5%), although the *summed model* over-estimated while the *multiplied mean* under-estimated total net carbon. Although the absolute village-level estimates using the *multiplied mean* method were, on average, 8.6% lower than the *summed model* method for gross carbon and 14.8% lower for net carbon for the nine SUCSES villages, when these carbon values were expressed as percent of available carbon, the differences between the two methods were negligible (the percent of NPP changed by 0.2% for gross and 0.4% for net carbon). It is therefore unlikely that using the *summed model* method would have resulted in substantially different results for the landscape-level analyses, especially for percent of NPP redirected. The *multiplied mean* method was also easier to implement than the *summed model* method because it did not require data for all the households in the study site (which are seldom available for most typical study sites) and did not require the use of statistical models to predict carbon values for every household.

5.4.2 Village-level carbon flows

This study aimed to first calculate demand and supply of carbon from the surrounding ecosystem at the village level. It did this by upscaling household-level gross and net carbon redirection by land-based livelihood activities, as well as carbon backflows to nature from these activities. Village-level carbon demand was then expressed relative to available NPP in the village resource use zone. Most HANPP studies, including those in Africa, have been conducted at national and regional levels (Haberl *et al.*, 2007; Krausmann *et al.*, 2012; Abdi *et al.*, 2014; Fetzel *et al.,* 2016). Only two other village-level studies on HANPP in Africa exist in the literature (Bartels *et al.,* 2017; Pritchard *et al.*, 2018). Furthermore, most studies have analysed the appropriation of NPP by humans by calculating harvested biomass in dry matter kilograms, as well as loss of biomass through land use change, often pooling these two dimensions of HANPP (Temper, 2016; Pan *et al.*, 2017; Andersen and Quinn, 2020). This study therefore contributes new knowledge on village-level carbon dynamics in a rural African context, by quantifying the flows of carbon from the surrounding ecosystem through livelihood activities, both as gross carbon removed (equivalent to $HANPP_{harv}$ in the literature), and as carbon redirected net of backflows to the environment (such as GHG) and assessing these relative to the available carbon (NPP) in the current environment. These findings make an important contribution to a much needed comprehensive analysis of the role of terrestrial ecosystem carbon such as this of the savanna ecosystem to the SSA (Sub-Saharan Africa) carbon balance (Bombelli *et al.,* 2009). Also, having an understanding of the evolution of human appropriation of the NPP at the regional level seems to be a crucial diagnostic element (Ciais *et al.,* 2011). Notably, this study dissected biomass into channels of carbon backflows such as fuelwood and livestock carbon emissions, as well as carbon in livestock dung, which is absent from analyses expressing HANPP as biomass. This is what makes up the further division harvested HANPP as 'used' components (that enter the socio-economic system), and 'unused', the part that is removed but is returned to the ecosystem such as livestock dung (Fetzel *et al.,* 2016).

Mean village level total gross carbon appropriation was between 2 334±2 847 tC and 2 175±1 133 tC. These values are comparable to village-level HANPP values calculated for six Zimbabwean villages by (Pritchard *et al.*, 2018), which ranged from 548 to 1 571 t DM year^{-1}. However, it should be noted that their values were expressed as tonnes of dry matter, not carbon alone, and they include HANPP due to land use change. The villages in their study were considerably smaller than those in this study. The mean total mean net carbon per village in this study was between 700±1 079 tC, and 666±347 tC. Because the few village-level studies such as Pritchard *et al.* (2018) did not factor in backflows, they did not present figures comparable to net carbon appropriation of NPP.

The findings of this study indicate that on average, households redirected about 11% of the total village NPP. This is relatively low in comparison to the two other village-level HANPP studies in Zimbabwe and Tanzania. The HANPP study in 6 villages in Zimbabwe ranged from

113% to 48% (Pritchard *et al.*, 2018). These percentages include both $HANPP_{harv}$ and $HANPP_{luc}$. The $HANPP_{harv}$ component of the Zimbabwean study also included construction timber and thatching grass harvested from the vegetation, which are now seldom used in Bushbuckridge (Ragie *et al.*, 2020), and thus, absent from the calculations in the present study. The authors also further indicate that $HANPP_{luc}$ contributed the most to these results. Thus, it is difficult to really ascertain whether $HANPP_{harv}$ was substantially lower or similar to this study. Unlike the Zimbabwe study, the Bartels (2014) study differentiated the results according to the two HANPP calculations. To this end, the study found that 32% of NPP_{harv} is redirected by the households in a Tanzanian village. It is further indicated that grazing of livestock makes up 85% of the total above-ground HANPP. In comparison to this study, the difference is that, the community of Ololosokwan in Tanzania is mainly a pastoralist community and their livelihood is largely based on livestock farming. On the other hand, the community of Bushbuckridge does not depend entirely on the local environment for their livelihood as they also depend on remittances, social grants, and limited non-farm income (Mograbi *et al.*, 2015). Thus, these differences between the two communities and the extent of their use of natural resources in their respective local environments would result in different HANPP results even though these studies were both conducted at village levels and both in savanna ecosystems.

Although the gross and net carbon differences between the two approaches used on a village-to-village basis are quite large in some cases (such as in the villages of Kildare and Lillydale), as a total, the difference is still small. The village of Justicia was one of the two villages with the highest gross carbon demand. This is plausible because Justicia has the highest number of households, and thus would have the highest demand of biomass use. However, in the context of fuelwood extraction as one of the land-based livelihood activities, this village is classified as an intermediate wood extraction site and has an exclusive access making it difficult to be accessed because it is fenced on two sides by private conservation land (Fisher *et al.*, 2011). Thus, one would expect the high gross carbon demand to somehow match with the intermediate wood extraction classification. This is one weakness of using a sample of household data averaged across villages to upscale carbon demand to village level; local-level nuance is lost. The other village with the highest gross carbon demand is the village of Kildare. Apart from having the highest number of households, it is also classified as a high wood extraction site attributed to immigration and an overall population increase (Fisher *et al.*, 2011). The high gross carbon demand is thus in line with the high population of households, and the high wood extraction classification.

The villages of Lillydale B, Xanthia, and Agincourt had the lowest net carbon demand in percentage at the village level. The least net carbon redirected by the village of Lillydale is in line with its population size which is the second lowest of all the villages. Also, the extraction of biomass and thus low carbon demand is restricted by the lowest NPP associated with the low rainfall received in this village. However, with regard to fuelwood extraction, this village was classified as a high wood extraction site and the village with the highest population increase (67.1%) over the period 1993-2008 (Fisher *et al.*, 2011). Once again, this highlights the limitation of upscaling demand using generic mean values that do not take village context into consideration. The least net carbon demand relative to available NPP (in percentage) associated with the villages of Xanthia and Agincourt is plausible because these villages have the highest NPP attributed to high rainfall (>700 mm) received in these villages relative to other villages. Also, these are the villages whose access to fuelwood by other villages is geographically restricted and thus classified as low wood extraction site (Fisher *et al.*, 2011).

Between fuelwood and livestock carbon backflows, fuelwood carbon backflows were the highest, followed by cattle and goat carbon backflows respectively, at the village level. The carbon backflows are still in line with the redirection of net carbon from the ecosystem analysed in Chapter 3 which indicate that livestock proportionally redirect more carbon followed by fuelwood. The carbon backflows from fuelwood are thus higher because the least net carbon between the two activities is redirected from fuelwood. Although rural settlements may contribute less to national GHG emissions through e.g. car exhaust emissions or using coal-generated electricity, they do contribute through the use of fuelwood and livestock ownership. This study thus fills a knowledge gap because it is the first to quantify these contributions to this component of the carbon cycle in a rural African village setting.

5.4.3 Landscape-level carbon flows

This study calculated carbon dynamics between villages and surrounding savanna vegetation at the landscape-scale in a rural socio-ecological system. The results on the redirection of NPP by the ~20,000 rural households in the landscape through the analysis of total gross and net carbon and thus the percentage of the total NPP are discussed below. A number of studies have investigated HANPP patterns at continental, regional and country levels (Krausmann *et al.*, 2012; Abdi *et al.*, 2017; Haberl *et al.,* 2014; Niedertscheider *et al.*, 2016). However, there is a lack of such data for African socio-ecological systems, such as lived-in landscapes. Also, as discussed for the village-level analyses, these studies focus on appropriation of dry matter by both harvesting and land use change, rather than tracing the flows and backflows of carbon in the socio-ecological system. As such, it is important to take this into consideration while interpreting these results relative to those in the literature.

The results on total gross and net carbon (including and excluding crops) from 2010 – 2014 show fairly steady increases. The highest difference was from 2010 – 2011, with an increment of 13% and 15%, respectively. The other higher increments were from 2011 – 2012 in total gross carbon (excluding crops) with 8%, and 2013-2014 in total gross carbon (including and excluding crops) with about 7% in both cases. Looking at the increment that has occurred in general from 2010 – 2014 as discussed above, this is in line with the increase in total populations in the villages from 2010 – 2014. As such, Bryceson (1996) indicates that the increase in population density of most rural areas has in many cases led to constraints on the availability of land. Also, population density has been observed as a major driver of HANPP (Krausmann *et al.*, 2012). This means the variability of NPP is not only influenced by physical factors such as precipitation which has been attributed to an increase in NPP (Bartels *et al.,* 2017), but also by social factors such as population. To this end, Abdi *et al.* (2014) observed that the Sahel population had a 31% increase from 2000 to 2010, which further drove NPP demand rates to increase from 19% to 41% over the same period. South Africa has a population growth rate of 1.43% (Lehohla, 2009); that means demand for natural resources such as fuelwood, land for grazing and cultivation is expected to grow which will ultimately result in higher NPP redirection among rural households in South Africa and possibly in the rest of the sub-continent.

This study established that households redirected a mean of ~13% as a proportion of total NPP at the landscape. This is similar to the 11% redirected at the village level as indicated earlier. This is lower as compared to other studies that were conducted at either regional, ecological zone, country or continental levels (Haberl *et al.*, 2007; Abdi *et al.*, 2014; Temper, 2016). A study in the Sahel region indicates that 41% of NPP (Abdi *et al.*, 2014) is redirected by humans. The difference here is attributed to among others the inclusion of biomass burning of forest resources for land clearing in the redirection of NPP by humans. In addition to this, they also counted agricultural by-products such as crop residues in their NPP demand calculations. These differences in method used account for the lower values in the present study. This study's HANPP findings are also lower than the 26% Temper (2016) found in Tana Delta, Kenya. The HANPP results of this study are indeed also lower as compared to the current 24% of what humans appropriate from NPP at the global scale (Haberl *et al.*, 2007).

The HANPP findings in this study shows the level of variability of NPP dynamics across savanna socio-ecological systems. Bartels *et al.* (2017) indicate that African semi-arid savannas are characterised by higher inter-annual precipitation and, since precipitation and NPP are highly correlated, also by NPP dynamics. Be that as it may, the lower HANPP of the Bushbuckridge area relative to other studies in Africa could be attributed to the focus in this study of direct flows of carbon for resource extraction and did not include changes in NPP as a result of land use change. These lower values could also be an indication that most households in the study site are not deriving their livelihoods directly from the local environment to the extent of other African contexts, and are depending more heavily on remittances and social grants to support their livelihoods (Ragie *et al.*, 2020). In addition, as shown in the previous chapters (Chapter 3), although most households depend on fuelwood for their energy needs, their participation in livestock farming and crop production is low. Another factor that could have contributed to the comparatively low percent of NPP redirection by humans is that the NPP totals for the whole landscape might have been overestimated by the MODIS method used as the MODIS NPP product tends to overestimate NPP from the tropics (Bartels *et al.,* 2017). This is considering the fact that studies have indicated that vegetation for instance from where fuelwood is derived is already strained due to consistent high demands from households (Maltitz *et al.,* 1995). The 11% and 13% redirected of total NPP at village and landscape levels is an indication of how humans convert landscapes by reducing net primary production (Andersen and Quinn, 2020). Also, an indication of human-induced alterations of biogeochemical cycles such as the carbon cycle (Krausmann *et al.,* 2009).

Interestingly, the mean annual gross proportion of NPP redirected by humans in the study savanna landscape is comparable to that removed by fire and wild indigenous herbivores in natural savanna landscapes (14.4%) under similar rainfall conditions (Archibald and Hempson, 2016). Fires in the study site tend to be infrequent, of low intensity and small extent, due to low fuel loads and active banning of burning in the rangelands by the chiefs. Thus, it seems that humans and their livestock in the study landscape appropriate a similar proportion of NPP to fire and wild herbivores in comparable natural landscapes, which is a surprising finding.

Notwithstanding the above, the fact that the amount of NPP redirected, both in absolute terms and as a proportion of available NPP, has been on the increase in the study landscape over the five-year study period is of an ecological concern. Despite the replacement of grazed and browsed NPP by compensatory regrowth (McNaughton, 1983) and the replacement, to some extent, of harvested fuelwood through coppice production (Twine and Holdo, 2016), the rates of regeneration may not keep up with the growing NPP demand in the landscape under current conditions. This is a concern considering the fact that the 11% and 13% of total NPP redirected both at village and landscape levels is done by a single species – humans (Andersen and Quinn, 2000). It is predicted that anthropogenic climate changes are likely to cause impacts on Africa's biodiversity which will be negative from an ecological perspective such as variability in available NPP (Midgley and Thuiller, 2011). As indicated in the previous section, the high NPP demand is associated with population size even at the landscape level. Thus, the highest NPP redirected by households in 2014 is in line with the highest number of households which was in 2014 relative to the other years. Likewise, 2010 had the lowest number of households across all years, and thus, it had the lowest NPP redirected by households. The study also found that the western and very eastern parts of the landscape had the highest NPP values, with lower NPP around the central and eastern villages. The highest values in the western part are attributed to higher rainfall patterns (>700 mm/year) than in the east (<600 mm/year). The western and very eastern sides of the landscape also had lower densities of villages, and this lower human pressure. This highlights the interaction between environment factors and demographic pressure on shaping available biomass in the landscape.

Just like with the village-level carbon backflows, fuelwood carbon emissions were still the highest at the landscape level, followed by cattle, and then goats. Findings on carbon backflows and carbon emissions in general and the activities responsible for them are some of the factors that are modifying the human appropriation of the NPP (HANPP) globally and regionally, which will further change the ecosystem productivity and structure, and the long-term balance of the savannas (Ciais *et al.,* 2011). Total goat carbon backflows did not increase steadily from 2010 – 2014. This is possibly attributed to the number of goats per year among the SUCSES households (as discussed in Chapter 3 of this study) which could also apply to the rest of the villages. The number of goats from 2010 – 2014 (Chapter 3) did not increase gradually from one year to the next. For example, 2013 had the highest number of goats of 5.67 and likewise, the highest goat carbon emissions were in 2013. Backflows such as manure are beneficial to ecosystems because they create nutrient cycles which lead to high productivity in plants (Temper, 2016). These findings add to a needed deeper knowledge of the African carbon cycle which is important as Africa is considered to have the potential of mitigating climate change through carbon sequestration and a reduction of emissions, which are highly required by the current international climate policy (Bombelli *et al.,* 2009).

5.5 CONCLUSION

This study sheds new light on carbon flows at village and landscape scale in a rural South African socio-ecological system. Most HANPP methodological approaches have been criticised because the variables are poorly quantified and have large margins of error because the numbers are from national datasets (Andersen and Quinn, 2020). This study addresses this gap by using a bottom-up approach that used data collected at the household level to upscale to village and landscape levels. This thus reduces the margins of error and offers new insights on local level carbon dynamics which increases our understanding of how human interaction with the landscape over-time affects NPP. To reduce carbon redirection at the continental level, it is crucial to understand carbon dynamics at the village and landscape levels where the land-based livelihood activities occur. Thus, all these concerns need an analytical study such as this which shed light on the land-based livelihood activities and how they shape southern Africa's savanna carbon cycle. This is useful for understanding the carbon balance in such socio-ecological systems. Williams *et al.* (2007) identified the need for continued and enhanced observations of Africa's carbon stocks, fluxes and atmospheric concentrations that will enable accurate measurements of Africa's carbon cycle and its sensitivity to natural and anthropogenic pressure and future climate as a major knowledge gap. This study provides an analysis of carbon stocks and flows at the landscape level which is a bottom-up method of estimating carbon sources from three anthropogenic activities at the village and landscape levels. This is especially important because most terrestrial carbon accounting studies have been focused on the biophysical carbon source-sink dynamics of ecosystem NPP at regional scales (Abdi *et al.,* 2014), neglecting the socio-economic factors, and this study provides insight into that.

This study's findings indicate that the amount of NPP redirected by humans as a proportion of total NPP at the village and landscape levels is similar; relatively lower as compared to other studies in the African context; and the carbon backflows of the land-based livelihood activities in rural savannas also contribute to GHG emissions. In addition, the results reveal that the amount of NPP redirected by humans and their livestock is comparable to that redirected by fire and wildlife in a similar ecosystem. These results give an overview of the complexity of savanna socio-ecological systems and how anthropogenic activities shape their ecological function as much as natural components such as wildlife do. Knowledge on the redirection of NPP carbon rural households gives a synopsis of the productivity of savannas by looking at NPP supply; how much biomass of that is appropriated by human activities and how much is available which helps in designing sustainability schemes in such systems. This is important for Africa whose HANPP levels have had a steep increase over the last century. In order to aim for solutions at the continental level, local (household and landscape) levels understanding is essential.

This study only did NPP calculations for the duration of the study period (2010 to 2014). With rural communities going through socio-economic changes in Africa, further research should model future carbon patterns at the household, village, and landscape levels in order to inform carbon mitigation policies accordingly.

CHAPTER 6

GENERAL DISCUSSION AND SYNTHESIS

6.1 INTRODUCTION

This study yields a number of important new insights on the influence of key rural land-based livelihood activities on the carbon cycle in a savanna socio-ecological system. These rural land-based livelihood activities were fuelwood harvesting, livestock farming, and maize crop production. First, I investigated annual household carbon redirection from the local ecosystem (Chapter 3). Second, I explored statistical relationships between household carbon redirection and household socio-economic and demographic relationships (Chapter 4). The study tested five hypotheses informed by literature on the influence of household socio-economic characteristics on the use of fuelwood, livestock farming and maize crop production and subsequently net carbon associated with these land-based activities. Third, I analysed local carbon demand and supply at village and landscape levels (Chapter 5).

6.2 SUMMARY AND DISCUSSION OF MAJOR FINDINGS

6.2.1 Annual household carbon redirection from the local ecosystem by fuelwood harvesting, livestock farming and crop production

The results indicate that fuelwood was the most prevalent land-based livelihood activity, followed by maize crop production, and then cattle and goat farming, respectively. Although fuelwood usage and maize production had the highest prevalence of use among all household land-based activities, this did not translate into the highest carbon consumption among households. The highest gross and net carbon consumption among both user-households and averaged across all households was rather redirected through cattle. Thus, although relatively uncommon, cattle owners have a disproportionate impact on carbon redirection in this savanna socio-ecological system. The second highest carbon consumption was redirected through fuelwood use among user-households and all households. Carbon consumed at the household level through maize crop production and goat ownership were the least of all the land-based activities, with goat ownership being the lowest of all.

Across all households, fuelwood use had the largest difference between gross and net carbon redirected, followed by cattle ownership and goat ownership, respectively. This is attributable to the total emissions associated with burning fuelwood, with only carbon in ash remaining as compared to total emissions from livestock. This indicates that although the amount of fuelwood harvested is high, the sum of net solid carbon permanently redirected out of the environment is proportionally lower than the net carbon redirected through either cattle or goat ownership. With user-households, gross and net carbon redirected through cattle ownership had the largest difference. This is indicative of the greenhouse gas emissions namely methane and CO_2 associated with an individual livestock (cattle or goat), and therefore their relative contribution to the amount of carbon redirected at the household level through land-based activities.

6.2.3 Statistical relationships between household carbon redirection and household socio-economic and demographic characteristics

Associations between selected household socio-economic and demographic characteristics and a) the likelihood of a household engaging fuelwood use, cattle and goat ownership, and maize production, and b) the net mass of carbon redirected from the local environment per household annually by these activities were investigated using multiple logistic and linear regression models, while controlling for year of study. With regard to multiple linear regression models, using five household socio-economic independent variables that were possible to compute from available household data, and have been identified in the literature as being predictors of resource use, the study tested the following hypotheses: Hypothesis 1 - larger households redirect more carbon via fuelwood, livestock, and maize crop production, and more carbon in total than smaller households; Hypothesis 2 - female-headed households redirect more carbon via fuelwood and maize crop production, but less through livestock, and less total carbon than male-headed households; Hypothesis 3 - households with a higher proportional number of females redirect more carbon through fuelwood and maize crop production, and less through livestock and less carbon in total, compared to those with fewer females; Hypothesis 4 - households headed by older people redirect more carbon via fuelwood, livestock, and maize crop production, and more carbon in total than households headed by younger people; and Hypothesis 5 - wealthier households redirect less carbon via fuelwood, but more through livestock and maize crop production and redirect more carbon in total than poorer households.

The results of analyses testing these hypotheses are summarized in **Table 6.1**. and **Table 6.2.** With the exception for cattle ownership, all land-based activities were positively associated with household size. The proportional number of females in a household also influenced the likelihood of all land-based activities except cattle ownership. However, the relationship was positive with fuelwood use and maize crop production, while with goat ownership, it was negative. The likelihood of fuelwood use and cattle ownership were negatively influenced by households headed by females. As for the age of a household head, it positively influenced all land-based activities' uses and ownership, except for fuelwood use. Household wealth had a negative influence on fuelwood use and a positive influence on goat ownership.

Net household carbon redirection by fuelwood use, cattle and goats increased significantly with household size, while net cattle carbon decreased with the same variable. Except for fuelwood net carbon that significantly decreased with the proportional number of females in a household, the rest of the variables significantly decreased with the same variable. Households headed by females had significantly negative relationships with net fuelwood net carbon, net maize carbon, and total net carbon (including maize). Apart from net goat carbon that was not significantly related, all variables significantly increased with the age of a household head. Fuelwood net carbon significantly decreased with household wealth, while the rest of the variables increased significantly with the same variable. Reflecting on these relationships, some of the findings supported the hypotheses, while others rejected them. This gives an indication that household socio-economic characteristics influence the use of natural resources and subsequently redirect carbon differently. The findings established that larger households, households headed by older people, and wealthy households redirect more carbon, and are thus main drivers of carbon demand in comparison to other variables.

Table 6.1: Summary of relationships between land-based activities and household characteristics.

Variables	Fuelwood use	Cattle ownership	Goat ownership	Maize production
Members	+	0	+	+
Prop. Female	+	0	-	+
Female Head	-	-	0	0
Head Age	0	+	+	+
Assets	-	0	+	0

Table 6.2: Summary of relationships between land-based activities net carbon and household characteristics.

Variables	Fuelwood	Cattle	Goats	Maize	Total (excl. maize)	Total (incl. maize)
Members	+	-	+	+	0	0
Prop. Female	+	-	-	0	-	-
Female Head	-	0	0	-	0	-
Head Age	+	+	0	+	+	+
Assets	-	+	+	+	+	+

6.2.4 Local carbon demand and supply at village and landscape levels

This section addressed three questions as follows: (1) what are the strengths and weaknesses of the two methods used of scaling up from the household level to the village level as compared to the actual values of the sample? (2) What is the mean gross and net village carbon demand including backflows from the local environment? (3) What is the total carbon supply and demand at the landscape level?

After assessing the accuracy of the two methods for upscaling carbon redirection from the household level, the summed model approach was more accurate than the multiplied means method for gross carbon. However, the multiplied mean method was easier to implement than the summed model method because it did not require data for all the households in the study site (which are seldom available for most typical study sites) and did not require the use of statistical models to predict carbon values for every household.

The study established that on average, households redirected ~11% of the total village NPP. This is relatively lower in comparison to other two studies done at the village level in Zimbabwe (113% - 48%) and Tanzania (32%). The difference is attributed firstly to the differences in local context such as the way their respective environments are used. For example, the Tanzania study environment's mainland-based activity is livestock farming, while the Bushbuckridge environment is dominated by fuelwood harvesting. Similarly, in the Zimbabwean study villages, construction material is still commonly harvested from the local environment, and was thus factored into the HANPP calculations, while this are not applicable in the present study. Secondly, methodology used to calculate HANPP is important. In the first instance, these other studies included loss of NPP through land-use change in the HANPP calculations, while the present study focussed on the harvested/consumed component assessment of carbon flows in the system. This highlights the importance of considering methodology used when comparing HANPP data. Importantly, this study also considered backflows of carbon to the atmosphere or soil, which are seldom included in HANPP studies. The carbon backflows were dominated by fuelwood both at village and landscape levels respectively. HANPP at the landscape level was similar to what was analysed at the village level (~13%). The redirected NPP levels had a steady increase from 2010–2014 with 2010 having redirected the least, while 2014 redirected the highest. It is still lower relative to HANPP studies at regional (41% in the Sahel), at an ecological zone (26% in the Tana Delta, Kenya), and at the global scale (24%).

6.3 IMPLICATIONS OF STUDY FINDINGS

African ecosystems play a major role in the global carbon cycle, and there is a need to understand the evolution of the human redirection of the NPP in Africa for diagnostic measures to take place at the regional level, and yet there is currently a lack of data on the African savanna carbon stocks (Ciais *et al.*, 2011). Reflecting on these research gap areas, this study quantified gross and net carbon patterns of fuelwood harvesting, livestock farming and maize crop production at the household, village and landscape levels in a rural African setting. It also analysed household socio-economic characteristics and their influence on the use and subsequently net carbon redirection through the three land-based activities. The study further quantified carbon backflows of harvested fuelwood and grazed biomass in an effort to determine GHG emissions from these activities. The redirection of NPP by households as a proportion of total NPP at the village and landscape levels were also analysed (**Figure 6.1**). The findings address the need to analyse livelihood strategies and socio-economic characteristics and how they influence household level NPP footprints (Pritchard et al. 2018). All these analyses give an overview of the drivers of the carbon cycle at the local level, a bottom-up approach which is crucial in contributing to the understanding of the African carbon cycle dynamics in socio-ecological settings. The findings are also informed by the need for continued and enhanced observations of Africa's carbon stocks, fluxes and atmospheric concentrations that will enable accurate measurements of Africa's carbon cycle and its sensitivity to natural and anthropogenic pressure and future climate (Williams *et al.*, 2007).

The assessment of two methodological approaches in calculating total gross and net carbon at the village and landscape levels suggests that for future studies that seek to calculate carbon consumption values for individual villages in a landscape, it is valid and appropriate to first calculate the carbon values for a suitably large and representative sample of households, and then multiply the mean values for the sample by the total number of households. In study contexts where there might be large differences between villages, such as village size, ethnic group or environmental conditions, it might be advisable to stratify the sample and upscaling calculations by strata.

Findings on carbon backflows at village and landscape levels respectively give an overview that rural settlements also contribute to GHG emissions through fuelwood and livestock activities, filling a knowledge gap as this has not been quantified as a component of the carbon cycle in Africa before. There is a lack of HANPP data for particular African socio-ecological systems, such as lived-in landscapes. Also, as discussed for the village-level analyses, these studies focus on appropriation of dry matter by both harvesting and land use change, rather than the flows and backflows of carbon in the socio-ecological systems. Data on HANPP give an indication of the environmental pressure exerted upon an area by human activities which serves as an early warning of land degradation among other ecological aspects.

The findings of this section are summarised in **Figure 6.2**. Through the removal of biomass, NPP is redirected at the household level by three land-based livelihood activities (fuelwood harvesting, livestock farming, and maize crop production). The removal of biomass is reflected in the calculation of gross and net carbon of these activities. On the other hand, the removal of biomass from the local ecosystem is influenced by a set of household socio-economic determinants: household size, proportional of females in a household, female head, head age, and number of assets. The influence is replicated in gross and net carbon patterns of each of the three land-based livelihood activities at the household level. Through the use of these activities, some of the carbon is returned to the ecosystem in the form of GHG emissions from fuelwood and livestock farming, and in the form of ash from fuelwood and dung from livestock. Household gross and net carbon is then upscaled to the village and landscape levels to give an overview of carbon mass removal from the ecosystem at these respective scales. Through gross and net carbon values at village and landscape levels, NPP redirection (in %) of the total NPP is calculated. At these levels, there are also determinants that influence NPP patterns, namely: village size, rainfall, and vegetation type.

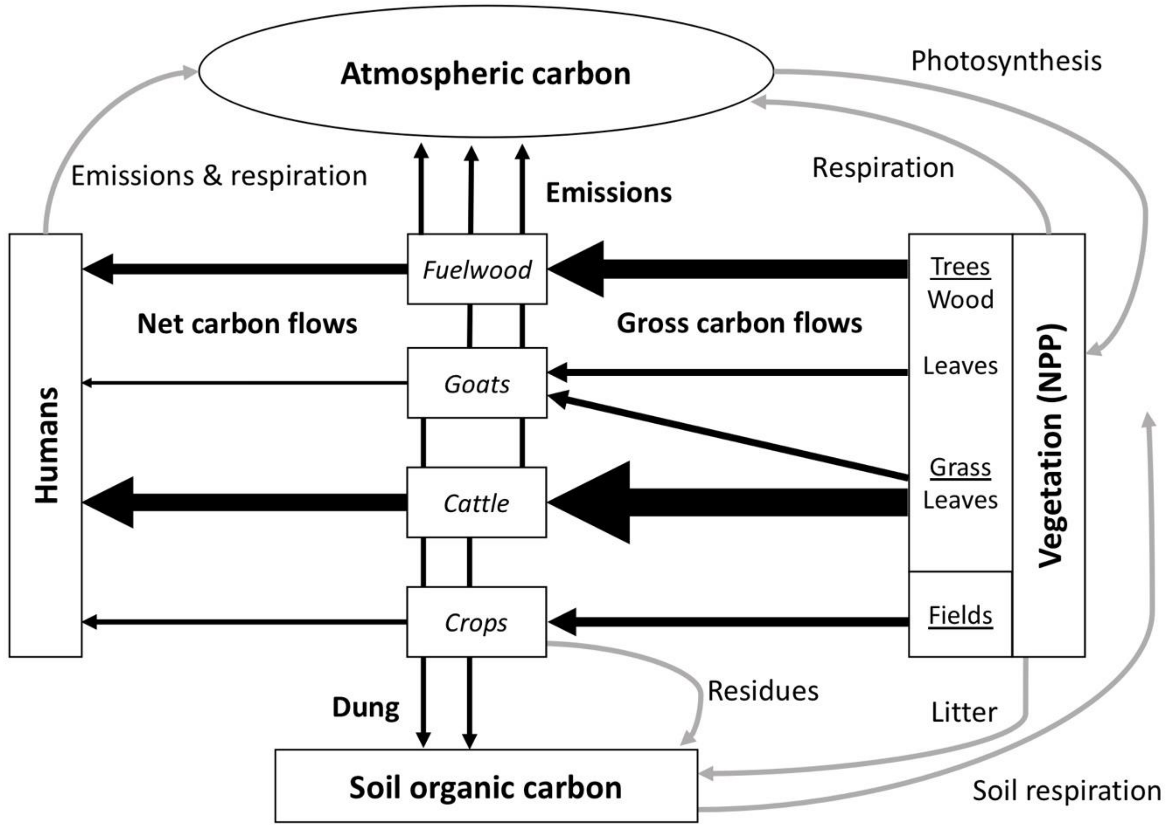


Figure 6.1: Carbon cycle in a rural African socio-ecological system. Thickness of black arrows illustrates relative amounts of carbon redirected by humans through livelihood activities. Grey arrows indicate aspects of the carbon cycle not investigated in this study.

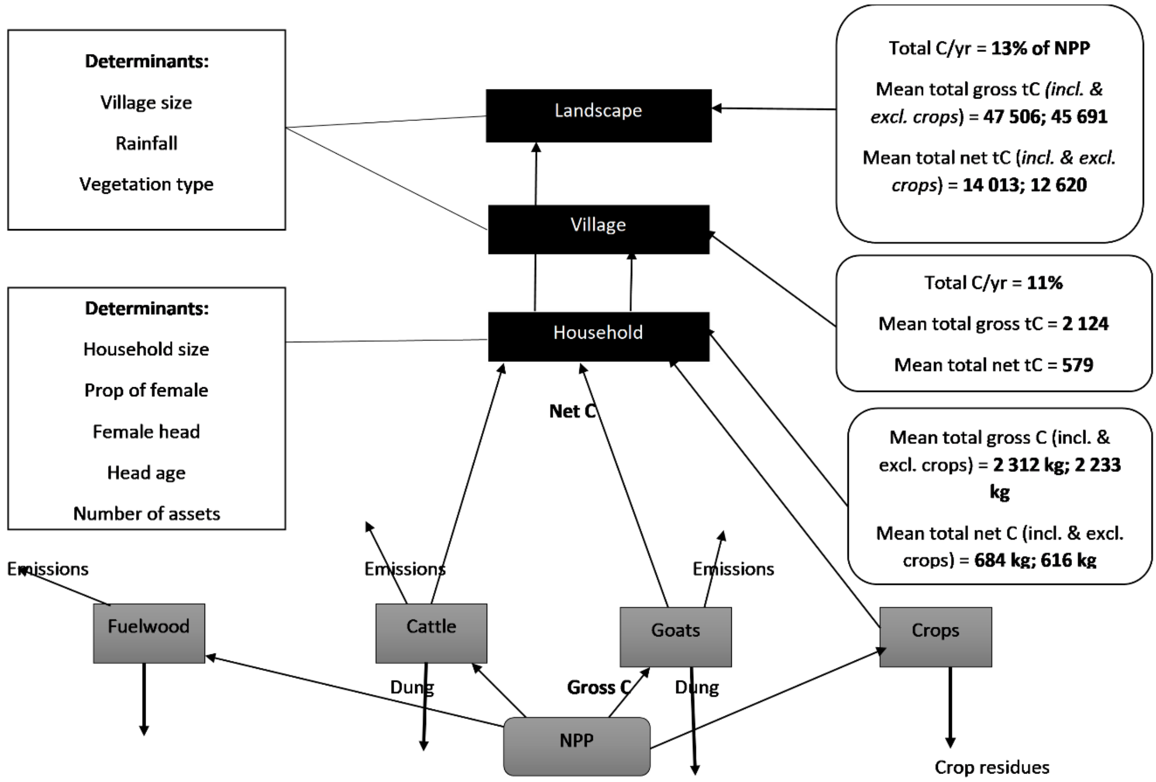


Figure 6.2: Conceptual summary of study findings

6.4 STUDY LIMITATIONS

Notwithstanding the robust findings of this study on the redirection of NPP at the local level in a savanna socio-ecological setting, the study had a few limitations. Firstly, the lack of a clear methodology to calculate carbon from livestock farming was limiting and thus the study depended on disparate literature to piece together the calculations, which proved a challenge as there are no clear and straightforward details. Secondly, due to the nature of data used for this study, the HANPP calculations only focussed on carbon appropriated through removal of biomass and did not include appropriations through land use change ($HANPP_{luc}$). Since this study used household-level data, information such as household field size and age would be needed to calculate household contribution to ($HANPP_{luc}$). Thirdly, household-level analyses were not stratified by village. This means that it was assumed that mean household carbon values were consistent across villages, whereas the upscaled analyses suggested that other unmeasured village-level factors influenced household carbon demand. Finally, comparison of the study's results was marred by a lack of similar studies at local scales such as household or landscape levels. This highlights the important scientific contribution of this study in this regard.

6.5 RESEARCH RECOMMENDATIONS

a) Further inquiry should identify easier and more accurate methods of calculating carbon footprints of land-based livelihood activities. This will encourage similar research to take place in areas that are especially vulnerable to climate change such as southern Africa. Also, HANPP studies at the local level such as this should analyse HANPP through both harvested biomass ($HANPP_{harv}$) and land use change ($HANPP_{luc}$). These aspects both play a role in shaping socio-ecological systems especially in the savanna ecosystems and thus would give a more accurate measurement of HANPP.

b) Further research should focus on household level contribution to HANPP from HANPPluc such as the one based on field sizes. This is valuable as it will give a complete evaluation of HANPP at the household level as crop production is one of the prevalent land-based livelihood activities among rural households in sub-Saharan Africa.

c) In addition to household socio-economic characteristics analysed in this study such as household size as village-level determinants, future HANPP studies should add more variables such as remoteness and resource governance system that could equally influence the use of natural resources in socio-ecological settings. This study has shown that each rural setting is governed by a set of socio-economic characteristics that are unique for each setting, and thus shape the use of resources. Resource governance is one of those that clearly have an influence on the way households use resources, a situation that has been alluded to in this study's literature as one of the reasons why there is a potential fuelwood scarcity.

d) Household, village, and landscape assessment of carbon redirection should be analysed in African contexts other than southern Africa such as in west, central, and east Africa. Sub-Saharan Africa is a huge sub-continent with various physical and social differences. Thus, the use and type of resources differ and these ultimately influence Africa's carbon cycle. It is therefore crucial to assess HANPP in all African settings.

e) Future studies should also focus on comparing total carbon footprints of households and settlements across rural-urban gradients. In order to inform carbon management strategies, a comparison across rural-urban gradients is necessary as these are two important components in the use of the environment and subsequently their influence on the carbon cycle.

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