The climate impact of land use change in the miombo region of south central Africa

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**ABSTRACT**

The African woodlands known as *miombo* are one of the world's largest currently relatively unexploited, but potentially arable, land resources. *Miombo* landscapes one of the top contemporary locations of conversion of dry forests to crop agriculture. This study investigates the net effect on climate forcing that results from different types of land use change in *miombo*, taking into account the multiple mechanisms through which the land interacts with the climate system, locally and globally. It finds that when *miombo* is converted to intensively cultivated commercial crops, the landscape-averaged 30-year net greenhouse gas forcing relative to intact woodlands is 309gCO$_2$e m$^{-2}$ y$^{-1}$, of which net emission of carbon dioxide amount to 66%, non-CO$_2$ greenhouse gas effects to 33%, plus unquantified contributions from ozone precursors and aerosols. We find that net brightening of the land surface resulting from clearing the woodlands generates a cooling effect larger than the greenhouse gas forcing (-1139gCO$_2$e m$^{-2}$ y$^{-1}$). Greenhouse gas forcings resulting from transformation to extensive subsistence agriculture that are 78% lower than those from the intensive commercial agriculture path, and 40% lower if a transformation which sets out to mimic ecological processes in the *miombo* landscape is undertaken. Once the effect of surface brightening is included, then the total forcing for extensive subsistence agriculture is -834gCO$_2$e m$^{-2}$ y$^{-1}$, about the same as intensive commercial, and eco-agriculture is -102gCO$_2$e m$^{-2}$ y$^{-1}$. Taking into account the account the larger areas required for to achieve the same production, intensive commercial agriculture is the more climate-protective option. Keywords: greenhouse gas, net radiation, deforestation.

**Patterns of land use change in the miombo landscape**

Various models project extensive land-use changes in Africa in the 21st century, particularly in the sub-humid woodlands, with climate consequences (e.g. Alcamo et al. 2011). The *miombo* landscape of south central Africa consists of a mosaic of drought-deciduous *miombo* woodlands, interdigitated by seasonal wetlands called *dambos* (CIFOR 1996, Abdallah and Monela 2007). Since pre-colonial times, land use in this landscape has been based on shifting cultivation, involving felling and burning woodland patches of about
a hectare in extent, planting mixed crops for one or 2 years, followed by a long fallow period that allows the woodlands and soil to regenerate. Beginning around the middle of the 20th century, this pattern began to change, in approximately the following sequence: 1) removal of valuable timber species by a process called “high-grading”; 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 each, and convert them on-site into charcoal for sale on urban markets, using traditional charcoal-making techniques; 3) small-scale subsistence farmers cut and burn the remaining small trees, shrubs and debris to fertilize one or a few crop cycles of for instance mixed maize, millet, cassava, cowpeas and squashes, before moving on to another patch of land, allowing secondary forest regrowth on the cleared area (Chidumayo 1999, Campbell et al. 1996).

Low-input (other than labour), low-yield smallholder agriculture remains an important contemporary land use. The increasing number of subsistence farmers is forcing progressively shortened fallow periods, more extensive woodland clearings, and cultivation in the seasonal wetlands in addition to the woodlands (Kutsch et al. 2011, Campbell et al. 1996).

In the 21st century, other patterns of land use are emerging, with the potential to replace or displace the traditional shifting agriculture system. They are driven by global demand for commodity crops, and a local desire for social development. An emerging pattern, favoured by several governments in the miombo region, is a version of the large-scale, high-input, high-yield commercial farming which has transformed the cerrado of Brazil, an ecologically similar landscape in South America. It draws its agronomic approach from high-production techniques – fertilization, mechanization, pesticides, herbicides and improved germplasm – developed in North and South America, translated to the African environment by commercial farming enterprises (Matson et al. 1997; Reardon et al. 1999; McIntire 2014). Mostly non-local capital and expertise is deployed to clear the miombo woodland to create individual fields hundreds of hectares in extent. The woodland which is cleared has often already been partially transformed by high-grading, charcoal production and shifting agriculture. Export-oriented commodity crops, such as maize and soybeans, are the main yields. In some locations, centre-pivot irrigation is also deployed, either to smooth out the inherently high interannual rainfall variability, or to extend the growing season so that multiple crop cycles are possible per year.

The third pattern of land use transformation we explore in this paper is a proposed alternative to the high-intensity commercial pattern described above. It is based on non-shifting smallholder agriculture but seeks to increase agricultural yields substantially above the levels typically achieved under subsistence agriculture by applying improved agronomic practices, 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” (the phrase we use), “agroforestry”, and “improved smallholder agriculture”. It emphasizes local livelihoods, family and local nutritional security and the integration of perennial crops, especially trees, with short-duration crops and livestock (Scherr et al. 2012). These aims are achieved through relatively labour-intensive methods of weed and pest control; increased inputs of nutrients (although lower than the levels under commercial high-input agriculture), often delivered through biological nitrogen fixation, manures and composts, but not excluding synthetic fertilizers; improved and diversified crop varieties, usually based on classical breeding techniques rather than genetic modification; and using a wide diversity of crop species pre-adapted to the environment (Scherr et al. 2012).
There is an ongoing debate regarding the most desirable pathway of land-use change in Africa (Pretty et al. 2011). The discussion has often been framed as a dichotomous choice between “extensification” and “intensification” (represented, respectively, by the “subsistence” and “commercial” land use patterns described above). Both sides of this debate claim environmental and social benefits. In reality, all three pathways explored in this paper above (i.e. subsistence, commercial and the in-between eco-agriculture) involve the transformation of miombo landscapes, just in different ways, to different degrees and with different extents. All have impacts on the climate system, which this paper sets out to explore.

How land-use change in the miombo region alters the climate

The link between land-use change, particularly deforestation, and the global increase in atmospheric greenhouse gas concentrations is well-established (Eva et al. 2006; Hill et al. 2013; Kim et al. 2016; Merbold et al. 2011; Metzger et al. 2006; Petrescu et al. 2015; Ryan et al. 2011, Sainju et al. 2006; Smith et al. 2013; Vagen et al. 2005). Clearing for agriculture of long-established native vegetation, which has reached carbon equilibrium with the atmosphere, has several important climate-system consequences. First, carbon stored in the soil and biomass is released into the atmosphere, ultimately as carbon dioxide. As a thought experiment, if half of the existing miombo extent were converted to cropland, and in doing so half of the carbon stored in the top 30 centimetres of soil and all the carbon stored in woody biomass were released over a period of 30 years, the mean rate of emission would be 0.2 PgC per year, making deforestation in miombo among the leading contributors to global climate change (Campbell et al. 1996).

Miombo landscapes also generate significant emissions of trace gases and radiatively active particles other than carbon dioxide, both in their “natural” and “transformed” states. The main miombo processes which result in emissions of methane (CH₄), nitrous oxide (N₂O), tropospheric ozone precursors and radiatively active aerosols include: wild and prescribed fires; enteric fermentation by ruminants (both wild and domestic); and emissions from the soil, especially denitrification and methanogenesis in dambo soils and from termites, both of which are features of miombo landscapes (Roberts 1988, Bullock 1992; Otter and Scholes 2000; Lal 2007; Nyamadzawo et al. 2014, 2015; Bell and Roberts 2016).

A less-documented climate effect is change in radiant energy exchange at the land surface when generally dark miombo woodland trees are replaced by generally brighter crops or a bare soil surface. When averaged over the year, the brighter surfaces absorb less solar radiation, leading to a cooling of the surface and the air above it. The accompanying seasonal shift in the ratio of latent to sensible heat that occurs when miombo trees, which are deep-rooted, long-leaf duration plants, are replaced by short-duration, shallow-rooted crops (assuming no irrigation), has a local-to-regional warming effect, but no net global effect, since the cooling provided by the increased evaporation of water is balanced by warming elsewhere in the atmosphere when the water vapour condenses again, as it must.

There are other mechanisms of interaction with the climate system, such as the decreased surface roughness when tall vegetation is replaced by short vegetation, but they are thought to be relatively minor at the global scale, even if locally important. A potential set of climate-miombo interactions may be mediated through aerosol
production and cloud nucleation (Pöschl et al. 2010), but we are unable to evaluate this mechanism for the miombo region at present.

Current methods of quantifying the climate regulation service provided by forests in Africa – which include the miombo woodlands – are almost exclusively focused on the net exchanges of carbon as carbon dioxide (an example is Houghton and Hackler 2006). There have also been attempts to quantify the non-CO₂ effects in Africa at large scale (Hickman et al. 2014), which show the non-CO₂ effects to be non-negligible. This paper sets out to quantify a wider range of climate-altering mechanisms, to see whether their inclusion in the assessment of net effects makes a difference to the conclusions reached.

When a landscape has multiple potential uses, a potential tradeoff is established between the different ecosystem services, and between benefits at the local, regional and global scales. Locally, there is a pressing need to provide nutrition, energy and livelihoods. At a global scale, there is a high demand for commodity crops, but also a need to limit global climate change. The “provisioning services” side of this tradeoff (i.e. the yields of food and energy crops) is relatively well-quantified, but the “regulating service” side (i.e. climate change mitigation) is poorly quantified.

The purpose of this research is 1) to quantify the changes in net radiative forcing (the “climate regulation service”) resulting from miombo landscape transformations of various types; and 2) to quantify the relative contribution to the change in the climate regulation service by carbon dioxide, non CO₂-greenhouse gases and biophysical mechanisms such as a brighter or darker land surface.

**Methods**

We calculated the net radiative forcing over a hypothetical but representative intact (“historical”) miombo landscape, including both woodlands and wetlands. We constructed our own spreadsheet-based model for this purpose, using relationships and data inputs detailed below. The same, largely intact landscape (here labelled “historical”) was hypothetically developed in three different ways: through extensive “subsistence” farming and charcoal cutting; through intensive, large-scale “commercial” farming; and using “eco-agriculture” smallholder techniques. The time course of net forcing resulting from net carbon dioxide (CO₂), methane (CH₄) and nitrous oxide emissions (N₂O), from all material sources (e.g. fires, cultivation, ruminants, termites, etc.) was quantified, as well as the change in surface reflectance (albedo), for the archetype miombo landscape and the three alternatives derived from it. In order to represent three land uses, the area and timing of the various land management activities which give rise to emissions or sinks were changed, along with the strength of the drivers associated with the key emission or sink processes. The various climate change mechanisms were compared by converting them to carbon dioxide emission equivalent (gCO₂e m⁻² y⁻¹), and subtracting the result from the forcing under the “historical” case.

The reference landscape was based on a real landscape in central Zambia (nominally somewhere in the area 14–15° S, 26–30° E). This part of Zambia is on the Central African Plateau with an elevation of about 1000 m. There are two seasons: dry (May to October) and rainy (November to April). Annual rainfall is 700–1,200 mm y⁻¹. The hot temperatures that would be expected in such a tropical location are moderated by the high elevation: the
monthly average daytime maximum reaches 32°C during the wet summer months and 23°C in the dry winter months; while the night-time minimum temperature ranges 8–17°C.

The fluxes of CO₂, CH₄, and N₂O were modelled at a temporal resolution of 1 year for a duration of 33 years, at a quasi-spatial resolution of 100 × 100 m over an extent of 10 × 10 km. The duration was selected to allow for a full clearing-to-recovery cycle. It also corresponds to the likely period over which land transformation in south central Africa will take place. It is shorter than the 100-year integration period often used for calculating global warming potentials, allowing the atmospheric legacy effects to be included. The characteristic spatial scale of the miombo landscape is established by the gently undulating pattern of drainage lines about 5 km apart, typical of granitic plateaus on which the landscape occurs. Thus a 10 × 10 km area can represent a typical landscape. This landscape was subdivided into a grid of spatial units of 1 hectare (ha), small enough to capture the landscape spatial pattern and the size of smallholder fields. Individual 1 ha grid cells were classified according to land cover, e.g. miombo woodlands in various stages of recovery after clearing; agricultural fields; and dambo bottomlands. We did not model every hectare in the 10 × 10 km landscape explicitly, but used this scheme to determine the area fraction of patches which were transformed in the same way in the same year. One pixel representing the patch was then modelled, and multiplied by the area fraction of its cohort.

Four land-use scenarios were simulated: historical, natural miombo, subsistence extensification, eco-agriculture and commercial intensification. The historical miombo landscape functioned as a reference state for comparison with the three other patterns. By historical, we mean the situation which prevailed around the middle of the 20th century: at that time the miombo landscape was largely intact, but included small patches undergoing long-return shifting agriculture. The proportions of each land cover type under each of the four scenarios were based on literature review, consultation with experts and looking at high-resolution satellite images of representative landscapes. Within each land cover type, the relevant natural processes and land-use perturbations that result in changes in climate forcing were modelled over time.

A monthly mean albedo (shortwave surface reflectivity) was assigned to each land cover type, based on observations of these land cover types in Central Zambia made by the Multiple-angle Imaging Spectro-Radiometer (MISR) sensor on the Terra satellite platform over a 12 month period (Verstraete et al. 2012). We selected three sets of target coordinates, based on an inspection of Google Earth images, to represent the various land covers. All targets were within a 50 km radius of Mkushi, Zambia. An appropriate target could not be identified for the eco-agriculture scenario, which is not yet an agricultural option practiced at large scale anywhere in the world, so we estimated its albedo characteristics as an equal area-weighted hybrid between the historical, subsistence and commercial landscapes, since it includes elements of all those land covers. Most targets were within the path of two overlapping MISR swathes, and some in 3 swathes, so the revisit period was as little as 3.5 days, or up to 30 days once the effects of cloud cover were included. The multi-angular, multispectral reflectances were processed using the MISR-HR workflow (Verstraete et al. 2012). The MISR albedo extracted this way, using the Joint Research Centre – Two-stream Inversion Package (JRC-TIPS), has advantages over other albedo products: it is technically robust, has a known and reported accuracy, and 275 metre ground sampling distance. The seasonal progressions of albedo for the three land cover cases are given in Table 2.
The GHG emission models we used are simple mathematical expressions generally based on the IPCC Framework, relying mainly on the equivalent of ‘Tier 1’ or ‘Tier 2’ methods (IPCC, Intergovernmental Panel on Climate Change 2014). In terms of the IPCC Framework, Tier 1 is the basic method, Tier 2 intermediate and Tier 3 the most demanding in terms of complexity and data requirements. Tier 1 and Tier 2 methods use similar simplified models, but whereas Tier 1 uses a general look-up table for parameters, based on studies worldwide, Tier 2 typically uses parameters derived by observations more closely associated with the specific context. Both are less detailed than a fully mechanistic ‘Tier 3’ model. For example, a Tier 2 method for emissions from fires multiplies the area burned by the potential fuel load, the fraction combusted, and a fuel type-dependent emission factor for each gas. In our case, for fires we used emission factors derived in the miombo region. A Tier 3 approach is more mechanistic and typically requires more detailed data (for instance, in the fire case, it may include seasonally varying emission factors, fuel loads and combustion completeness) that are presently unavailable for miombo landscapes. For the biggest fluxes, NEE, fire and charcoal-making, we used locally adapted and parameterized models. For emissions from herbivores, termites, wetlands nitrogenous fertilizers we used general models, with local activity drivers but parameters derived globally. The equations represent net exchanges of CO₂, CH₄, and N₂O between land and atmosphere resulting from the natural processes and land-use perturbations within each applicable land use scenario.

The main mechanisms through which the net exchange of greenhouse gases are altered through miombo region land-use change are briefly described below. This list is not exhaustive, but it contains many more processes than the typical approach of considering changes in the carbon stocks alone, and we believe it captures the most substantial effects.

**Changes in Net Ecosystem Exchange (NEE).** The classical change-in-carbon-stock approaches applied in climate regulation service calculations are intended to quantify this flux. The main processes are the loss, over a period of years following woodland clearing, of carbon from woody biomass and soil, and the loss of carbon from flooded soils in dambos when they are drained. Loss of biomass C occurs mostly in the first year, but soil C declines exponentially, losing about half of the 0–30 cm stock in 20 years. If woodlands are allowed to regrow, or wetlands are re-flooded, recovery of the stocks follows a sigmoid pattern, over a period of about 30 years, to the pre-disturbance level (Chidumayo 2002; Merbold et al. 2009, 2011).

**Changes in the fire regime.** Miombo landscapes are among the most frequently burned ecosystems in the world. The woodlands burn on average once every 2 years, and the dambos annually (Archibald et al. 2010). The net emissions of carbon dioxide resulting from wild fire are considered to be zero, because regrowth in the following seasons takes the CO₂ up again. Any long-term trends due to subtle changes in the fire regime are picked up as NEE changes. For CH₄ and N₂O there is little to no local re-absorption of the gas in its original form. Their emission is calculated as a product of the mean fraction of the area burned annually, the fuel load consumed (this incorporates the fuel load exposed to fire and fraction actually combusted, which is typically high), and an emission factor (Scholes et al. 1996). Under commercial agriculture, the burned area is restricted to those areas that remain under woodland and dambo; under subsistence agriculture the number of ignitions may go up, but the fuel load goes down
because biomass is diverted to other uses. The pyrogenic emissions following clearing are calculated using emission factors for smouldering rather than flaming combustion, since the fuel consists of large-diameter woody parts (Ward et al. 1996), and the portion of woody biomass converted to charcoal is handled separately (Merbold et al. 2009). Under eco-agriculture, we assumed reduced burning relative to natural miombo, but not to the same degree as under commercial agriculture, and a partial continuation of charcoal production.

Changes in the number and type of large mammalian herbivores. Large mammal herbivores produce methane through enteric fermentation, and some methane and nitrous oxide from dung and urine. Miombo landscapes have a low inherent large mammal biomass, due to low fertility (Hempson et al. 2015). Subsistence agriculture reduces the natural herbivory to close to zero and replaces it with livestock. To date, commercial agriculture in this region is not animal-based. One of the key markets for the maize and soy produced is animal fattening in export markets, but remote emissions resulting from this end use were not part of our calculation. Eco-agriculture integrates animals into the agricultural system, at about the same stock density as subsistence agriculture.

Changes in the abundance of termites. Termites also exhibit enteric fermentation. Termite mounds are a very conspicuous feature of miombo woodlands, and persist in subsistence and eco-agriculture, but disappear in the cultivated parts of commercial agriculture (Frost 1996; Sanderson 1997).

Changes in wetland inundation. Apart from the soil carbon stock dynamics discussed under NEE, flooded soils generate CH₄ and N₂O. If the soils are drained, these sources are reduced. Currently, dambo agriculture is mainly on drained or seasonally dry parts of the wetland, rather in flooded wetlands, for instance through paddy rice production. The emissions of methane are estimated using data in Otter and Scholes (2000) and Nahlik and Mitsch 2010).

Charcoal production. On clearing, the stems down to a diameter of about 7 cm are converted to charcoal, for which there is a ready urban market. Charcoaling is partial pyrolysis, which generates both CH₄ and N₂O. In the miombo region it is performed in traditional earthen kilns, quite inefficiently, and with substantial emissions of greenhouse gases (Woolen et al. 2016). Charcoaling features to some degree in all three land use pathways on initial clearing, but only in an ongoing, substantial way in the subsistence agriculture pathway.

Application of nitrogenous fertilizers. A fraction of nitrogen applied to crops is emitted as N₂O, regardless if it is applied as synthetic fertilizer, manure or biologically fixed nitrogen (IPCC, Intergovernmental Panel on Climate Change 2014). The fraction lost is relatively low in miombo, since the soils are well-drained. Nevertheless under the relatively high fertilization rates applied in commercial agriculture (still below the fertilization rates applied in commercial agriculture in places where fertilizer is much cheaper than it is in Central Africa), the emissions are substantial. Eco-agriculture N₂O emissions were assumed to be half those of commercial agriculture because fertilization rates are lower. Fertilization is minimal under subsistence agriculture. The equations used to quantify these processes are summarized in Table 1.

Converting the effect of surface albedo changes to a global climate forcing expressed in gCO₂e units can be achieved by perturbing a known area of land surface in a three-dimensional Earth System Model, which takes into account many of the possible lateral
and vertical spatial interactions, the lifespan of the various gases, their radiative effects, and some of the chemical interactions. This is an extremely computationally-demanding approach. We approximated the effect using a one-dimensional, simple radiative transfer model (Bird et al. 2008) to calculate the change in radiant forcing at the top of the atmosphere, accounting for the multiple reflections and absorptions by clouds and aerosols. The presence of clouds strongly modulates the effect of surface brightness changes. Under cloudless conditions the Earth’s brightness is mainly dictated by surface properties, but when clouds are present, they typically dominate the reflectivity as observed at the top of the atmosphere. The required inputs (Table 2), in addition to the time-course of surface albedo, are the site location (in order to calculate the extra-terrestrial incoming solar radiation) and the cloud cover by month. The latter were obtained from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) cloud cover product (MOD-06). The change in top-of-atmosphere radiative forcing in W m\(^{-2}\) was then expressed in terms of the equivalent emission of CO\(_2\) that would have the same forcing, using the procedures described in Bird et al. (2008) and Kirschbaum et al. (2011), both based on the Ramaswamy et al. (2001) estimate that a doubling of atmospheric CO\(_2\) (from 350 to 700 ppm) results in a radiant forcing of 3.7 W m\(^{-2}\) over the entire surface of the Earth.

The magnitude of the albedo effect on global warming as calculated here is debatable, since the method we used is an approximation (as are all approaches, to varying degrees), but its sign is not. The largest quantitative uncertainties come not from the measurement of albedo, or from the changes in top-of-atmosphere net radiation, but from how the change in radiative forcing is expressed in CO\(_2\)-e terms.

**Results**

The choice of integration period has a big impact on the result obtained. The carbon balance impacts (CO\(_2\)) on the climate are mostly realized in the first years following landscape transformation, and then continue at a diminishing rate, whereas impacts due to changes in the net exchange of methane and nitrous oxide are ongoing. The climate regulation service, like all other services, is a flow of benefits, and therefore ought to be expressed on a per area, per unit time basis. However, the carbon balance approach, for simplicity, is often expressed without the time dimension, as if it were a once-off emission; or the emissions are equally distributed over the accounting period. When averaged over the integration period, the annualized carbon emissions associated with the conversion of natural woodland to cropland become progressively diluted, the longer the period chosen. Thus if you chose a short integration period (such as 3 years), the CO\(_2\) effects resulting from land conversion apparently dominate the service (disservice in this case), whereas if you chose a long period, for example, 100 years, the initially smaller, but ongoing non-CO\(_2\) effects dominate. Here we chose 33 years because that corresponds to an important timescale of the system – the woodland recovery period.

The climate regulation service provided by four versions of the miombo landscape, is shown in Figure 1. To express this as an anthropogenic forcing, resulting from land use changes, the historical forcing must be subtracted, since although the historical landscape includes human disturbances, they were of a type and intensity that is believed to have been present before the modern era. Considering only the change in forcing resulting from the three main greenhouse gases, the loss of climate regulation service (i.e. positive
Table 1. Equations and parameters used for calculating net greenhouse gas emissions from miombo landscapes. Throughout it is assumed that woodlands originally made up 75% of the landscape and wetlands (dambos) 25%. All net emissions are expressed in gGas m$^{-2}$y$^{-1}$. The emissions are calculated over a 10 $\times$ 10 km area and 33 years, but expressed as averages per square metre per year for the whole landscape, which contains former woodland and dambo, each modified to a certain degree. This procedure smooths over the temporal dynamics, which may be at different stages in different parts of the landscape.

| Process                        | Equation                                                                 | Variables (units) | Values under land use pathways                                                                 |
|--------------------------------|--------------------------------------------------------------------------|-------------------|------------------------------------------------------------------------------------------------|
| Area fractions                 | Fraction of original woodland converted to fields                        | %                 | Historic Commercial Subsistence Ecoagric                                                                 |
|                               | Fraction of original dambo converted to fields                           | %                 | 3 0 100 75 20                                                                                       |
| NEE Woodland NEE dambo         | NEE = \((C_{t-1} - C_t)\times A_{wd} + 44/12; C_t = C_{t,dam} + C_{t,clr}\) |                  | Scenario assumptions                                                                                |
|                               | \(C_{t,wdl} = (1 + (C_{t-1} - C_t)/C_{t,ini})e^{-t}\) during regrowth: \(C_t = C_{t,ini}/(1 + (C_{t-1} - C_t)/C_{t,ini})e^{-t}\) |                  | Merbold et al. 2009, 2011, Chidumayo 1988, Frost 1996                                                |
|                               | At clearing 95% of aboveground biomass \(C\) and belowground \(C\) is released to atmosphere as \(CO_2\) in the first year, 60% after first passing through charcoalization. |                  |                                                                                                    |
| Fire \(CH_4\) from woodland    | \(E_{CH_4,wdl} = A_{wdl} \times FL_{wdl} \times EF_{CH_4,wdl} + E_{CH_4,clr} = A_{wdl} \times FL_{wdl} \times EF_{CH_4,clr}\) |                  | Ward et al. 1996, Scholes et al. 1996                                                                |
|                               | \(E_{N_2O,wdl} = A_{wdl} \times FL_{wdl} \times EF_{N_2O,wdl} + E_{N_2O,clr} = A_{wdl} \times FL_{wdl} \times EF_{N_2O,clr}\) |                  |                                                                                                    |
|                               | After clearing \(N_2O\) from woodland from dambo after clearing          |                  | Archibald and Hempson 2016; Hempson et al. 2015                                                     |
|                               | \(E_{CH_4,LSU} = LHB/450 \times EF_{CH_4,ent} \times 1000/1,000,000\)   |                  | Wolf et al. 2017                                                                                   |
|                               | \(E_{N_2O,LSU} = LHB/1000 \times 0.63 \times 365 \times EF_{N_2O,LSU} \times 1000/1,000,000 \times 44/28\) |                  | IPCC, Intergovernmental Panel on Climate Change 2014                                                 |

(Continued)
### Table 1. (Continued).

| Process          | Equation                                                                 | Variables (units) | Values under land use pathways | References          |
|------------------|--------------------------------------------------------------------------|-------------------|--------------------------------|---------------------|
| Termites CH₄     | \( E_{\text{CH₄,ter}} = \text{NM} \times \text{TB} \times \text{EF}_{\text{CH₄,ter}} / 10,000 / 1000 \) |                   | Historic                      | Frost 1996 Sanderson|
|                  |                                                                          | NM (mounds/ha)    | 3.75                          |                     |
|                  |                                                                          | TB (gDM/mound)    | 9.5                           | 1997 Nauer et al.   |
|                  |                                                                          | \( \text{EF}_{\text{CH₄,ter}} \) (mgCH₄/gDM/y) | 0.4                           |                     |
|                  |                                                                          | \( \text{CH}_4,_{\text{ter}} / 10,000 / 1000 \) | 0.94                          | 2018                |
| Flooded dambo CH₄| \( E_{\text{CH₄,dam}} = \text{d}_{\text{fld}} \times \text{EF}_{\text{CH₄,dam}} \) |                   |                               | Nahlik and Mitsch 2010 |
| Charcoal CH₄     | \( E_{\text{char,CH₄}} = \text{FL}_{\text{char}} \times \text{EF}_{\text{char,CH₄}} \) | \( \text{FL}_{\text{char}} \) (gCH₄/kg char⁻¹) | 62 (1 kg of dry wood produces 0.28 kg charcoal) | Pennise et al. 2001 |
|                  |                                                                          | \( \text{EF}_{\text{char,CH₄}} \) (gCH₄/kg char⁻¹) | 0.131                        |                     |
| N₂O              | \( E_{\text{N₂O,fert}} = \text{N}_{\text{fert}} \times \text{EF}_{\text{frt,N₂O}} \times 1000 / 10,000 \) | \( \text{N}_{\text{fert}} \) (kgN ha⁻¹ y⁻¹) | 600                           | IPCC, Intergovernmental Panel on Climate Change (2014) |
|                  |                                                                          | \( \text{EF}_{\text{frt,N₂O}} \) (gN₂O gNfert⁻¹) | 0.02                          |                     |

**Notes**
- A area fraction (nd)
- E emission (gGas m⁻² y⁻¹)
- EF emission factor (mgGas gfuel⁻¹)
- C carbon density (gCm⁻²) of biomass or soil
- FL fuel load (gm⁻²) the sum of fuel types, including grass, litter and twigs. Savanna tree stems and green leaves seldom burn.
- r intrinsic growth rate of biomass, or carbon in the soil (g g⁻¹ y⁻¹) as they recover from clearing
- d intrinsic decay rate (y⁻¹) applied to topsoil carbon when converted to agriculture
- nd no dimension (usually because it is a dimensionless fraction)
- wdl woodland
- dam dambo
- clr clearing
- frt fertilizer nitrogen applied to crop fields, including from biological nitrogen fixation and manure
- LSU large stock unit equivalents per km², where a LSU is the metabolic equivalent of a 450 kg steer.
forcing) was greatest when the entire landscape was converted to commercial agriculture through intensive techniques (309 gCO$_2$e m$^{-2}$ y$^{-1}$). Conversion via through extensive shifting cultivation, providing the smallest net forcing per unit land area (66 g CO$_2$e m$^{-2}$ y$^{-1}$). Conversion to eco-agriculture falls in between these extremes (184 g CO$_2$e m$^{-2}$ y$^{-1}$).

All three major greenhouse gases contribute to the forcing, to different degrees under the different scenarios. In the case of conversion to commercial agriculture, the net contribution by changes in the CH$_4$ (a small reduction in emissions, mostly by eliminating termites) are only 1% of the greenhouse gas total forcing, while under subsistence agriculture, the reduced CH$_4$ caused mainly by draining dambos for cultivations had an effect amounting to 27% of the net forcing. The contributions from N$_2$O, resulting from the application of nitrogenous fertilizers or biological nitrogen fixation in crops such as soybeans is substantial in high-input agriculture, at 34% of the total greenhouse gas forcing, and even higher as a proportion under eco-agriculture, because both CO$_2$ and CH$_4$ emissions were reduced relative to commercial agriculture. N$_2$O only accounted for 8% of the greenhouse forcing under subsistence agriculture, since nitrogenous fertilizers are hardly used, the planting of biological nitrogen-fixing crops is minor, and the manure used is hardly different to the excreta generated by wild herbivores in the historical case.

The contribution of the various processes that contribute to the forcing are reported in Table 3. The process of CO$_2$ emission as a result of conversion of natural vegetation to croplands remains dominant (despite the note regarding the effects of time averaging, above). The next most important greenhouse effect (especially once converted to CO$_2$ e terms) is CH$_4$ production in *dambos*, but like N$_2$O production from the volatilization of urea and manures, these effects are also strong in the historical case, and therefore do not constitute large anthropogenic effects once the historical emission is subtracted. Charcoal production is a significant driver under subsistence extensification. The effect of nitrogenous fertilizers is potentially substantial under both the commercial and eco-agriculture scenarios. For all practical purposes, changes in emissions from termites can be ignored as negligible.

Table 2. The inputs used to calculate change in top-of-atmosphere radiative forcing as a result of land cover induced surface albedo changes at a location 14 °S.

| Month | Cloud cover fraction | Intact woodland Surface albedo | Subsistence agriculture Surface albedo | Commercial agriculture Surface albedo | ToA ΔWm$^{-2}$ | ToA ΔWm$^{-2}$ |
|-------|----------------------|-------------------------------|----------------------------------------|--------------------------------------|----------------|----------------|
| Jan   | 0.70                 | 0.22                          | 0.22                                   | 0.22                                 | 2.756          | 0.26           | -8.270         |
| Feb   | 0.72                 | 0.22                          | 0.22                                   | 0.22                                 | 0.000          | 0.26           | -11.143        |
| Mar   | 0.57                 | 0.21                          | 0.22                                   | 0.22                                 | -2.767         | 0.26           | -13.838        |
| Apr   | 0.41                 | 0.21                          | 0.22                                   | 0.22                                 | -2.630         | 0.27           | -15.783        |
| May   | 0.15                 | 0.20                          | 0.20                                   | 0.20                                 | 0.000          | 0.25           | -12.093        |
| Jun   | 0.16                 | 0.19                          | 0.24                                   | 0.24                                 | -11.269        | 0.25           | -13.523        |
| Jul   | 0.14                 | 0.18                          | 0.21                                   | 0.21                                 | -6.763         | 0.27           | -20.289        |
| Aug   | 0.23                 | 0.17                          | 0.19                                   | 0.19                                 | -4.832         | 0.24           | -16.914        |
| Sep   | 0.10                 | 0.19                          | 0.20                                   | 0.20                                 | -2.640         | 0.23           | -10.558        |
| Oct   | 0.32                 | 0.22                          | 0.22                                   | 0.22                                 | 0.000          | 0.24           | -5.551         |
| Nov   | 0.54                 | 0.18                          | 0.21                                   | 0.21                                 | -8.372         | 0.24           | -16.745        |
| Dec   | 0.56                 | 0.23                          | 0.21                                   | 0.21                                 | 5.521          | 0.26           | -8.282         |
| mean  |                      | 0.203                         | 0.213                                  | -2.583                               | 0.253          | -12.749        |
| SD    |                      | 0.021                         | 0.013                                  |                                      | 0.013          |                |
Simultaneously considering the effects of albedo change and greenhouse gas-mediated forcing alters the conclusions reached. In all altered land-use scenarios, greenhouse gas fluxes resulted in positive forcing changes while changes in albedo resulted in negative forcing changes, i.e. a net cooling effect on the global climate. The clearing of dark vegetated
Table 3. Net greenhouse gas emissions by a historical miombo landscape and by three land use patterns derived from it, by the process resulting in the net emission. The values are averaged over a 100x100km landscape and a 33 year period. It is assumed that 25% of the landscape is historically under dambos and 75% under woodland. The gases are given in units of mass of that gas per square metre per year, and can be converted to CO₂e by multiplying CH₄ values by 21 and N₂O values by 289. Converting the top of atmosphere radiative forcing change, in Wm⁻² to CO₂e m⁻²y⁻¹ requires multiplying by about 31.

| By Process                    | Gas     | Historical | Commercial | Subsistence | Eco-agriculture |
|-------------------------------|---------|------------|------------|-------------|-----------------|
| NEE woodland+dambo            | CO₂     | 9.3260     | 213.5894   | 89.3812     | 52.6336         |
| Wildfire CH4 woodland+dambo   | CH₄     | 0.2790     | 0.1818     | 0.2226      | 0.1638          |
| Clearing fire CH4             | CH₄     | 0.0252     | 0.0288     | 0.0356      | 0.0252          |
| Wildfire N20 woodland+dambo   | N₂O     | 0.0244     | 0.0159     | 0.0195      | 0.0143          |
| Clearing fire N2O             | N₂O     | 0.0013     | 0.0015     | 0.0019      | 0.0013          |
| Large herbivore CH4           | CH₄     | 0.0600     | 0.0000     | 0.0600      | 0.0470          |
| Large Herbivore N2O           | N₂O     | 0.3614     | 0.0361     | 0.3614      | 0.3614          |
| Termite CH4                   | CH₄     | 0.0014     | 0.0001     | 0.0014      | 0.0004          |
| Flooded dambo CH4             | CH₄     | 2.8356     | 2.8356     | 1.8999      | 2.2685          |
| Charcoal making CH4           | CH₄     | 0.1728     | 0.1973     | 0.2442      | 0.1728          |
| Charcoal N2O                  | N₂O     | 0.0004     | 0.0004     | 0.0005      | 0.0004          |
| Fertilizer N2O                | N₂O     | 0.0000     | 0.7054     | 0.0234      | 0.5482          |
| Albedo change                 | Wm⁻²    | 0          | −27.7      | −21.9       | −6.9            |

woodlands reveals lighter exposed topsoil in both the subsistence scenario and in the commercial scenario. Under eco-agriculture, where perennial trees form an important component of the system, the difference was assumed to be less marked, but this assumption could not be verified by remote sensing, since this land-use pattern is not yet sufficiently widespread for suitable targets to be identified. Converting this albedo change effect into CO₂e terms is approximate. An ongoing forcing of 1Wm⁻² locally would correspond to a once-off emission of 1000 to 1400 gCO₂. Averaging over the 33 year period, to be consistent with how we treated the once-off clearing emission, gives a value of about 31.5 gCO₂ W⁻¹ m⁻²y⁻¹. Considering the combined forcing, the commercial agriculture has a net forcing of −92.6, eco-agriculture −57.3, and subsistence agriculture −14.9 gCO₂e m⁻²y⁻¹.

The data on albedo forcing represent a novel finding related to land use and land cover changes in the miombo region. They suggest that the net effect of miombo conversion to agriculture may not be to promote further global warming but to slightly reduce it. There is robust evidence supporting the cooling potential of bright cropping systems elsewhere. For instance, the summer time effect in the mid-latitudes of North America and Eurasia, which according to some research could cool the atmosphere by as much as 1°C (Myhre et al. 2013). This is in contrast to the findings of some previous modelling studies in tropical Africa (for instance Paeth et al. 2009) which project a regional surface warming as a result of forest clearing. It is unclear whether their model includes a realistic representation of surface reflectivity changes. They attribute the change largely to changes in the latent heat to sensible heat fluxes, which as noted above contribute to regional but not global effects.

Another perspective is provided by expressing the forcing, instead of on a land area basis, on a per unit agricultural product basis. This involves further approximations since the spectrum of agricultural produce changes across the three land uses, and there is substantial variation between individual farmers in terms of what is planted and what yields are achieved. For illustrative purposes, we will consider only the staple
carbohydrate crop, expressed on a dry matter basis. Maize dominates this category in all three land-use scenarios and is supplemented by cassava in the subsistence and eco-agriculture scenarios. The ratios of staple crop yield per hectare planted are in the order of 10:8:1 for commercial, eco-agriculture and subsistence farming. When adjusted for the fraction of the landscape planted in a given year in each of these scenarios, these become 120:80:1. Dividing the anthropogenic greenhouse gas-only forcing by these area-adjusted values leads to the conclusion that the net global climate forcing resulting from extensification of subsistence agriculture is likely to be much larger than that from either commercial or eco-agriculture because of the larger area required by the former to deliver the same quantum of food. The weakness in this line of reasoning is that in a globalized economy, land use change will not stop simply because local food needs are satisfied. In the absence of other constraints such as forest or water resource protection policies, any of the land use patterns could expand to encompass the entire available area.

Conclusions

Looking at the climate regulation service purely through a carbon dioxide emissions lens can lead to very misleading conclusions. At a minimum, the full suite of major greenhouse gases, and all the major processes leading to a net change in their emissions, must also be considered. The additional biophysical effects, such as changes in surface reflectivity, should also be considered, since in radiative forcing terms they are quantitatively in the same order of magnitude as the carbon dioxide flux changes.

Governments in the miombo region are faced with important land-use decisions. They must ensure food security for a growing population and encourage economic investment and growth, without compromising the livelihoods of the poorest of the poor or damaging the environment, locally and globally. This study shows that these decisions can be guided, among other considerations, by calculations of the net change in climate regulating services that result from different landscape configurations.

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