THE CLIMATE REGULATION SERVICE PROVIDED BY *MIOMBO* LANDSCAPES

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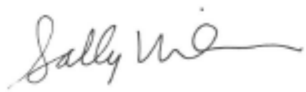
JOHANNESBURG

DECLARATION

I declare that this Dissertation is my own, unaided work. It is being submitted for the Master of Science Degree at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



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ABSTRACT

The African *miombo* woodlands are perhaps the world's largest relatively unexploited but potentially arable land resource, located on a subcontinent where population growth remains high and demands for food security and development are pressing. This study aims to quantify the tradeoff between landscape transformation of various types and the climate regulation service provided by the *miombo* landscape. Net radiative forcing, expressed in terms of its carbon dioxide emission equivalent (CO_2e) over a one century horizon was calculated for an intact ('historical') *miombo* landscape and for three hypothetical but observation-constrained derivatives: one developed through extensive subsistence farming; another by intensive, large-scale commercial farming; and one developed using 'eco-agriculture' improved smallholder techniques. The time course of net radiative forcing resulting from net carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions, from all significant sources (including production and decomposition processes, fires, cultivation, enteric emissions, termites, etc.) was assessed, as well as the net change in surface reflectance (albedo) for the four representative landscapes. It was found that the loss of climate regulation service was greatest when the entire landscape was converted to commercial agriculture, with conversion via subsistence extensification, offering the most protection for the climate regulation service. Conversion to eco-agriculture falls somewhere in between. If the loss of climate regulation service is expressed per unit agricultural production, the pattern is reversed, favoring commercial intensification as the choice mode of production. It was found that contrary to the conventional approach of evaluating the climate regulation service entirely on the basis of net carbon storage, the changes in other greenhouse gases (notably CH_4, but also to a smaller extent N_2O), and surface albedo made substantial contributions to the changes in the climate regulation service provided by *miombo* landscapes.

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INTRODUCTION: Why this work matters

The tradeoff between agriculture and climate protection in Africa

Economic development feeds on forests; at least historically this has been true. America's booming post-Industrial Revolution economy gobbled up nearly all of the forests east of the Mississippi, with states like Ohio losing 90 percent of its woodlands and wetlands. In 1972, Brazil constructed its Trans-Amazonian Highway to connect "land without men to men without land", and so the settlers came to develop agriculture. Soon over 700,000 square kilometers (km^2) of the Amazon forest were transformed by cattle ranchers, timber loggers, and illegal miners. By the end of the 1980s, deforestation of the Brazilian rain forest drew global attention, both for its massive emissions of carbon dioxide (CO_2) and biodiversity losses. In recent years, joint efforts have reduced Amazonian deforestation in "hot spots" like the states of Rondônia and Mato Grosso by over 80 percent (Wharton, University of Pennsylvania 2010). Although Brazil has been commended for its successful anti-deforestation policies, an unintended consequence is the rapid deforestation occurring on the Amazonian fringe, in the unprotected *cerrado* biome, comprising of savanna forest and grasslands. Currently, the *cerrado* is threatened by many of the same deforestation drivers that once dominated the Amazon, including soy production, cattle ranching and charcoal making with implications on how to manage mixed tree-grass landscapes, without pitting forests and savannas against each other. This is particularly relevant for tropical dry forest systems, which account for nearly half of the world's tropical and subtropical forests, covering large parts of Africa, Latin America, and the Asian Pacific (Grainger 1999). Originally occupying approximately 3.6 million km^2 and spanning several countries from Angola in the west to Tanzania in the east, the *miombo* woodlands are among the world's largest relatively unexploited but potentially arable land resources on a subcontinent where population growth remains high and demands for food security and economic development are pressing (Malmer and Nyberg 2008, Williams et al. 2007). Low soil fertility, the presence of diseases like the tsetse fly-transmitted trypanosomiasis, and a lack of infrastructure are among the factors that have preserved *miombo* to date, all of which are now subject to change. Known and cost-effective agricultural techniques can fix soil acidity and nutrient deficiencies; the tsetse fly has been effectively controlled over most of the area, and regional political stability indicates infrastructure improvements as highly probable (CIFOR 1999). Moreover, and perhaps most forceful, is the growing global demand for commodity crops and associated foreign investments into African farming. If patterns played out in dry forests in the Americas and Asia are replicated in Africa, these developments will eat up *miombo*, impacting an estimated 100 million people, most of whom live on less than one dollar per day and depend on the woodlands for basic goods like food, fuel, shelter and medicine (Ryan et al. 2016).

People have inhabited *miombo* since the Early Stone Age. Historic land use has been based on various forms of shifting cultivation, involving conversion by fire and long fallow periods that allow the woodlands and soil to regenerate. Shifting agriculture remains an important contemporary land use. Generally agriculture development in *miombo* proceeds in the following sequence: 1) removal of valuable timber species by a process called 'high-grading'; this began about a century ago, and stocks of the most valuable trees are now largely exhausted; 2) incursion of charcoal-makers, especially along roads leading to regional towns and cities, who remove the remaining large trees in patches of a few hectares and convert them on-site to charcoal for sale on urban markets, using traditional charcoal-making techniques (mainly the earth-mound kiln); 3) small-scale subsistence farmers burn the remaining debris to fertilize one or a few crop cycles, e.g. maize, millet, cassava, cowpeas and squashes, before moving on to another patch of land, allowing secondary forest regrowth on the cleared area (Chazdon 2008, Chidumayo 1999, CIFOR 1996). Increasingly though, the growing number of subsistence farmers means that they are unable to support their families on the available land, forcing shorter fallow periods, more extensive woodland clearings and drainage of seasonal wetlands in the landscape, locally referred to as *dambos* (Kutsch et al. 2011, CIFOR 1996). Exacerbating the situation are climate-related stressors such as higher than usual temperatures and unpredictable rainfall (Williams et al. 2009, Kutsch et al. 2008).

In 2016, a prolonged and severe drought, brought on by El Niño weather patterns, devastated vast tracts of farmland across southern Africa. Malawi declared a state of emergency; nearly 20 percent of its population was hungry. Likewise, Lesotho, Namibia, Mozambique, Zambia and Zimbabwe also suffered from acute food shortages (Aljazeera 2016). Countries like Malawi and Zambia, who are dependent on hydroelectricity, are more frequently dry, in the dark, or both. Seeking supplemental income, failed farmers often exploit the woodlands to harvest and prepare charcoal for sale on nearby urban markets (Kutsch et al. 2011). Because of easy transport, storage and low cost, charcoal is the preferred cooking fuel in urban areas where access to electricity is either limited or unreliable. African cities are among the fastest growing in the world, with an average growth rate of 4 percent per year. Every 1 percent increase in the level of urbanization is estimated to result in a 14 percent increase in charcoal consumption. Considering the inefficiencies of current charcoal-making techniques, i.e. 5-10 tonnes of wood are needed to make 1 tonne of charcoal and 60-80 percent of the wood's energy is lost the process, extensive clearing will be necessary to satisfy growing demands (Chidumayo and Gumbo 2010). Simultaneously, calls for commercial agriculture and agribusiness development from foreign interests are apparent in *miombo*. The World Bank has urged Africa to use its "untapped" land and water resources to create jobs, boost yields and increase exports of surplus crops (World Bank 2013). To this end, other patterns of food production have emerged with the potential to replace or displace the traditional system of shifting agriculture.

Two novel types of agriculture are being practiced in *miombo*. The first is a version of the large-scale, high-input commercial farming which has dominated ecologically-similar landscapes like the *cerrado* in South America and draws its agronomic approach from the American Midwest, translated to the African environment by commercial farmers in South Africa and Zimbabwe, in particular. Non-local capital and expertise is deployed to clear large individual holdings (hundreds of hectare in extent), on either lightly-occupied land or land transformed (sometimes considered degraded) by shifting agriculture. Commodity crops, usually export-oriented, such as maize, soybeans and biomass-derived fuels are grown using improved germplasm, relatively large per hectare inputs of lime, nitrogen, phosphorus and other nutrients, mechanized cultivation, center-pivot irrigation in some cases, and chemical methods to control weeds and pests (Matson et al. 1997, McIntire, 2014, Reardon et al. 1999). The second is a largely experimental alternative which seeks to increase agricultural production substantially above the levels typically achieved under traditional shifting agriculture, while avoiding the worst of the negative environmental and social aspects of large-scale, high-input operations. This style of agriculture has been variously called 'eco-agriculture', 'agroforestry', and 'improved smallholder agriculture'. Eco-agriculture emphasizes local livelihoods, nutritional security and integration of perennial crops (mostly trees) with short-duration crops and livestock on plots more permanent in time and space compared to shifting agriculture. These aims are achieved through labor-intensive land use via increased (but low, compared to the high-input agriculture described above) inputs of fertilizers, improved and diversified crop varieties (usually based on classical selection techniques rather than genetic modification and often using a wide range of species per-adapted to the environment), tighter closure of nutrient cycles and use of non-chemical methods for weed and pest control (Sherr et al. 2012). The above options have been framed in the international discussions about land use in Africa as a choice between 'extensification' and 'intensification', with both sides claiming environmental and social benefits. In reality, all three patterns described above (i.e. shifting, commercial and eco-agriculture) will involve the transformation of *miombo* landscapes, just in different ways and to different degrees.

The link between land use, particularly deforestation, and global climate change is well-established (Eva, Brink and Simonetti 2006, Hill et al. 2013, Kim et al. 2016, Lal 2004, Merbold 2011, Metzger et al. 2006, Petrescu et al. 2015, Ryan et al. 2010, Sanju et al. 2006, Scholes and Scholes 2013, Smith et al. 2013, Vagen Lal and Singh 2005). Clearing of 'climax' native vegetation for agriculture has two major climate-system consequences. Firstly, a release of carbon from soil and biomass into the atmosphere as carbon dioxide. Assuming half of the carbon in the top 30 centimeters of soil and all the carbon in woody biomass is released in half of the existing *miombo* extent over the next thirty years, the mean rate of release will be 0.2 Pg. carbon per year, which would make deforestation in *miombo* among the leading contributors to global climate change (CIFOR 1996). It would account for nearly one fifth of the current total carbon released from land use change around the world and around 2 percent of total greenhouse gas (GHG) forcing (CIFOR 1996). The second, and less documented effect, is change in radiant energy exchange at the land surface (i.e. an increase in albedo when dark woodland vegetation is replaced by bright soil or crops). Other, more minor effects include decreased surface roughness when tall vegetation is replaced by short and a shift in the ratio of latent to sensible heat when long-duration evergreen plants are replaced by short-duration, seasonally-green plants, which, if occurring on millions of hectares, could result in increased atmospheric stability and a decrease in the formation of rain-generating convective storms, as well as an adjustment to the global net radiative forcing (Frost 1996). The *miombo* woodlands also generate a thought-to-be small but possibly significant emission of trace gases and radiatively-active particles other than carbon dioxide, which influence the global radiation budget (CIFOR 1996). *Miombo* processes which result in emissions of methane (CH_4), nitrous oxide (N_2O), tropospheric ozone precursors and aerosols include: wild and prescribed fires, enteric fermentation by ruminants, and emissions from the soil (especially denitrification and methanogenesis in the *dambo* soils and from termites, both of which are features of *miombo* landscapes) (Bell and Roberts 1991, Bullock 1992, Lal 2007, Nyamadzawo et al. 2015, Nyamadzawo et al. 2014, Otter and Scholes 2000, Roberts 1988). Thus, a potential tradeoff is established between the regional and global scales: on the one hand, the need to provide local food, energy and promote livelihoods; and on the other, the desire to limit global climate change. The 'provisioning services' side of this tradeoff (i.e. food and energy crop yields) is relatively well documented, but the 'regulating service' side (i.e. the climate change mitigation elements) is poorly quantified (Levin 2009).

Policy efforts such as the Reducing Emissions from Deforestation and Forest Degradation (REDD) program seek to mitigate climate change by reducing net emissions of GHGs through enhanced forest management, thereby preserving their climate-regulating function (Bond et al. 2009, Larson 2011, Skutsch and Ba 2010, Skutsch et al. 2011). This function has mostly been presented purely in terms of the terrestrial carbon stored in biomass and soils. In reality, there are several mechanisms through which the landscape interacts with the global climate system, including exchanges of carbon dioxide, methane, nitrous oxide, radiatively-active particles, radiant energy and sensible heat (Ansley et al. 2006, Djossou et al. 2018, Kirschbaum et al. 2011, Merbold 2014, Sorrano et al. 2014, Rees et al. 2006).

Research objectives and hypotheses

The purpose of this research is to quantify the tradeoff between landscape transformation for agricultural purposes of various types, occurring at different extents and intensities, and the climate regulation service provided by *miombo* landscapes of south Central Africa, which consist of a mosaic of dry forest and interdigitating *dambo* wetlands. I expected that as the extent of land cover transformation and intensity of disruption of natural structure and processes increases, the climate regulation service in *miombo* would decrease due to increased net emissions of carbon dioxide, methane and nitrous oxide (Figure 1). Potentially counteracting this effect, the clearing of perennial woodlands to reveal lighter underlying soil is expected to increase albedo, cooling the land surface at regional scale. To test the aforementioned hypotheses, I calculated the net radiative forcing (RF) and its carbon dioxide emission equivalent (CO_2e) over a one century horizon for a representative intact ('historical') *miombo* landscape; one developed through extensive subsistence farming and charcoal cutting; one developed using intensive, large-scale commercial farming techniques; and one developed using 'eco-agriculture' smallholder techniques. The time course of net RF resulting from net carbon dioxide, methane and nitrous oxide emissions, from all significant sources (e.g. fires, cultivation, ruminants, termites, etc.) was quantified, as well as the change in surface reflectance (albedo), for the four landscapes derived from the same archetype, thus addressing the aforementioned limitations of the current carbon-centric approach to quantifying the climate regulation function provided *miombo* and the potential consequences of land use change on service delivery.

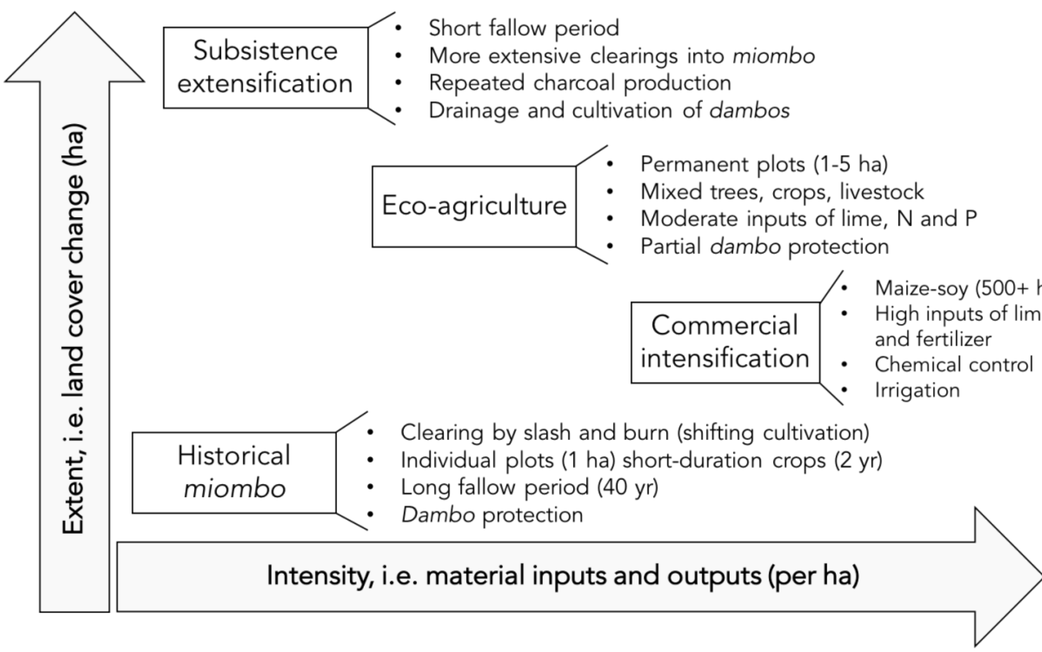


Figure 1. Schematic of land use scenarios (boxes) and characteristics (bullets), as related to the climate regulation service hypothesis. Axes represent land use intensity (x) and extent of land cover change, i.e. transformation, (y). Axes labels are in or per hectare (ha).

The structure of the chapters which follow

The chapters of this thesis are organized to be easily converted into two separate manuscripts for the purpose of subsequent publication in appropriate peer-reviewed scientific journals. The first manuscript is based on Chapters 1-3 and focuses on the current state of *miombo*, in terms of ecology and human activity, and the known and unknown tradeoffs between land use and the climate regulation service provided by the landscape. The second manuscript consists of Chapters 4-5 and presents my research methods, models, metrics, results and discussion.

More specifically, the first chapter provides an overview of *miombo* ecology, emphasizing its unique capacity to be a potentially globally-significant climate regulator, if managed effectively. The next chapter considers both historic and current directions of land use across the *miombo* region, regarding both direct and indirect drivers of deforestation. The third chapter offers a literature review, outlining the substantive findings and methodological contributions to the topic of ecosystem services, much of which is focused on provisioning services. The review closes with an evaluation of existing information, indicating a need for more research on the tradeoff between land use change and the climate regulation service provided by *miombo* with greater consideration for trace gas emissions and the albedo effect. Chapter four provides a detailed account of my research methods, including: sampling technique (i.e. a discussion of resolution and scale), greenhouse gas flux and albedo models with associated driver variables and parameters, which were obtained from relevant literature sources and climate metrics. The final central chapter presents important results and related discussion, offering new data to fill the aforementioned gap.

The concluding chapter synthesizes the developments of Chapters 1-5, demonstrating how the findings of this work help advance present knowledge on the effect of land use, particularly agricultural transformation, on *miombo* ecology with attention to delivery of the climate regulation service, culminating in recommendations for improved dry forest resource management to minimize the tradeoff between agricultural production and service provision across the *miombo* region of south Central Africa. It also identifies opportunities for future research, including the need to address the indirect drivers of the anticipated land use change, i.e. socioeconomic determinants.

CHAPTER 1: The ecology of the *miombo* landscape

Extent, geology, landscape evolution, and soil characteristics

The *miombo* belt spans south central Africa from east to west, from near the equator to about 15 degrees south of the equatorial plane. Originally covering an estimated 3.6 million km^2, the woodlands extend from Tanzania and southern Democratic Republic of Congo (DRC) in the north to Zimbabwe in the south, and across the continent from Angola through Zambia and Malawi to Mozambique (Abdallah and Monela 2007, Campbell et al. 2007, CIFOR 1996, Olson et al. 2001). Situated within the sub-humid tropical zone of Africa, the region receives unimodal summer rainfall (mean annual rainfall ranges from 710-1,365 millimeters) and experiences warm temperatures throughout the year (mean annual averages ranging from 18.0-23.1 degrees Celsius). The distinctive gently undulating landscape coincides with the African and post-African planation surfaces that form the Central African Plateau, largely on granitoid basement complex rocks of the African Shield. These ancient pediplains have been preserved through centuries of periodic uplifting and warping of the continental shield and date back 25-100 million years. The underlying geology comprises mainly of metavolcanic rock and metasediments, including intrusive granites, schists and quartzites (CIFOR 1996, Desanker 1997). Seasonally-waterlogged, treeless, grassy drainage lines called *dambos,* occupying in some cases up to one-third of the area, are intermingled with the woodlands which occupy the slightly higher terrain between them (i.e. 'interfluves'). Fed by rainfall and drainage surrounding uplands, *dambo* soils are moist for an extended period every year, clayey and rich in nutrients and organic matter (Abdallah and Monela 2007, Bell and Roberts 1991, Bullock 1992, CIFOR 1996, Faulkner and Lambert 1991, Kiss 1990, Roberts 1988, von der Heyden and New 2003). Conversely, upland soils are generally sandy, heavily leached and low in organic matter, nitrogen and phosphorus. This is partly because of the acidic bedrock from which the soil is derived, but also due to long periods of weathering under warm and wet climactic conditions (CIFOR 1996, Desanker 1997). The resulting catenary sequence forms the basic landscape unit in *miombo*, comprising of woodlands on the well-drained soils of the interfluve and hydromorphic grasslands in the *dambo* bottomland (Figure 2).

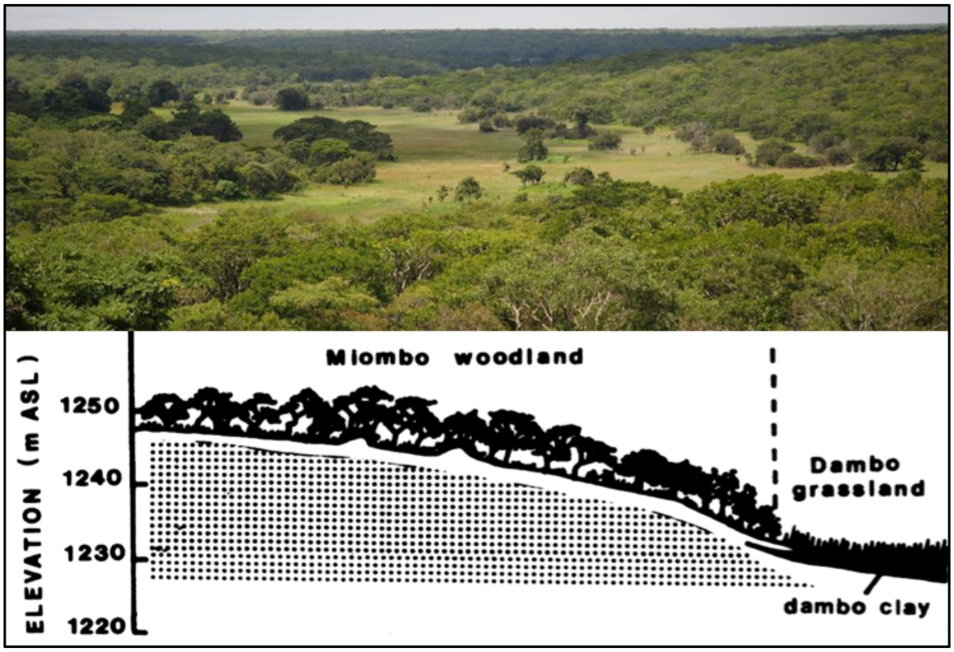


Figure 2. Photograph (top) and schematic (bottom) of distinctive catenary sequence of the landscape with light-colored grassy bottomlands (*dambos*) and darker wooded uplands (*miombo*).

Dominant vegetation, nutrient cycling and carbon storage

Trees from the legume subfamily *Caesalpinioideae* (specifically a tribe known as the Dialea), such as *Brachystegia*, *Julbernardia*, and *Isoberlinia* are dominant in the woodlands, perhaps due to their ability to internally recycle nutrients through mechanisms like carbohydrate storage and substantial recovery of nitrogen and phosphorus from leaves before leaf fall (Abdallah and Monela 2007, Campbell et al. 2007, Chidumayo 2002, CIFOR 1996, Desanker 1997). Tree growth rates in both mature and regrowth *miombo* are relatively similar, approximately 3 percent per year as determined by rates of nitrogen and phosphorus uptake (uptake is mainly controlled by soil moisture, i.e. rainfall). Nitrogen and phosphorus uptake rates thereby control the carbon cycle and resulting primary productivity, capping net primary production (NPP) at 900-1,600 grams per square meter per year in *miombo*. Because of the sclerophylly of the leaves and their high tannin content, decomposition is slow, and herbivory is constrained. Only very large ungulates, like elephants, in low stocking densities can process the material (Frost 1996).

Termites are also important in nutrient cycling in *miombo* because they are able, with the assistance of cellulose-decomposing fungi growing in their mounds, to break down difficult-to-decompose materials (Desanker 1997). To maintain the fungi, termites collect dead organic matter and surface litter. The accumulation of nutrients within the nests creates "hot spots" with relatively high total nitrogen and bioavailable phosphorus and a range of other nutrients. These fertile patches support a unique diversity of plant and bird species. Anaerobic digestion within the guts of termites is a potentially significant source of methane in these termite-dominated landscapes (Frost 1996, Sanderson 1997).

Dry season fires on average burn a third of the *miombo* landscape every year, though some facets burn annually, and others rarely burn. Depending on the fire regime (i.e. frequency, season and intensity), fires alter nutrient cycling via oxidation of organic matter before it can reach decomposers. Fires also perturb the radiation balance locally, regionally and globally due to the pyrogenic emission of radiatively-active gases (e.g. methane, nitrous oxide and non-methane volatile organic carbon and nitrogen oxides which interact to form tropospheric ozone) and aerosols (e.g. soot and ash particles in the smoke) which have light-scattering and absorption effects and on cloud formation (Bertschi et al. 2003, Harley et al. 2003, Haywood et al. 2003, Jost et al. 2003, Kirchstetter et al. 2003, Langmann et al. 2009, Li et al. 2003, Pilewskie et al. 2003, Ross et al. 2003, Sa et al. 2003, Scholes and Andreae 2000).

Unless completely uprooted, *miombo* trees regenerate readily by coppice from stumps and root stocks after disturbance. In most *miombo*, biomass accumulation with increasing age is associated with regrowth. The annual increment of the woody-plant biomass is no more than 3-4 percent in mature stands. These rates, which define the upper limit of the carbon sink strength, could increase slightly under an atmosphere high in carbon dioxide, but given the pervasive nutrient limitations, an increase in net primary productivity of greater than 15 percent is unlikely. For this reason, along with low rates of herbivory and decomposition, *miombo* biomass and necromass can act as a stable carbon pool. Likewise, *miombo* soils, particularly those in *dambos* which are rich in organic matter, can also serve as a storage site for carbon (Bell and Roberts 1991, Bullock 1992, Frost 1996, Hansen et al. 2008, Jindal, Swallow and Kerr 2008, Munishi et al. 2010, Nyamadzawo et al. 2015, Pan et al. 2011, Ribeiro et al. 2013, Ryan Williams and Grace, 2011, Woollen Ryan and

Williams 2012).

The main technique that has been suggested for increasing carbon uptake in *miombo* is the reduction in fire frequency; the main technique for retaining existing carbon stores involves the restriction of woodland clearance and *dambo* cultivation. Experiments in many parts of Africa, including some in *miombo* woodlands, have shown woody biomass and soil carbon to increase if fires are excluded (Trapnell et al. 1976). Permanent fire exclusion is virtually impossible in the strongly seasonal *miombo* climate, but a reduction in frequency from the current annual-to-triennial norm to once a decade is probably achievable at reasonable cost. This would simultaneously increase net carbon dioxide uptake (photosynthesis is little affected, but pyro-respiration is delayed, resulting in an increase in biomass and necromass carbon stocks), and decrease the emission of methane and ozone precursors. The net climate impacts of changes in aerosol emissions are ambiguous. Some smoke particles are radiation-absorbing; others are reflective. The clouds they help form can be ice or liquid water, and high or low altitude, all of which have different net radiative forcing. The net carbon uptake following a change in fire regime would last twenty to fifty years, until the woodlands reach a new equilibrium carbon density. The carbon storage benefits of *miombo* management can be extended beyond the initial 20-50 year period by harvesting the carbon-containing products (principally timber) sustainably and either converting it to long-lived products such as furniture and buildings or by using it as an energy source in place of fossil fuels.

In the long term, the occurrence rather than suppression of fires may help to sequester carbon. A small fraction of the carbon burned (less than one percent) is converted to highly decay-resistant forms such as charcoal and black carbon ('soot') (Andreae 1993). This is one of the few mechanisms by which carbon can be removed from the biosphere for long periods of time. It is the naturally-occurring version of the biochar production and incorporation suggested for carbon sequestration in cropped landscapes (République Française et al. 2017). Coupled with the shading effect of smoke particles and the clouds they nucleate, the net long-term effect of fires on the global energy and carbon balance may be close to neutral.

Thus, if managed to maximize carbon storage, a total of approximately 6-10 Pg. of carbon could be taken up by *miombo* over a period of half a century, with about half of the change in carbon stocks occurring in the soil and the rest in the biomass (Williams et al. 2008).

Disease dynamics: 'sleeping sickness' and the great rinderpest epidemic

Until recently, the blood-sucking tsetse fly, carrier of the parasites that cause trypanosomiases or 'sleeping sickness', effectively limited human and livestock populations in the woodlands. In 1901, an epidemic erupted in Uganda, killing more than 250,000 people. Around the same time, the great rinderpest epidemic ravaged the continent's ungulate populations; ninety percent of the region's cattle were lost and a similar fraction of wild ungulates. A combination of efforts, including slaughter of infected livestock, pesticide campaigns, and trapping and sterilization of male tsetse flies have been successful in controlling trypanosomiases. Steps to eradicate rinderpest were mostly successful, allowing both human and cattle population densities to increase and potentially increase above historical levels in the future (Frost 1996).

CHAPTER 2: Directions of land use in *miombo*

Small-scale shifting cultivation

Compared to climatically similar areas elsewhere in Africa, human population densities over much of the *miombo* region are still relatively low, averaging about 15 persons per square kilometer, ranging from less than 50 people in some countries like Angola and up to 200 in others such as Zambia. Historic and current land use has been based on various forms of shifting cultivation, involving fallow periods that allow the woodlands and soil to regenerate. Slash-and-burn (i.e. ash-fertilization, also called 'swidden') agriculture in particular is widely practiced in *miombo*. The practice was adapted in theory to deal with the generally infertile soils of *miombo*, especially in the wetter regions where woody plant biomass is high and cut trees regenerate rapidly through resprouting. The most common of these practices in *miombo* is large-circle *chitemene*, a system which uses the foliage and outer branches of felled trees for kindle. The resulting ash is concentrated into large piles or 'ash beds'. The deeper the bed, the less tillage required, which is good for farmers without livestock. More fuel also means a hotter fire, more complete combustion of plant material and suppression of weeds during the first few years of cultivation. The land is then cultivated until the crop yields fall to a level too low to support the farming household and is subsequently abandoned. Sometimes livestock are mixed in to the *chitemene* system to provide draught power and manure. Owning even a small number of cattle can provide measurable benefits in the form of meat, milk, blood, hides and skin, dung fuel, and transportation as well as opportunities for bartering or cash sales at urban markets (Abdallah and Monela 2007, CIFOR 1996, Chidumayo 1999, Dovie, Shackleton and Witkowski 2006, Frost 1999, Mearns 1996). High-grading, where possible, and charcoal production are often concurrent in these systems (Desanker et al. 2000).

However, as the demand for food, charcoal and timber increases, along with the growth of the rural and especially urban populations, the cycle of cutting and burning has shortened in duration. This does not permit the biomass resource and nutrient levels to recover between iterations. The result is land degradation and declining crop yields, forcing extension of cleared areas further and further into intact woodlands and progressively into more fertile *dambo* soils (Adeyolanu et al. 2013, Chidumayo and Kwibisa 2003). This dynamic is made worse by demographic pressures and climate-related stressors, particularly when agriculturally-based population density increases in and close to forested areas. This is likewise true of communal areas centralized around *dambos*, which are more often farmed during times of drought and food insecurity. In subsequent chapters, I will term this pattern of land use 'subsistence extensification'.

Commercial intensification

Permanent agriculture is also emerging across the region particularly in Malawi, Zambia and Zimbabwe where large 'farm blocks' dominate the landscape (Desanker et al. 1997). It can transform intact or slightly-used *miombo*, in other cases it replaces land already transformed, and possibly degraded, by subsistence agriculture. Large-scale, foreign-funded and run operations raise issues of land tenure and its capture by elites, the displacement and marginalization of the rural poor, and the tension between local food security and production for export. Although presented as a 'food security' intervention, the crops grown are often destined for export and non-human consumption, rather than local nutrition, and the loss of smallholder opportunities and access to wild food sources may paradoxically reduce local food security (Wily and Mbaya 2001).

Because of the large scale, the fields often span both former woodland and former *dambo* soils. The yields per hectare are typically tenfold the yields achieved by the low-input, small-scale farming on nutrient-depleted lands, described above. Thus, in principle, this land use trajectory would require less clearing of land to achieve the same outputs as the subsistence trajectory described above, but in practice it may drive a net expansion of deforested areas if the demand for products is global and unconstrained by local demand, as it has in southeast Asia and South America. I will use the phrase 'commercial intensification' to describe this type of land use.

Eco-agriculture

Parts of the development community have suggested, researched and promoted a third trajectory. It aims at achieving most of the increased yield of commercial intensification, while creating and maintaining livelihood opportunities for smallholder farming household but avoiding the social and environmental sustainability challenges raised by both of the above patterns, particularly by mimicking the diversity and tight nutrient cycling of *miombo* woodlands (Dewees et al. 2010, Edmeades 2003, Falkowski et al. 2000). The trajectory has been given many names; here I call it 'eco-agriculture'. Eco-agriculture would lead to a landscape mosaic with relatively fine grain and high diversity (of both farming enterprises within a landscape and crops – trees, short-duration crops and livestock – on individual farms). Land use is labor-intensive rather than capital-intensive and involves increased inputs of fertilizers and improved seed varieties relative to subsistence extensification (thus is not necessarily strictly 'organic' in the narrow sense), but also aims for tighter closure of nutrient cycles and greater reliance on non-chemical methods of pest control.

Each of the above patterns involves the conversion of semi-natural landscapes to agriculturally-transformed ones, with impacts on associated ecosystem processes, including ecosystem service[1]

[1] I am aware of the changes in nomenclature proposed by Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), in which 'ecosystem services' become 'Nature's Contribution to People', provisioning services become material contributions, cultural services become non-material contributions, regulating services become regulating benefits, and supporting services are now regarded as ecosystem processes (Pasqual et al.

delivery (Figure 3). The provisioning service side of this tradeoff (i.e., crop production) has been well-documented (Ryan et al. 2016). However, less is known about the cultural and regulating services side, including climate regulation. The next chapter provides a literature review summarizing what is known about the ecosystem services provided by the *miombo* landscape, tradeoffs between land use, particularly agriculture, and ecosystem service delivery, and finally suggests that more work is needed to make the most informed recommendations for future land use plans across the region.

Figure 3. Photographic depictions of (from left) subsistence extensification, commercial intensification and eco-agriculture. Credits (from left): K.L. Bothi; World Agroforestry Center, Charlie Pye-Smith.

CHAPTER 3: Literature review

Ecosystem services concept: Millennium Ecosystem Assessment (MEA) to present

Defined initially in 2005, as part of the Millennium Ecosystem Assessment (MEA), ecosystem services are the benefits people obtain from ecosystems. Per the MEA, services can be categorized as provisioning services such as food, water, timber and fiber; regulating services that affect climate, floods, disease, wastes and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits, and supporting services such as soil formation, photosynthesis and nutrient cycling. Human well-being is fundamentally tied to the flow of these services (Reid et al. 2005). In 2016, the MEA framework was enhanced by the Intergovernmental Science-Policy

2017). Since these proposals are not fully established and the existing literatures uses the Millennium Ecosystem Assessment (MEA) (2003) scheme, I will use the older terms.

Platform on Biodiversity and Ecosystem Services (IPBES) in its Methodological Assessment of Scenarios and Models of Biodiversity and Ecosystem Services, which asserts the complementary roles of scenarios and models, with scenarios describing possible futures for drivers of change or policy interventions and models translating those scenarios into projected consequences for nature and nature's benefits to people. Thus, any comprehensive assessment of human well- being requires the integration of modelling across multiple sectors (e.g., agriculture, energy, rural livelihoods, etc.), thereby dealing with a broader set of relevant goals and values than those mediated exclusively by ecosystems. To date, much of the research on ecosystem services provided by *miombo* has been focused on provisioning services.

Sometimes referred to as 'social woodlands', *miombo* is home to more than 100 million rural people and supports an additional 50 million people in urban areas, regionally and internationally, with critical goods and services (Table 1). Some people satisfy basic needs such as food, shelter, medicine and fuel from *miombo*, while others engage in a mix of income-generating activities like manufacture of charcoal, cultivation of crops and livestock rearing, and to a lesser extent logging for valuable timber species (Abdallah and Monela 2007, Campbell et al. 2002, Dewees et al. 2010, Frost 1996, Nshubemuki and Mbwambo 2007).

Fruits, flowers, seeds, tubers, bulbs and shoots are some of the wild foods growing in *miombo*. Local people routinely forage for fungi and insect foods, which become especially critical sources of nutrition in times of food shortage. Honey, mushrooms, wild spinaches, caterpillars and termites provide a safety net for women and children who are more susceptible to dietary deficiencies (Chidumayo and Gumbo 2010). Construction materials such as poles for houses, fences and granaries as well as grasses for thatched roofs, can be sourced. Natural fibers provide the raw materials for necessities like baskets, ropes, clothing, nets, brooms, and mats. Medicinal plants, indigenous to the woodlands, are an important part of wellness, offering relief from numerous diseases like tuberculosis, diarrhea, and skin rashes (Abdallah and Monela 2007, Campbell et al. 2002, Chidumayo and Gumbo 2010, Weigers et al. 2006). These goods have substantial economic value, accounting for approximately 25 percent of cash and subsistence income in rural areas and averaging USD 9 billion per year across the region (Ryan et al. 2016).

Table 1. A summary of the main provisioning services from *miombo* woodlands, with an estimated ranking of their importance to a range of beneficiaries, as adapted from Ryan et al. (2016).

	beneficiary				
product	local use as a safety net	local subsistence consumption	rural markets	urban/regional markets	international
wild foods					
wild fruits	high	high	medium	medium	medium
wild vegetables	medium	medium	low	no reports	no reports
mushrooms	low	medium	medium	low	no reports
edible insects	medium	medium	medium	medium	low
honey	low	low	medium	medium	low but increasing
bushmeat	medium	high	medium	medium	low
building and craft materials					
barks and fibres	low	medium	medium	medium	no reports
thatching grass	medium	high	high	medium	no reports
construction poles	low	high	medium	low	no reports
medicinal plants	low	high	high	high	medium

Miombo is also the primary source of wood fuel consumed in both rural and urban areas. Rural communities typically use firewood, obtained from dead wood or wood cut for other purpose, to meet household energy needs (Abdallah and Monela 2007, Beck and Nesmith 2001, Campbell et al. 2002, Chidumayo 1993, Chidumayo 1988, Chidumayo 1987, Kutsch et al. 2011, Syampungani et al. 2009). Charcoal, on the other hand, is harvested and processed for sale in regional urban markets (Abdallah and Monela 2007). Most charcoal is produced in earth kilns made by covering a pile of logs with soil, igniting the kiln and allowing carbonization under limited air supply. Ninety percent of the aboveground biomass in *miombo* is suitable for charcoal making by this method. Usually only logs with a butt girth of greater than 10 cm are used. Smaller branches with butt girths of less than 10 cm and main stems with girths of less than 30 cm are not used. The mass efficiency of the kilns is 23% on an oven dry weight basis (i.e. a yield of 0.23 kg charcoal per 1.0 kg of wood). The energy efficiency, on the other hand, is around 13%, i.e. 0.13 MJ of energy embodied in charcoal from 1.0 MJ in the wood used to make it (Kutsch et al. 2011). Road transportation is the primary method for moving wood-derived fuel from production sites to urban consumption centers, although some charcoal in Malawi and Tanzania is moved by rail (CIFOR 1996, Kutsch et al. 2011). Because of easy transport and storage, charcoal has quickly become the preferred cooking fuel in urban areas where access to electricity is limited or unreliable. Sub-Saharan African cities are among the fastest growing in the world, with an average growth rate of 4 percent per year. For every 1 percent increase in the level of urbanization, it is estimated to result in a 14 percent increase in charcoal consumption (Chidumayo and Gumbo 2010). The total employment in the traded wood fuels sector is between 1.4 and 2.5 million people with a traded value of USD 780 million per year (Ryan et al. 2016). This figure may be considerably higher given that most charcoal makers and dealers do not obtain licenses, as required. Consequently, much of the business is conducted illegally. Because of the difficulties of policing wood fuel cutters and charcoal makers who are widely scattered and often work in remote locations, the woodlands are increasingly exploited (CIFOR 1996; Kutsch et al. 2011).

Miombo also delivers a few valuable timber species. For example, Mozambique's forestry sector benefits from high acceptance of some of its premium and first class timber species in overseas markets and has relatively easy access to these markets. The export market is dominated by Chinese companies and is highly selective, i.e. takes few species only – namely, *Dalbergia melanoxylon* (local name Pau preto); *Pterocarpus angolensis* (Umbila); *Afzelia quanzensis* (Chanfuta) and *Millettia stuhlmannii* (Jambirre). In the national market a slightly wider range of species is accepted, although preference is clearly given to the same species. In 2005, timber exports reached around USD 65 million, approximately 4 percent of total exports (Dewees et al. 2010). Based on international trade statistics, the overall value of wood exports from the region was about USD 166 million per year (Ryan et al. 2016). Little effort is made by the forest operators to develop new markets which would allow them to utilize a wider range of species. Illegal timber harvest and trade has very negative implications competitiveness of operators complying with the regulations.

In addition, the woodlands provide two key services to agriculture: nutrient supply and soil erosion regulation. Nutrients are supplied by *miombo* through both woodland-field lateral transfers and the inter-temporal transfers provided by shifting cultivation. The former, a widespread traditional practice, involves the spreading of termite mounds, generally higher in clay and other nutrients, onto fields. More substantial is the lateral transfer of nutrient-rich manure from grazing livestock. Shifting cultivation delivers nutrients accumulated in the soil and plants through cutting and burning (Refer to Chapter 2: Directions of land use in *miombo*). The regulation of soil erosion is achieved by interception of high-energy rain drops and by the structural integrity that the vegetation gives the soil. In extreme situations (e.g. pervasive drought of 2016), soil erosion regulation is critical given the negative impact of soil loss on crop yields. Williams et al. (2016) estimated in semi-arid Zimbabwe, removal of the top 1 cm of soil reduced yields by 14 percent; while removal of the top 20 cm reduced yields by 75 percent. In this experiment, the amount of fertilizer applied was doubled and still unable to compensate for the effect of even the most moderate erosion.

Equally important is the woodlands' role in hydrological regulation by altering the timing, location and quality of water flows. Floods have displaced approximately 9 million people and caused USD 1.5 billion of damage in the region over the last 30 years. Climate-related fluctuations in seasonal water flows have restricted water available for drinking, cropping, livestock and hydroelectricity generation. Generally, vegetation slows the passage of water through a catchment and can increase infiltration into the soil and ground water. However, literature suggests that this effect may be limited in *miombo* given the intense and prolonged nature of the rainfall typical of the region (Ryan et al. 2016). The hydrological characteristics of *dambos* are relatively well studied. Research reports that different *dambos* can both increase and decrease dry season flows, flood responses and catchment evapotranspiration. Recent research also underscores the significance of *dambos* as a back-up water resource for both farming and grazing during drought (Ryan et al. 2016).

As detailed in Chapter 1: The ecology of the *miombo* woodlands, the *miombo* region contributes to global climate regulation via the uptake of carbon dioxide and the storage of carbon. It is around the conservation of this function that policymakers and international donors have rallied.

Carbon-centric conservation through REDD+

Reducing emissions from deforestation and forest degradation, while simultaneously promoting the conservation, sustainable forest management and enhancement of forest carbon stocks in developing countries (i.e. a cluster of ideas given the acronym REDD+) was first negotiated under the United Nations Framework Convention on Climate Change (UNFCCC) in 2005. Its goal is mitigating climate change through reducing net emissions of GHGs, particularly carbon dioxide, through enhanced forest management in developing countries. REDD+ programmes have been initiated in *miombo* country members such as DRC, Mozambique and Tanzania (Bond et al. 2009). REDD+ is supported by twenty international donors, with most contributions to date coming from Norway, the United States, Germany, Japan and the United Kingdom. Between 2006-2014, twenty-one countries pledged approximately USD 5 billion to REDD+.

In many *miombo* countries, land tenure insecurity discourages investments in longer-term assets with limited to no immediate returns, in other words the woodlands and *dambos*. Therefore, for both land managers and users, the return from landscapes converted to agriculture exceeds returns from undisturbed woodlands. This dynamic is made worse by demographic pressure, particularly when agriculturally-based population density increases in and close to woodlands. This is likewise true of communal areas centralized around *dambos*. REDD+ programmes attempt to shift the outcome of the tradeoff between agricultural production and the conservation of other ecosystem services, climate regulation services especially, by making payments to individuals, communities, local and national governments where commitment to conservation is demonstrated (Bond et al. 2009).

In theory, REDD+ is an elegant solution to changes in land use where a global benefit is in opposition to a local benefit. However there have been issues in its implementation, including: establishing a baseline of forest cover against which payments can be made, monitoring and reporting, ensuring long-term sustainability, and addressing related legal and policy issues (Bond et al. 2009). The singular focus on carbon stocks in REDD+ programmes may potentially lead to perverse outcomes. In *miombo* a significant fraction of the impact on the global climate may operate through other trace gases and radiatively-active particles generated by natural processes like wild fire, termites, and ungulates (Refer to Chapter 1: The ecology of the *miombo* landscape) and land use perturbations like the burning of biomass fuels for energy and the burning of agricultural residues. Moreover, REDD+ fails to integrate the relationship between land use and albedo effects in its methodology. The albedo of agricultural land can be very different from that of the natural landscape, especially when the latter is a dark foliage forest, and the former exposes light-colored soils. The albedo of forested land is generally lower than that of open land because the greater leaf area of a forest canopy and multiple reflections within the canopy resulting in a higher fraction of incident radiation being absorbed. Therefore, it is possible that conversion of natural landscapes to agricultural ones may result in regional cooling, and if sufficiently extensive, to a globally effect of a magnitude sufficient to warrant an adjustment to the carbon-only numbers (Desanker et al. 1997).

CHAPTER 4: Methods, models, and climate metrics

The landscapes, which were hypothetically transformed in this study through simulation modelling, were based on real landscapes in central Zambia. Zambia is located between 350-2,164 m in elevation, largely on the Central African Plateau. There are two seasons: dry (May to October) and rainy (November to April). Annual rainfall varies between 500-1,400 mm, with most areas receiving 700-1,200 mm per year. The high temperatures expected in a comparable tropical location are moderated by the generally high elevation. The average daytime maximum is 30 °C during the summer months. The dominant woody ecosystem formation is *miombo* occurring on the main plateau, from Kabwe in the center of the country toward Isoka in the northeast, on the southern plateau around Choma and Kaloma and in the Copperbelt region. *Dambos* are widespread. Presently, all the land use patterns described above occur in Zambia (Figure 4).

Figure 4. High resolution satellite images depicting (from left), 'historical' *miombo* woodlands, 'subsistence extensification' and 'commercial intensification' land use patterns within a 50 kilometer (km) radius of Mkushi, Zambia. Image sourced from Google Maps. Not depicted here, but practiced at a small scale, is 'eco-agriculture' (Jack 2014).

Resolution, scale and sampling approach

Fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were modeled and analyzed at a temporal resolution of 1 year, for a duration of 100 years; and a spatial resolution of one hectare over an extent of 10 x 10 kilometers (km). The characteristic scale of the landscape—about 5 km – is established by the gently undulating pattern of drainage lines typical of granitic plateaus on which the landscape was formed. Thus, I represented the *miombo* 'landscape' using a 10 x 10 km area, subdivided into a grid of spatial units of 1 hectare (ha), small enough to capture the characteristic landscape spatial pattern. A duration of one century was selected to correspond with the convention integration period used for GHG and allow time for clearance-recovery processes to be represented.

Four grids within the same broad soil and climate zone were represented in total, one for each land use scenario: historical, natural *miombo*; subsistence extensification; eco-agriculture and commercial intensification. The historical *miombo* landscape functioned as a control for comparison with the three other patterns. Each grid was sampled in its entirety ('wall-to-wall') and individual grid cells were classified according to land cover, e.g. *miombo* woodlands (W) in various stages of recovery or agricultural production (fields) and *dambo* bottomlands (D) based on literature review. Within each land cover type, relevant natural processes and land use perturbations (resulting in emissions or uptake) were modeled for the three major GHGs, i.e. CO_2 , CH_4 and N_2O (Figure 5).

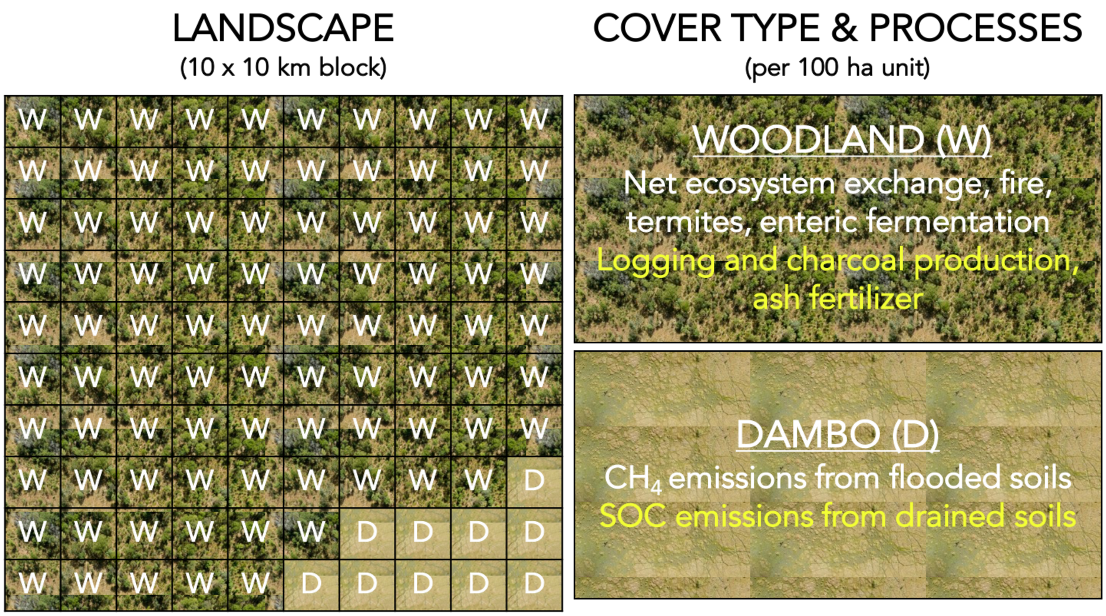


Figure 5. 'Historical' *miombo* landscape represented by 10 x 10 km grid and divided into sampling units by cover type. Hypothetical natural processes (white) and land use perturbations resulting in emissions (yellow) are detailed. Similar grids were established for 'subsistence extensification' and 'commercial intensification', based on observed landscapes, and for 'eco-agriculture' based on a hypothetical landscape since this form does not yet exists on a landscape basis.

Models: Greenhouse gas (GHG) fluxes and albedo

GHG flux models aim to represent exchanges of CO_2, CH_4, and N_2O between land and atmosphere resulting from the following natural processes and land use perturbations within each applicable land use scenario (Figure 6).

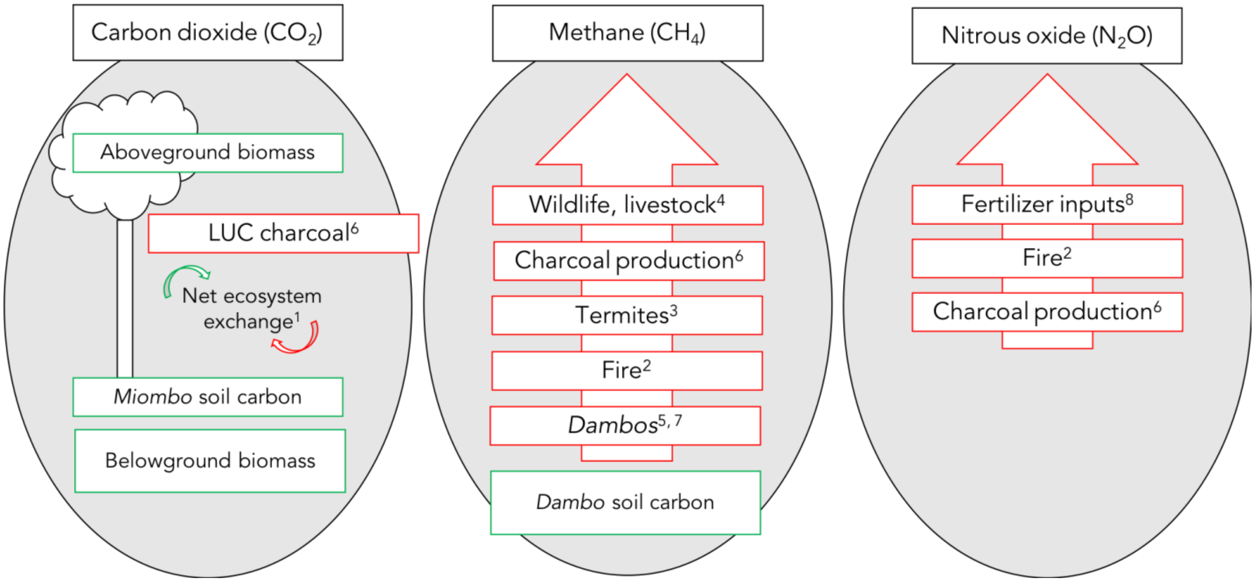


Figure 6. Conceptual model of GHG fluxes between land and atmosphere. The processes are numbered for reference in the text. Green rectangles represent carbon stocks while red rectangles associated with arrows representing GHG fluxes to the atmosphere. The green arrow represents CO_2 flux into the landscape via Net Ecosystem Exchange (NEE), the red arrow i.e. CO_2 efflux.

The GHG flux models are comprised of simple mathematical equations representing the various natural processes and perturbations occurring in the four land use scenarios (Table 2). The parameter and driver variable values used in the equations were determined through literature review. Some parameters remained constant across all land use scenarios while others varied depending on the land use scenario (Table 3). The equations generally reflect the Intergovernmental Panel on Climate Change (IPCC) 'Tier 2' approach to flux estimation. Meaning, the method is more detailed than a simple look-up table assignment of a value (i.e. Tier 1 approach), but less detailed than a fully mechanistic model (i.e. Tier 3 approach), which would have required driver and parameter values that are presently unavailable for these landscapes (IPCC 2006).

Table 2. Mathematical equations with driver variables, associated units and literature review sources from which values were derived. Numbers (1-8) refer to the natural processes and land use perturbations depicted in Figure 6. Where needed, units were harmonized.

Ref	Process$_{(GHG\ FLUX)}$	Variable	Value (for H; S; E; C)[1]	Units	Source
1	Net ecosystem Exchange$_{CO2}$ = Carbon density at time$_t$ – Carbon density at time$_{-1}$	**Carbon density** includes AGB, BGB, woodland soil C, dambo soil C	Dynamic logistic growth model run for biomass components and exponential decay model for soil C	gC/m^2/y	Kutsch et al. 2011
2	Fire$_{CH4N2O}$ = Area • ΣFuel load • CE • EF	**Area** Area burned **ΣFuel load** Woodlands & *dambos* **CE** Combustion efficiency **EF** Emission factor, CH_4;N_2O	1; .94; .40; 28 150+316, respectively .80 2.40; .21	Fraction t DM/km^2; Mg/km^2 Fraction g GHG /kg fuel burned	Archibald et al. 2010 Otter & Scholes 2000 Shea et al. 1996
3	Termites$_{CH4}$ = Mounds • Biomass • EF	**Mounds** Number per area **Biomass** DM termite per mound **EF** Emission factor, CH_4	500 9.5 .08	Mounds/km^2 g termite DM/mound g CH_4/g termite DM	Frost 1996 Goffinet 1976
4	Enteric fermentation$_{CH4}$ = Density • EF	**Density** Livestock density per area **EF** Emission factor, CH_4	5000; 5000; 10,000; 0 12	kg LW/km^2 g CH_4/kg LW/y	Archibald & Hempson 2016
5	*Dambos*$_{CH4}$ = Area • Duration floods • EF	**Area** of landscape *dambos* **Duration floods** **EF** Emission factor, CH_4	1 270 229,000,000	km^2 days g CH_4/km^2/y	Mitsch et al. 2007 Scholes and Otter 2000
6	Charcoal$_{CO2CH4N2O}$ = Total char out:wood in • ABG used • EF	**Total char out:wood in** Charcoal produced per wood used **AGB used** to produce charcoal **EF** Emission factor, CO_2 CH_4 N_2O	0.28 .6 55	ratio fraction g CH_4/kg charcoal/y	Ryan et al. 2011 Kutsch et al. 2011 Kutsch et al. 2007
7	*Dambo* drainage$_{CH4}$ = Area • EF	**Area** area drained, cultivated **EF** Emission factor, CH_4	0; 800; 500; 0 229,000,000	km^2 g CH_4/km^2/y	Nahlik and Mitsch 2011
8	Fertilizer$_{N2O}$ = Area • Rate • EF	**Area** Fertilized with inputs **Rate** Fertilization rate **EF** Emission factor, N_2O	0; 0; .60; .72 0; 0; 100; 500 .02	fraction of landscape which is field kg N/ha/y g N2O/g N applied	Davidson et al. 2009

[1]Some values differ among the different land use scenarios. Where applicable, values are reported in order according to reference letters H, S, E, and C which denote historical woodlands, subsistence extensification, eco-agriculture and commercial intensification, respectively.

Table 3. The processes and related assumptions for each land use scenario, including historic, subsistence extensification, eco-agriculture and commercial. Note: Subscript denotes the GHG flux associated with the process. Numbers (1-8) refer to the natural processes and land use perturbations depicted in Figure 6. Emissions were calculated on a whole-landscape basis (10x10 km) over a 100-year period.

Ref.	Process$_{\text{(GHG FLUX)}}$	Historical	Subsistence extensification	Eco-agriculture	Commercial intensification
1	Net ecosystem exchange$_{CO_2}$	Assumed to be 0 (i.e. in steady state)	Net reduction in biomass and soil C	Moderate (50%) net reduction in biomass; no net reduction in soil C	Total loss of biomass in 72% of woodland and 90% of *dambos*. 50% soil C loss in 20 years
2	Fire$_{CH_4 N_2O}$	Fire return period: 2 years	Biennially in remaining woodlands and *dambos* (Also, from charcoal production; see below)	Biennially in remaining woodland	Biennially in woodland remnants
3	Termites$_{CH_4}$	Termites in all woodlands area	Termites exist in remaining woodland	Termites exist in remaining woodland	Termites exist in woodland remnants
4	Enteric ferm$_{CH_4}$	Methane emissions from wildlife at low densities	Methane emissions from subsistence-level cattle (5000 kgLW/km^2)	Stocking rate increases (doubles) due to feed supplementation from crop residues	No livestock or wildlife; grain produced is exported outside of landscape
5	*Dambos*$_{CH_4}$	10 percent of landscape	10 percent of landscape	10 percent of landscape	10 percent of landscape
6	Charcoal$_{CO_2 CH_4 N_2O}$	Not produced in significant quantities	Cyclic clearing biomass in target size range converted to charcoal	Sustainable charcoaling based on mean annual increment in woodlands	Once-off, at initial clearing
8	*Dambo* drainage (cultivation)$_{CH_4}$	Full production in *dambo* area	80% of *dambos* drained and cultivated, thus emitting CO_2 but not CH_4	50% of *dambos* drained and cultivated	CH_4 emissions from the 10% *dambo* area, plus CO_2 emissions from area cultivated
9	Fertilizer input$_{N_2O}$	Not present	Not present	Fert rate: 100 kgN/ha/y	Fert rate: 500 kg N/ha/y

Regarding the albedo model, several satellite-derived surface albedo products are available, including Sea-Viewing Wide Field-of-View Sensor (SeaWIFS), Medium Resolution Imaging SpectroRadiometer (MERIS), and Moderate Resolution Imaging SpectroRadiometer (MODIS). The products provide estimates approximately every ten days in the absence of cloud cover and at a spatial resolution of 1 to 1.5 kilometers, and approximate the above definition to varying, and often unspecified, degrees. For the purpose of the albedo model, I opted to use the Multi-angle Imaging SpectroRadiometer (MISR) instrument, which has been in continuous operation since February 2000, providing global coverage on a 9-day repeat. Most sites are within the path of two overlapping swathes, and many in 3 swathes, so the revisit period can be as little as 3.5 days, excluding cloud cover. The MISR albedo extracted by the Joint Research Center – Two-stream Inversion Package (JRC-TIPS) is technically robust and advantaged for its known and reported accuracy, 275 meter ground sampling distance, nine simultaneous view angles, bands at 446, 558, 672, and 867 nanometers (nm) for integrating the full spectra (Scholes et al. 2017).

Therefore, I selected three sets of target coordinates based on an inspection of Google Earth images to represent landscapes of 10 x 10 km dominated by the historical, subsistence extensification and commercial intensification land uses. All targets were included in a single swath, within a 50 km radius of Mkushi, Zambia (Refer to Figure 4 above). An appropriate proxy could not be identified for the eco-agriculture scenario, which is not yet an agricultural option practiced at large scale. Methods for estimating its albedo are discussed below.

The effect of albedo changes on global climate forcing can be understood by perturbing the surface in a full, three-dimensional global circulation model, which takes into account all the possible lateral spatial interactions and the full atmospheric radiative transfer process, but this is an extremely computationally-demanding approach. To achieve an approximate estimate understanding, I used the Bird et al. (2008) one-dimensional, simple radiative transfer model, which provides an estimate of albedo at the top of atmosphere (TOA) by using a formulation to account for multiple reflections and absorptions by clouds and aerosols (Scholes et al. 2017).

Bird et al. (2008) calculate the RF from albedo changes at the TOA. Surface albedo measurements are changed to effective albedo (α_{eff}), which takes into account cloud cover, by:

$$\alpha_{eff} = \frac{k_c(1-S)\cdot\left(1-2\alpha_v(1-\alpha_{\text{atm}})\right)+\alpha_v(1-\alpha_{\text{atm}})^2}{1-k_c\alpha_v(1-S)}$$

Where: k_c is the opacity of the clouds (~0.55 from Angstrom equation for South Africa),

S is the fraction of possible sunshine (sunshine hours/daylight hours), which is 1-cloud fraction,

α_v is the surface (vegetation) albedo, the sum of ground and BHR above, and

α_{atm} is the proportion of energy absorbed by atmosphere (0.165, Scholes et al. 1999, 0.2 from Angstrom equation for southern Africa)

Bird uses monthly top of atmosphere solar radiation ($R_{TOA,m}$) estimated from:

$$R_{TOA,m} = \frac{R_{annual}}{\pi}\cos\left(\lambda+\eta\cos\left[\frac{(6.5-m)\pi}{6}\right]\right)$$

Where: R_{annual} is the average incoming solar radiation at ToA, the solar constant (1360 W m^{-2})

λ is latitude,

η is the inclination of the Earth's axis, and

m is month of the year

The forcing is calculated on a monthly basis, and then summed to a year. Thus, the equation becomes:

$$F_{\text{albedo.Bird}} = F_{a,m} = -\frac{A}{12A_{Earth}}\sum_{m}^{12} R_{TOA,m}\cdot\Delta\alpha_{eff,m}$$

Where: $R_{TOA,m}$ is monthly top of atmosphere radiation (W m^{-2})

A is the area (m^2) over which an albedo change occurs between the two land cover types

A_{Earth} is area of the earth (5.1×10^{14} m^2),

$\Delta\alpha_{eff,\,m}$ is monthly albedo change taking cloud cover into account, and

m is the month of the year

In the Bird et al. (2008) model, the cloud cover by month must be known, since it is the presence of clouds, and the associated high albedo, which determines the landscape reflectivity, as opposed to the land surface. Cloud data was obtained for each of the targets from the MODIS cloud cover product (i.e. MOD-06). Given the proximity of the target coordinates, it was only necessary to obtain one set of cloud data to generate the four models (Figure 7).

Climate impact metrics

Radiative forcing (RF, W m^{-2}) is the fundamental metric to assess the climate impact factors which cause the global atmosphere to warm or cool. RF is the net change in the energy balance of the Earth system due to some imposed perturbation. It is conventionally integrated over an agreed period, such as 20 or 100 years, to allow for the fact that different radiatively active gases disappear at different rates from the atmosphere. The forcing due to albedo changes are relatively easy to express as RF (Myhre et al. 2013).

The more conventional way to express climate impacts converts the net RF from each process to the equivalent emission or uptake of carbon dioxide that would have given the same forcing, i.e. CO_2e. Carbon dioxide is chosen as the reference gas because it is the largest single contributor to anthropogenic radiative forcing (Gohar and Shine 2007). It is generally the metric of choice because policymakers find it easy to understand. However, converting albedo forcing to CO_2e is quite complex. A quick-and-dirty estimate can be made as follows. The global radiant forcing in 2010 was 2.1 W/m^2 (over every m^2 of the Earth's surface, an area of 5.1 x 10^{14} m^2 (IPCC 2013). The CO_2eq emissions at that time were around 40 $PgCO_2$/y. Thus, the forcing per local m^2 works out at in the order of 41 gCO_{2eq} /m^2 per W/m^2 of RF. The more exact solution I used was calculated using the Bird (2008) formulation in a program, listed in **Appendix A.** Pascal program for calculating radiative forcing.

For the purpose of this research, I investigated the effect of various types of land use patterns on the climate regulation service provided by the *miombo* landscape by calculating both RF and its

CO_2e over a 100-year time period according to and using the equations provided by IPCC (Myhre et al. 2013).

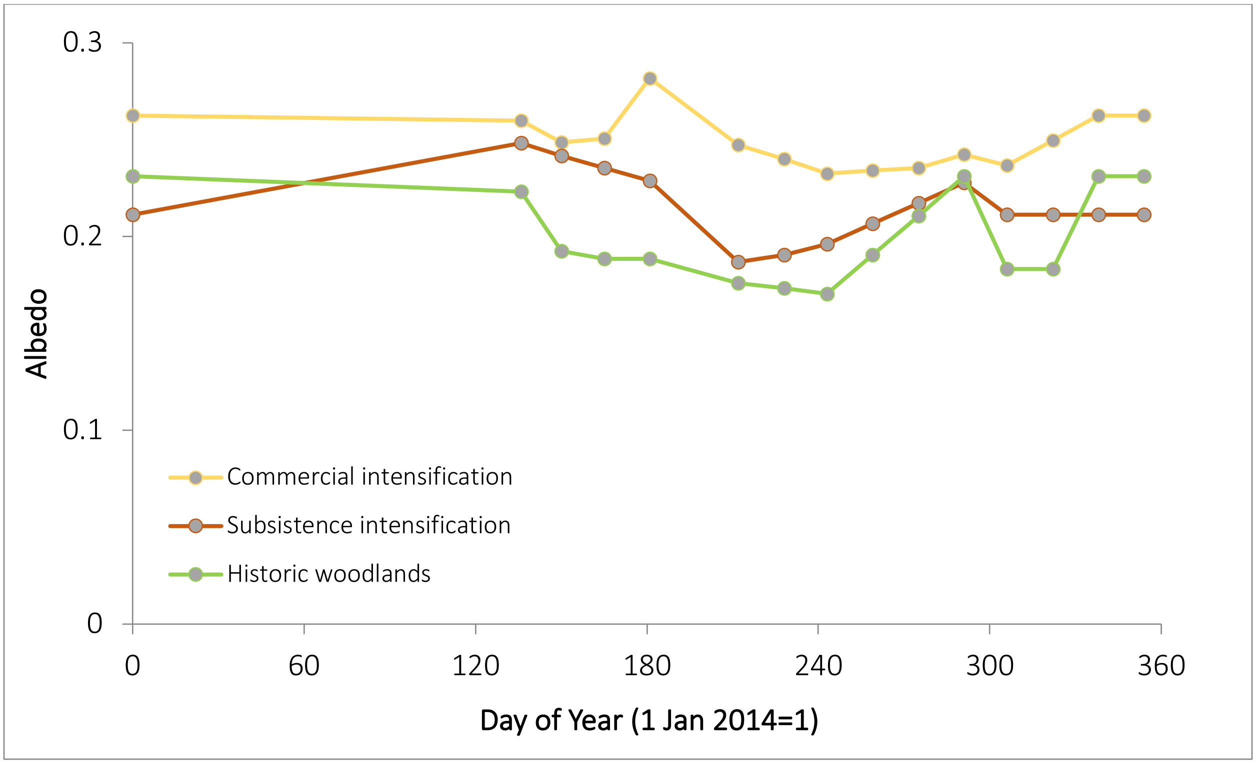


Figure 7. The seasonal progression of MISR-HR hemispherically-integrated shortwave albedo for landscapes of 10x10 km^2 (for locations see figure 4), i.e. historical woodland-dominated, subsistence extensification-dominated and commercial intensification-dominated.

CHAPTER 5: Results and discussion

Radiant forcing due to albedo changes

The calculated change in radiant forcing due to changes in surface reflectivity (albedo) under the different land use scenarios and their CO_2 equivalent are presented in Table 4. Note that the surface reflectivity, averaged across the year, is higher for subsistence agriculture than for the historical woodland landscape, and higher still under commercial agriculture. The implication being that more radiant energy is reflected back into the atmosphere, resulting in a *cooling* effect (negative values on the subsequent figures), which somewhat offsets the warming caused by GHG emissions.

Table 4. The changes in radiant forcing across the different land use scenarios.

Month Number	RToA W/m^2	Cloud Fraction	Albedo Historic	Albedo Subsistence	ToA alb Historic	ToA alb Subsistence	Effective change	Forcing W/m^2*10^{-12}	CO_2e kg/m2	Albedo Commercial	ToA alb Commercial	Effective change	Forcing W/m^2*10^{-12}	CO_2e kg/m2
1	425.2	0.7	0.23	0.22	0.511	0.51	0.001	-0.00088	-496	0.26	0.514	-0.003	0.00271	1522
2	414.2	0.72	0.22	0.22	0.522	0.522	0	0	0	0.26	0.526	-0.004	0.0032	1794
3	384.3	0.57	0.21	0.22	0.432	0.433	-0.002	0.00131	733	0.26	0.44	-0.009	0.00664	3730
4	333.6	0.41	0.21	0.22	0.341	0.344	-0.003	0.0018	1011	0.27	0.358	-0.017	0.01098	6163
5	277.6	0.15	0.2	0.2	0.198	0.198	0	0	0	0.25	0.222	-0.024	0.01297	7285
6	240.8	0.16	0.19	0.24	0.198	0.222	-0.023	0.01103	6195	0.25	0.226	-0.028	0.01326	7443
7	240.8	0.14	0.18	0.21	0.183	0.197	-0.015	0.00683	3836	0.27	0.227	-0.044	0.02062	11576
8	277.6	0.23	0.17	0.19	0.228	0.236	-0.008	0.00441	2478	0.24	0.256	-0.029	0.01557	8744
9	333.6	0.1	0.19	0.2	0.167	0.172	-0.005	0.00338	1898	0.23	0.187	-0.021	0.01355	7610
10	384.3	0.32	0.22	0.22	0.295	0.295	0	0	0	0.24	0.302	-0.007	0.00516	2900
11	414.2	0.54	0.18	0.21	0.409	0.414	-0.006	0.00458	2571	0.24	0.42	-0.011	0.00927	5205
12	425.2	0.56	0.23	0.21	0.429	0.426	0.004	-0.003	-1684	0.26	0.435	-0.006	0.0046	2581
Mean	346	0.383	0.203	0.213	0.326	0.331	-0.005	0.00245	**1378**	0.25	0.343	-0.017	0.00988	**5546**

Radiative forcing under various land use scenarios

The tradeoff between landscape transformation for various types of agriculture and the climate regulation service provided by the *miombo* landscape, expressed in net RF and its CO_2e over a 100-year time horizon, was variable among the four land use scenarios (Figure 8). It was found that the loss of climate regulation service was greatest when the entire landscape was converted to commercial agriculture through intensive techniques, with conversion via shifting cultivation, providing the most service protection among the food production land use scenarios, resulting in 47,023 and 7,732 Mg CO_2e/km^2/year, respectively (i.e. the positive RF associated with commercial intensification was nearly double that of RF from subsistence extensification). Conversion to eco-agriculture falls somewhere in between, resulting in 16,808 Mg CO_2e/km^2/year.

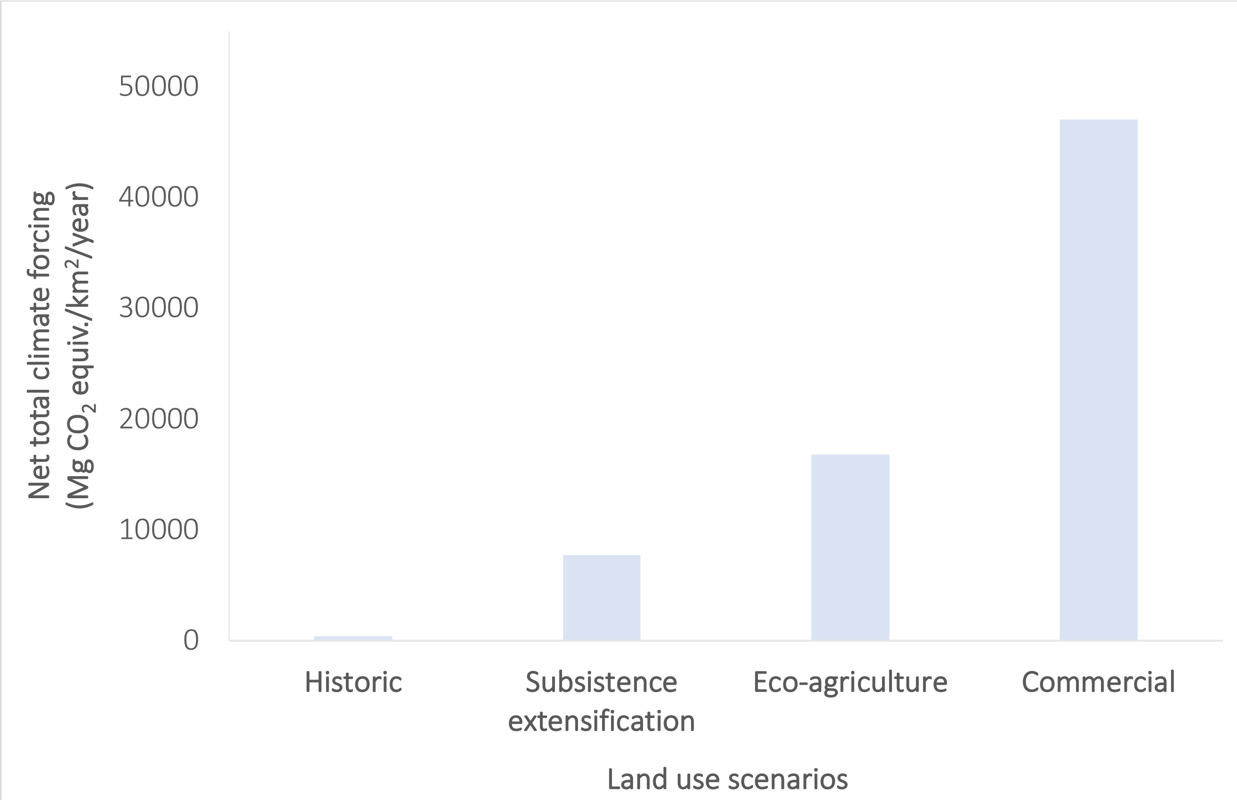


Figure 8. The tradeoff between landscape transformation for different types of agriculture and the climate regulation service provided by *miombo* landscapes, expressed in net total climate forcing in Megagrams (Mg) of CO_2 equivalent per square kilometer per year, for the four land use scenarios. Among the food production land use scenarios, the climate service was most protected under subsistence extensification, followed eco-agriculture, and commercial intensification.

Radiative forcing considering GHG fluxes and albedo effects

Both GHG fluxes and changes in albedo contributed to the net total climate forcing for each of the different land use scenarios (Figure 9). In all altered land use scenarios, GHG fluxes resulted in positive RF while changes in albedo resulted in negative RF, i.e. a net cooling effect (by definition, since the historical landscape is the reference point, its albedo effect is considered zero, and its GHG balance is also considered zero – though note later comments regarding the methane emissions from the historical woodland). From this I can infer that the change in land use, i.e. the near total transformation from darker vegetated woodlands to lighter exposed topsoil in the subsistence extensification scenario and cropped fields in the commercial intensification scenario, increased the land surface albedo, leading to stronger negative RF in these scenarios compared to eco-agriculture.

These data represent a completely novel finding related to land use and land cover changes in the *miombo* region. However, there is robust evidence supporting the cooling potential of certain cropping systems elsewhere; particularly compelling is the summer time effect in certain regions, such as the mid-latitudes of North America and Eurasia which could cool by as much as 1° C in June, July and August according to some research (Myhre et al. 2013). However, what is less certain and more difficult to quantify are the impacts of land use change and the resulting change in albedo on non-radiative processes, such as effects of land cover change on evapotranspiration or physiological impacts of CO_2 and O_3 except where these cause further impacts on radiation such as through cloud cover changes (Myhre et al. 2013).

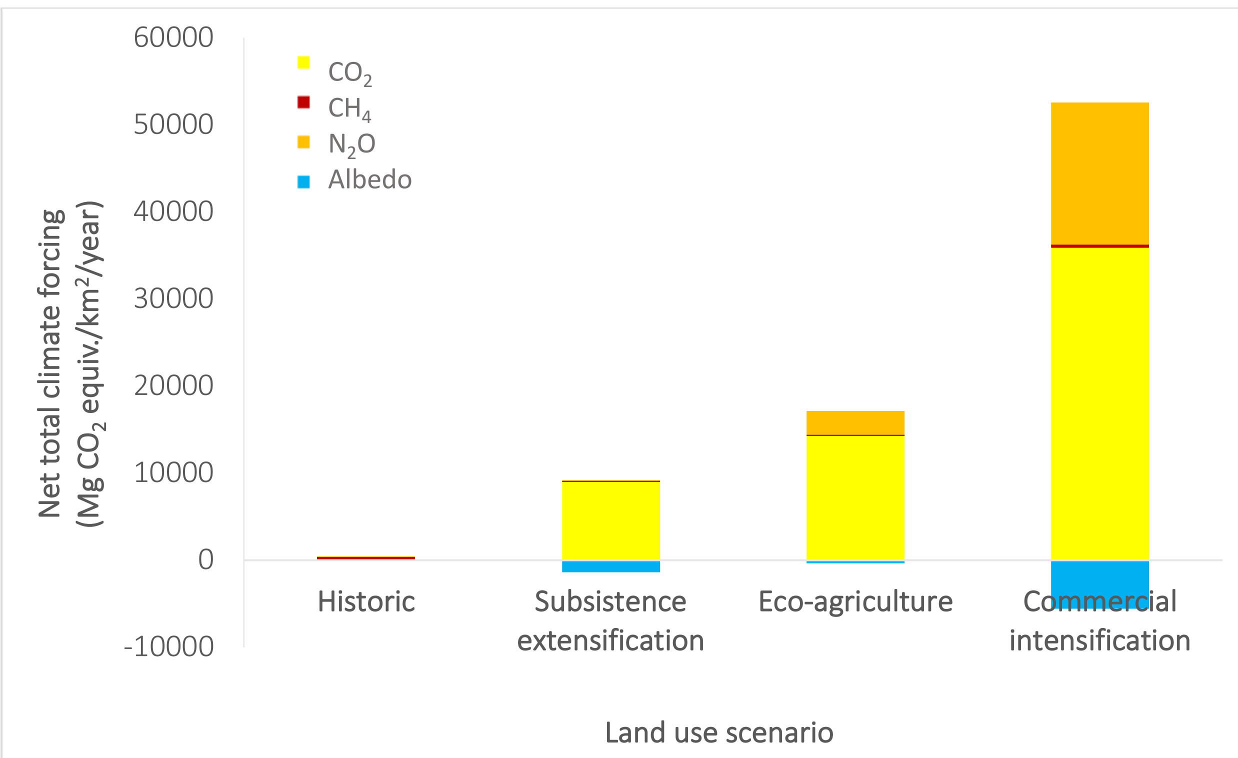
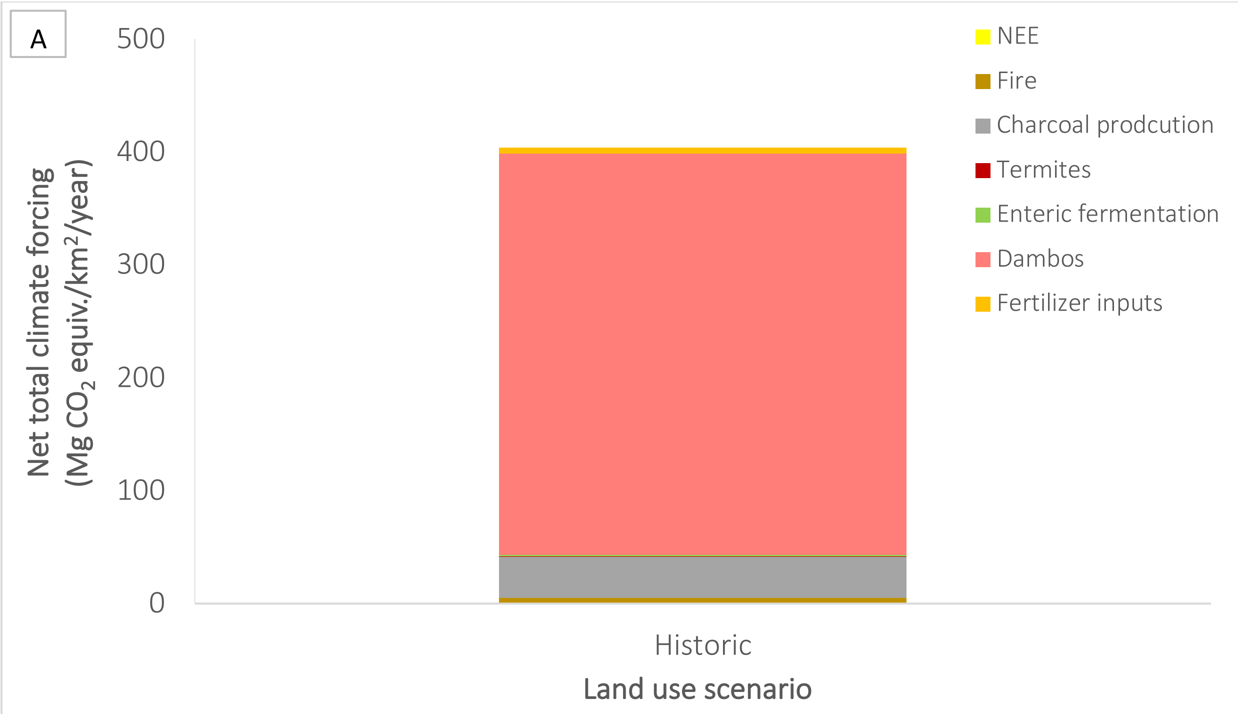


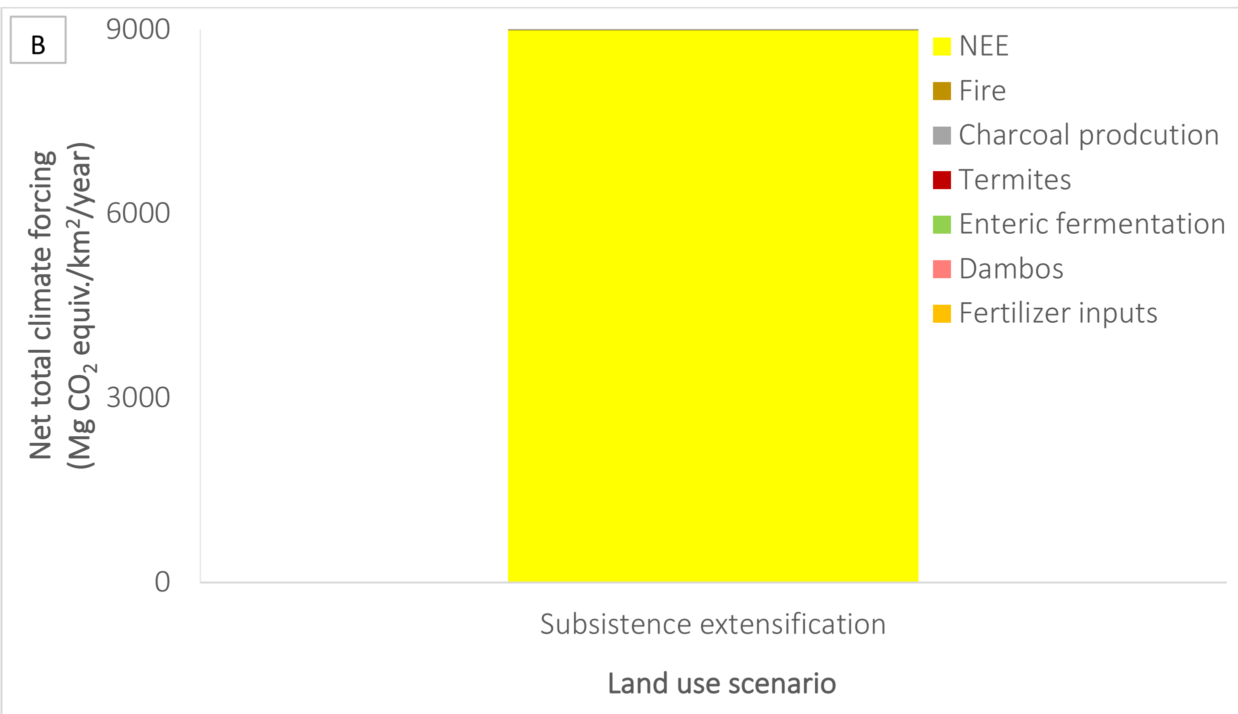
Figure 9. Radiative forcing from GHG fluxes and changes in albedo, expressed in net total climate forcing in Megagrams (Mg) of CO_2 equivalent per square kilometer per year, for the four land use scenarios. GHG fluxes resulted in positive RF while changes in albedo resulted in negative RF.

Radiative forcing by agent

The GHG species (CO_2, CH_4 and N_2O) contributed differently to the net total climate forcing in each of the transformed land use scenarios (Figure 10). In the historical woodland scenario, which is used as the pre-anthropogenic reference case, the CO_2 emissions are assumed to be zero, since the landscape is assumed to be in 'steady state'. However, CH_4 emissions, primarily from wildfire and undisturbed *dambo* soils during flooding and periods of saturation, do occur even in steady state, and unlike CO_2 are not balanced by CH_4 uptake processes. They contributed nearly 100% of the net total positive forcing, i.e. 399.09 Mg CO_2 equiv./km^2/year calculated for this landscape (Figure 10a). Since this effect predates the modern period (nominally since 1750), the *anthropogenic* forcing resulting from historical methane emissions could also be considered zero, but I have left them as a small positive to simply illustrate the point. Given that the 100-year Global Warming Potential (GWP) of methane is twenty-eight times that of CO_2, this finding reinforces the importance of incorporating CH_4 in RF calculations when considering land use and its effect on the climate regulation service provided by *miombo* landscapes (Myhre et al. 2013).

Otherwise, our findings were generally consistent with the literature, indicating CO_2 as the primary forcing agent among GHG emissions resulting from agricultural transformation. This is largely due to the immediate and irreversible loss of CO_2 to the atmosphere via the removal of aboveground biomass in the initial clearing for both charcoal production in the subsistence extensification land use scenario and subsequent field preparation in the commercial intensification scenario (Figure 10b-d). Emissions of nitrous oxide from fertilizer inputs contributed 15 and 30% of the total positive RF in the eco-agriculture and commercial intensification land use scenarios, respectively (Figure 10c-d).


A
500
400
300
200
100
0
Net total climate forcing
(Mg CO2 equiv./km2/year)
NEE
Fire
Charcoal prodcution
Termites
Enteric fermentation
Dambos
Fertilizer inputs
Historic
Land use scenario


B
9000
6000
3000
0
Net total climate forcing
(Mg CO2 equiv./km2/year)
NEE
Fire
Charcoal prodcution
Termites
Enteric fermentation
Dambos
Fertilizer inputs
Subsistence extensification
Land use scenario

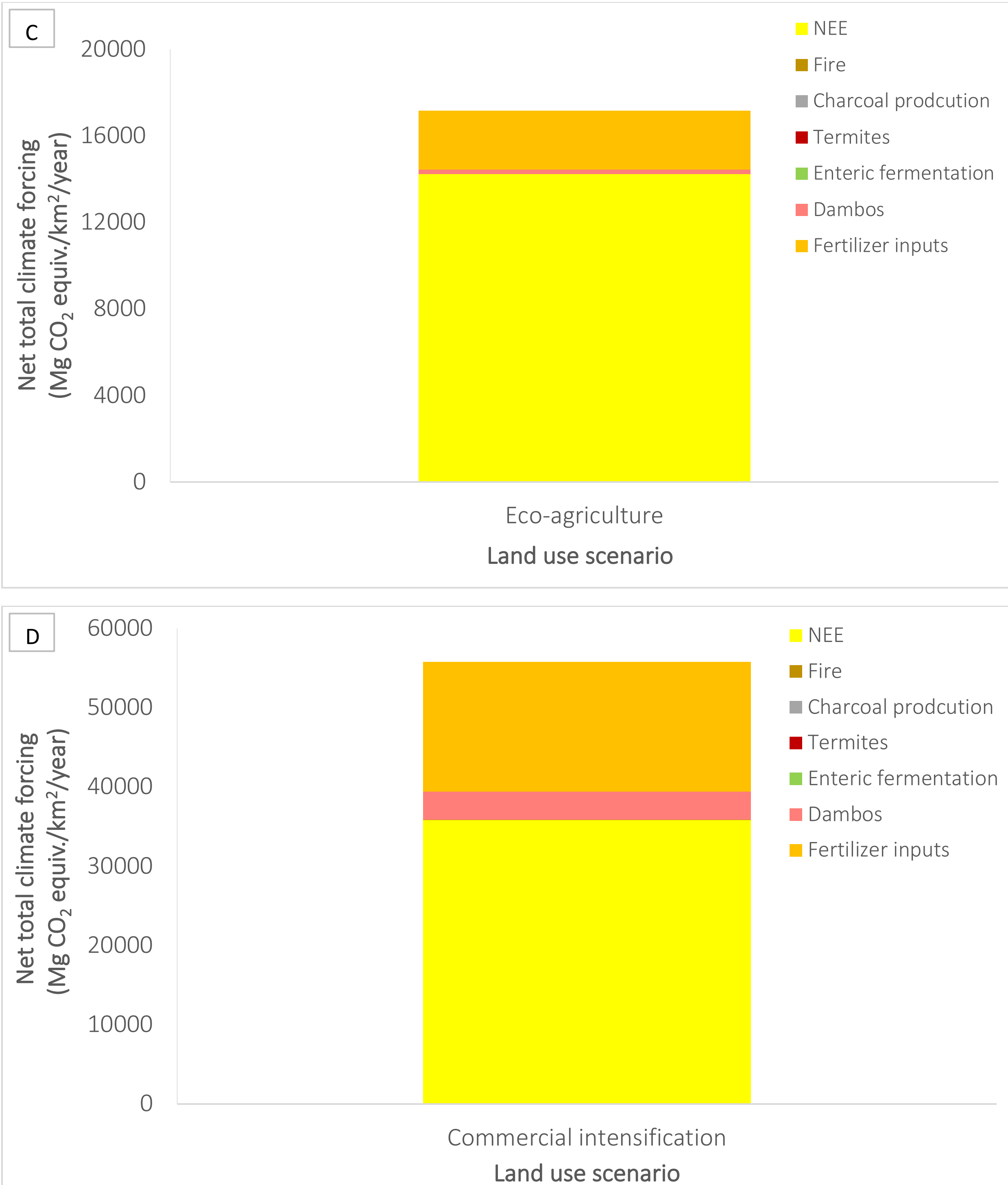


Figure 10. Radiative forcing by forcing agent (GHGs) in total positive RF budget for each land use scenario.

Radiative forcing per unit food

In addition to quantifying the tradeoff between landscape transformation for agricultural development and the climate regulation service provided by *miombo*, I evaluated the effectiveness of each land use scenario in minimizing the tradeoff, in other words, what type of agriculture provides maximum protection of the climate regulation service while simultaneously yielding the highest unit food per area (Figure 11). When the loss of climate regulation is expressed per unit agricultural production, the trend presented in Figure 7 is reversed, favoring commercial intensification as the choice pattern of production.

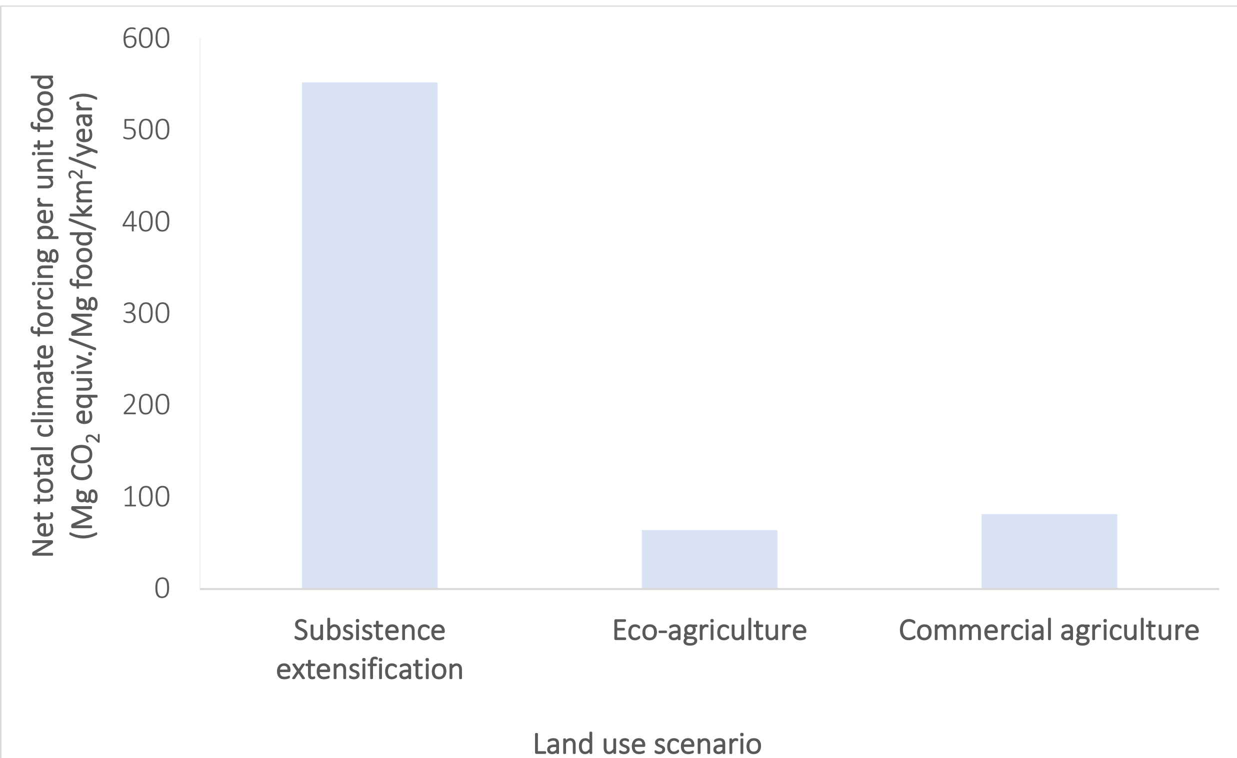


Figure 11. The tradeoff between climate protection and food production, expressed in net total climate protection per unit food produced, with the units Megagrams (Mg) of CO_2 equivalent per Mg food produced square kilometer per year. Negative net total climate forcing per food unit indicates a minimal tradeoff. Note: yields are assumed to be 14, 260, and 576 Mg food produced per square kilometer per year for the subsistence extensification, eco-agriculture and commercial intensification land use scenarios, respectively (FAO STAT 2017).

Therefore, in response to the debate around agricultural intensification or extensification, the data offer evidence supporting commercial agricultural intensification, provided that the extent of production is restricted to that which satisfies local demands. However, the United Nations Food and Agriculture Organization (FAO) predicts, in response to the growing global population and resulting demands for exports, that sub-Saharan Africa will need to add more than 100 million ha of cropland by 2050, most of which is destined for export. Moreover, the FAO estimates that the region could conceivably add over 400 million ha, thus potentially exposing *miombo* countries to what would be the absolute worst-case scenario, i.e. expansive intensive commercial agriculture with devastating consequences on the woodlands, the ecosystem services it provides, biodiversity and rural livelihoods (FAO 2017).

Uncertainty and future work

Governments in southern Africa are then faced with some important decisions – how to ensure food security for a growing population and likewise encourage economic investment and growth, without compromising the life-lines for the poorest of the poor or damaging the environment. Future research has the potential to influence these development pathways, e.g. through land use and spatial planning, by providing policy-relevant information about the environmental and socioeconomic costs and benefits of different development options. The findings presented above can bolster our understanding of the environmental tradeoffs related to different types of agricultural development, however, more complex are the socioeconomic drivers. Pervasive poverty across the *miombo* region is at the crux of the tipping point that could lead to the near-total destruction of the woodlands as described in the scenario above (exacerbated by the likely continued expansion of shifting cultivation and charcoal production among rural communities), but its causes and impacts on land use are complex. Future land use development is highly dependent on the relative rates of population versus economic growth that cannot be projected with confidence far into the future.

For example, consider the relationship between populations versus economic growth as related to trends in charcoal consumption. The current population in sub-Saharan Africa is expected to double by 2050 relative to the present, with approximately 60% of the population living in rural areas, and annual urban growth rates at nearly 4% (the most rapid in the world). Presently, domestic energy needs in both rural and urban areas are satisfied primarily by charcoal (FAO 2017). Due to missing alternatives in energy supply and pervasive unemployment, charcoal production has become a full-time job for migrant workers who ‘buy’ trees from local communities, produce charcoal and then leave. Migrant producers are not bound to the land or invested in the ecosystem services provided and are therefore less incentivized to use the resource sustainably. Over the last decade, charcoal production has become unsustainable in many areas, including western Kenya, southern Malawi, and the area around Harare in Zimbabwe, Ndola and Lusaka in Zambia among others (Kutsch et al. 2011). Meaning the fraction of the landscape cleared annually exceeds the fraction that is able to regrow.

To reduce this pressure, charcoal kilns of higher efficiency could be introduced along with improvements to post harvest management. More modern, but still simple designs, could achieve a three-fold increase in efficiency to traditional earth kilns while simultaneously reducing the production of methane, non-methane hydrocarbons and aerosols. However, new technologies to improve efficiency of charcoal production very often meet social or traditional barriers that prevent implementation. Thus, and in relation to improving post-harvest management, more studies on rural development and likewise investments linked to stronger governmental and local (communal) land management are essential. Furthermore, the charcoal production market system was analyzed in depth during the 1990s, but more recent developments are not available. Recent forest inventories and realistic data on clearing rates, re-growth and turnover times are also sparse (Kutsch et al, 2011).

Charcoal production, however, is only one aspect of the development pattern. Improvements in the aforementioned areas, as well as significant advancements in conservation agriculture and land restoration practices, rural education with an emphasis on natural resource management, especially among young people, and improved policy instruments pertaining to land use, planning (e.g. for multiple uses, such as in the eco-agriculture scenario) and tenure collectively present an opportunity to save the *miombo* before it’s too late.

CHAPTER 6: CONCLUSIONS

In conclusion, I reflect on the original purpose of the study: to quantify the tradeoff between landscape transformation of various types and the climate regulation service provided by the *miombo* landscape. I expected that as the extent of land cover transformation and intensity of disruption of natural structure and processes increases, the climate regulation service in *miombo* would decrease due to increased net emissions of CO_2, CH_4, and N_2O. Potentially counteracting this effect, the clearing of perennial woodlands to reveal the lighter underlying soil is expected to increase albedo, cooling the land surface at regional scale.

I achieved the above goal by modeling GHG fluxes from all significant sources and changes in albedo to calculate the net radiative forcing, expressed in terms of its carbon CO_2e, over a one century horizon for the historical *miombo* (reference) land use scenario and three other representative patterns of transformation.

Consistent with my hypotheses, it was found that the loss of climate regulation service was greatest when the entire landscape was converted to commercial agriculture through intensive techniques. Conversely, conversion via subsistence extensification offered the most protection for the climate regulation service, and transformation via eco-agriculture was somewhere in between. When the loss of climate regulation was expressed per unit agricultural production, the pattern was reversed, favoring commercial intensification as the choice pattern of production. Also consistent with my expectations, were the contrasting positive and negative RF from GHG emissions and albedo effects, respectively. It was found that contrary to the conventional approach of evaluating the climate regulation service entirely on the basis of net carbon storage, the changes in other greenhouse gases (notably methane, but also to a smaller extent nitrous oxide), and the changes in surface albedo, made substantial contributions to the changes in the climate regulation service provided by *miombo* woodland.

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Appendix A: Pascal program for calculating albedo radiant forcing

```
Program  Albedos;
{RJ Scholes CSIR Jan 2009, modified Wits Feb 2018}

{calculates the change in radiative forcing resulting from surface albedo changes
Follows Bird DN, Kunda M, Mayer A, Schlamadinger B, Canella L, and
Johnston M. 2008 Incorporating changes in albedo in estimating the climate
mitigation benefits of land use change projects. Biogeosci Discussions 5, 5111-5143}

{the input file has month, cloud fraction, albedo of the reference area and albedo
of the changed area}

{uses wincrt;}
Const RTOAa=1360.0; {W/m2}
     kc=0.699;  {transparency of cloud about 0.65, clear=0, opaque=1}
     Ab=0.221;  {atmospheric absorption, about 0.2}
     AreaEarth=5.1e14; {m2}
     inclination=-23.5/180*pi; {inclination of earth axis in radians}
     latitude=-33.5; {site latitude, degrees, negative South}
     AreaProject=1.0; {area affected by albedo change, m2}
     nrec=12; {number of data records in input file}

var
        lat,Sun,NetForcing,deltAlbedo,ReferenceAlbedo,ChangeAlbedo,CloudFrac,m,RTOA,CO
        2eq,

        EAReference,EAChanged,sumR,SumForce,Sumcloud,SumA0,sumA1,SumEA0,SumEA
        1,SumDelt,SumCO2eq:real;
   line,rec,t:integer;
   header:string[70];
   infile,outfile:text;
{-----------------------------------------------------------------------------------------------}
function EffectiveAlbedo(var SurfaceAlbedo,SunFrac:real):real;
  {Bird et al equation 9}
  begin
  EffectiveAlbedo:=(Kc*(1.0-Sunfrac)*(1.0-2.0*SurfaceAlbedo*(1.0-Ab))
                    +(SurfaceAlbedo*sqr(1.0-Ab)))
                    /(1.0-Kc*SurfaceAlbedo*(1.0-SunFrac));
  end;
{-----------------------------------------------------------------------------------------------}
function ForcingEquivalent(var CO2pulse:real; var t:integer):real;
{returns the W/m2 equivalent of a CO2 pulse (grams) at time t after injection into atmosphere}

{Decay constants from Archer, D, H Kheshgi & E Maier-Reimer 1997
 Multiple timescales for neutralisation of fossil fuel CO2. Geophys Res let 24, 405-408}
```

```
const
    a1=0.75;
    a2=0.135;
    a3=0.035;
    a4=0.08;
    T1=365.0; {years}
    T2=5500;  {years}
    T3=8200;  {years}
    T4=200000;{years}
    Mco2=44.0095; {molecular mass of CO2 gCO2/mol}
    Mair=28.95; {g/mol, molecular mass of dry air}
    massair=5.148e15; {mass of the atmosphere, Mg}
    F2x=3.7; {W/m2, radiant forcing due to doubled CO2, from IPCC}
    pCO2ref=383;{reference atm CO2 concentration, ppmv}

begin

ForcingEquivalent:=(F2x/ln(2))*((CO2pulse*Mair)/(pCO2ref*MCO2*massair))
                  *(a1*exp(-t/T1)+a2*exp(-t/T2)+a3*exp(-t/T3)+a4*exp(-t/T4));
end;

{-----------------------------------------------------------------------------------------------}
function CO2Equivalent(var forcing:real; var t:integer):real;
{returns the CO2Eq (grams) of a net radiative forcing (W/m2) in year t after injection}
{Bird et al equation 28}
{Decay constants from Archer, D, H Kheshgi & E Maier-reimer 1997 Multiple timescales for
 neutralisation of fossil fuel CO2. Geophys Res let 24, 405-408}
const a1=0.75;
    a2=0.135;
    a3=0.035;
    a4=0.08;
    T1=365.0; {years}
    T2=5500;  {years}
    T3=8200;  {years}
    T4=200000;{years}
    Mco2=44.0095; {molecular mass of CO2 gCO2/mol}
    Mair=28.95; {g/mol, molecular mass of dry air}
    massair=5.148e15; {mass of the atmosphere, Mg}
    F2x=3.7; {W/m2, radiant forcing due to doubled CO2, from IPCC}
    pCO2ref=383;{reference atm CO2 concentration, ppmv}

begin
CO2Equivalent:=((forcing *ln(2))/F2x)*((pCO2ref*MCO2*massair)/(Mair))/
       (a1*exp(-t/T1)+a2*exp(-t/T2)+a3*exp(-t/T3)+a4*exp(-t/T4));
end;
```

```
{-------------------------------------------------------------------------------------------}
Begin
{file assignments..........................................................................}
assign(infile,'commerc.asc');
reset(infile);
readln(infile,header);
for line:=1 to 2 do readln(infile);

assign(outfile,'commerc.csv');
rewrite(outfile);

lat:= latitude/180.0*pi; {site latitude, in radians}
t:=0; {calculating only in the instantaneous year of injection}
{calculate deltaCO2, the change in CO2 (g) from project}

{set the annual accumulators to zero.......................................................}
SumR:=0.0;SumForce:=0.0; SumDelt:=0.0;SumCloud:=0.0;
SumA0:=0.0;SumA1:=0.0;SumEA0:=0.0;SumEA1:=0.0; SumCO2eq:=0.0;
writeln(header); writeln(outfile,header);
writeln('Month RToA    Cloud   Surface Albedo    ToA albedo          Forcing  CO2e   ');
writeln('      W/m^2  Fraction Refnce Changed Refnce  Changed EffDelt  pW/m^2    g/m^2   ');
writeln('----+-------+-------+-------+-------+-------+-------+-------+-------+--------');

writeln(outfile,'Month,RToA,Cloud,Albedo,Albedo,ToA alb,ToA alb,Effective,Forcing,CO2e');
writeln(outfile,'number,W/m^2,Fraction,Reference,Degraded,Reference,Degraded,change,W/m^
        2x10^-12,kg/m2');


for rec:=1 to nrec do
  begin
  readln(infile,m,cloudfrac,ReferenceAlbedo,ChangeAlbedo);
  RTOA:=(RTOAa/pi)*cos(lat+inclination*cos((6.5-m)*pi/6.0));
  Sun:=1-CloudFrac;
  {calculate effective albedo of the surface taking clouds into account...................}
  EAReference:=EffectiveAlbedo(ReferenceAlbedo,Sun);
  EAChanged:=EffectiveAlbedo(ChangeAlbedo,Sun);
  deltAlbedo:=EAReference-EAchanged;

  {calculate the radiative forcing in this measurement period.............................}
  NetForcing:=-(AreaProject/AreaEarth)*RTOA*DeltAlbedo;
  CO2eq:=CO2Equivalent(Netforcing,t);
  {accumulate for the annual calculation..................................................}

        SumR:=SumR+RTOA;SumForce:=SumForce+NetForcing;SumCloud:=SumCloud+Clou
        dFrac;
```

```
        SumA0:=SumA0+ReferenceAlbedo;SumA1:=SumA1+ChangeAlbedo;SumDelt:=Sumde
        lt+deltAlbedo;

        SumEA0:=SumEA0+EAReference;SumEA1:=SumEA1+EAChanged;SumCO2eq:=Sum
        CO2eq+CO2eq;

  {write it out...........................................................}
  writeln(m:5:2,
        RTOA:8:1,CloudFrac:8:4,ReferenceAlbedo:8:4,ChangeAlbedo:8:4,EAReference:8:4,
          EAChanged:8:4,DeltAlbedo:8:4,(NetForcing*1.0e12):8:5,CO2eq:8:0);
  writeln(outfile,m:5:2,',', RTOA:8:1,',',CloudFrac:8:4,',',ReferenceAlbedo:8:4,',',
  ChangeAlbedo:8:4,',',EAReference:8:4,',',EAChanged:8:4,',',DeltAlbedo:8:4,',',
  (NetForcing*1.0e12):8:5,',',CO2eq:8:0);
  end;
Close(infile);

writeln('----+-------+-------+-------+-------+-------+-------+-------+-------+-------');

writeln('Mean
        ',SumR/nrec:8:1,SumCloud/nrec:8:4,SumA0/nrec:8:4,SumA1/nrec:8:4,SumEA0/nrec:8:4
        ,
        SumEA1/nrec:8:4, SumDelt/nrec:8:4,(SumForce/nrec*1.0e12):8:5,SumCO2eq/nrec:8:0);
writeln(outfile,'Mean,',SumR/nrec:8:1,',',SumCloud/nrec:8:4,',',SumA0/nrec:8:4,',',
        SumA1/nrec:8:4,',',SumEA0/nrec:8:4,',',SumEA1/nrec:8:4,',',SumDelt/nrec:8:4,',',
        (Sumforce/nrec*1.0e12):8:5,',',SumCO2eq/nrec:8:0);
Close(outfile);
End.
```