Impacts of land use change due to biofuel crops on climate regulation services: five case studies in Malawi, Mozambique and Swaziland

Carla Romeu-Dalmau[a,b]*, Alexandros Gasparatos[c], Graham von Maltitz[d] , Alastair Graham[e], Jacob Almagro-Garcia[f], Beccy Wilebore[a,b] and Katherine J. Willis[a,b,g,h]

[a] Department of Zoology, University of Oxford, OX1 3PS, UK.

[b] Oxford Martin School, 34 Broad Street, OX1 3BD, UK.

[c] Integrated Research Systems for Sustainability Science (IR3S), University of Tokyo, Japan.

[d] Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa.

[e] Geoger Ltd., 6a St Andrews Court, Wellington Street, Thame, OX9 3WT.

[f] Wellcome Trust Centre for Human Genetics, University of Oxford, Oxford, UK.

[g] Department of Biology, University of Bergen, PO Box 7803, 5020 Bergen, Norway.

[h] Royal Botanic Gardens, Kew, Richmond, TW9 3AE, UK.

* Corresponding author: carla.romeu-dalmau@zoo.ox.ac.uk

Department of Zoology, University of Oxford, OX1 3PS, UK. Tel: +44(0)1865281326; Fax: +44(0)1865271249.

Abstract

Understanding changes in carbon sequestration due to land conversion is key for elucidating the true potential of biofuel landscapes to provide climate regulation ecosystem services. In this study, we focus on the two most promoted biofuel crops in southern Africa, Jatropha and sugarcane, to analyse the land use change effects and associated carbon impacts of growing biofuel crops in five study sites in Mozambique, Malawi and Swaziland. We found that, considering a 20-year cycle, carbon stocks in aboveground biomass are higher for sugarcane than for Jatropha. However, as soil organic carbon (SOC) is generally the main carbon pool, total carbon stocks (considering biomass and soil) will highly depend on SOC. Our results show that, in our study sites, sugarcane replaced land uses with low carbon stocks (low-density forest and agriculture), and as a result carbon gains occurred due to land use change. In the Jatropha projects, carbon gains are observed in the smallholder scheme as agricultural land was converted to Jatropha, but carbon debts occurred in the Jatropha plantation as high-density forest was cleared to grow this feedstock. Finally we show that, if a plantation of sugarcane or Jatropha is envisioned to be located in the studied regions, more forested land could potentially be converted into sugarcane (30-44% of forest) than into Jatropha (24-32%), without creating carbon debts due to land conversion. To our knowledge, this is the first comparative study of the carbon impacts of land use change of the main biofuel crops in southern Africa.

Keywords: sugarcane, Jatropha, southern Africa, biofuel feedstock, carbon sequestration, ecosystem services.

1. Introduction

Biofuels in southern Africa have been promoted to boost economic growth, rural development and the energy security of countries that are highly dependent on traditional biomass and imported fossil fuels [1]. The two most promoted biofuel crops in the region have been Jatropha (for straight vegetable oil and biodiesel) and sugarcane (for bioethanol) [2].

Jatropha (*Jatropha curcas* L.) is a perennial shrub that produces seeds with up to 35% oil content that can be converted to liquid biofuel [3]. Although Jatropha is native to Central America, today it is found in tropical areas worldwide, where it is used as a living fence for livestock control (due to Jatropha's toxicity), and/or to produce oil for soap and lighting [4]. Between 2000 and 2008, almost every country in southern Africa started promoting Jatropha as a biofuel crop to be grown in large plantations or smallholder projects [2,5]. This was largely based on promises of high yields under arid conditions and degraded soils [5]. Today, most Jatropha projects in southern Africa have collapsed or are not economically viable. This is due to several reasons including overestimated Jatropha yields under arid conditions, underestimated labour and maintenance costs, and a lack of investor support which eventually led to low profitability and a lack of financial viability [5].

Sugarcane (*Saccharum officinarum* L.) is a perennial tall grass cultivated mainly in the tropics but also in some sub-tropical areas. Besides sugar, other products can be derived from sugarcane. These include bagasse, the cane residue that can be used as fuel in cogeneration plants, and molasses, the syrupy by-product of sugar production that can be converted to ethanol. In southern Africa, sugarcane ethanol has historically been produced mainly for nonfuel purposes, but some countries including Zimbabwe, Malawi and Kenya started blending sugarcane ethanol with petrol in the early 1980s [6]. Today, within the region, only Malawi is producing ethanol from sugarcane for biofuel purposes [7].

Besides boosting economic growth, rural development and energy security, it has been argued that biofuel production and use in African countries can reduce greenhouse gases (GHG) emissions when compared to conventional fuels [1]. However, GHG savings will largely depend on which type of land cover has been converted for biofuel production. If landscapes rich in carbon (e.g. forests) are cleared to grow biofuel crops, then large carbon debts can be created. This is due to changes in aboveground (AG) and belowground (BG) biomass, and soil organic carbon (SOC), which could outweigh the GHG emission reductions achieved during the biofuel's whole life cycle [8–10].

Carbon sequestration is linked to climate regulation, which is a key regulating ecosystem service [11,12]. Therefore, changes in carbon stocks (whether losses or gains) due to conversion into biofuel landscapes, imply changes in the provision of climate regulation services [13]. Several reviews and empirical studies at the interface between biofuels and ecosystem services have identified climate regulation as a key ecosystem service to be considered during the assessment of ecosystem services trade-offs in biofuel landscapes [14–17].

The aim of this study is to assess the impact of direct land use change due to biofuel crop expansion on climate regulation services in southern Africa. We use a range of non-field (remote sensing, secondary data analysis), and field-based methods (biomass surveys, soil organic carbon analyses), to estimate the changes on carbon stocks (including AG/BG biomass and SOC) associated with direct land use conversion in five study sites across southern Africa. The selected projects are currently growing Jatropha or sugarcane (the two main feedstocks in southern Africa) either in smallholder schemes or industrial plantations. These types of feedstocks (Jatropha, sugarcane) and scales of feedstock cultivation (smallholder, plantations) represent the dominant modes of biofuel production in the region as identified in a previous literature review [1]. By choosing five operational projects that have passed the establishment phase, and by combining several field and non-field techniques to gather site-specific data, we are able to assess how the main configurations of feedstocks in southern Africa differently impact the carbon stored in soils and biomass.

To our knowledge, this is the first comparative study of the carbon impacts associated with the two main feedstocks (Jatropha and sugarcane) and dominant modes of production (smallholder and plantations) adopted in southern Africa. While there are some studies about the effects of Jatropha on carbon stocks in Africa [18–22], there is a critical lack of empirical research on sugarcane as identified in a recent meta-analysis [1]. To the authors' best knowledge, the only study that has considered the carbon impacts of land use change due to sugarcane ethanol production in Africa (Malawi) has made substantial assumptions [23].

2. Material and methods

2.1. Study sites

The five study sites are located in Malawi, Mozambique and Swaziland (Table 1). The two Jatropha projects (BERL, a smallholder scheme in Malawi and Niqel, an industrial plantation in Mozambique) were initiated around 2008 during the Jatropha "boom" that happened in several countries of southern Africa [2,4]. Despite the widespread collapse of the Jatropha sector in the region, these two projects are among the very few that are still operational in southern Africa and show some signs of long-term viability [5].

The three sugarcane projects (located in Swaziland and Malawi) have a longer history and are more mature both from the production and the market side. The industrial plantation in Malawi (Illovo) has been providing feedstock for the production of ethanol for transport since the early 1980s. In fact Malawi is currently the only country in southern Africa producing significant quantities of sugarcane ethanol for transport [7]. In Swaziland, the Royal Swaziland Sugar Corporation Ltd (RSSC) has been distilling ethanol only for non-fuel uses (e.g. alcoholic beverages and pharmaceuticals). However, RSSC is interested in the production of sugarcane ethanol for the transport sector and has embarked in some pilot projects (Nick Jackson, CEO of RSSC, interview with authors, 2016 March 11), while the government of Swaziland has been working on a National Biofuel Strategy and Action Plan that aims to develop the biofuel ethanol industry in the upcoming years [24,25].

<<Table 1>>

2.2. Land use change

To study the land use change that occurred at each study site, we compared the land uses before Jatropha and sugarcane was planted to present land uses, both inside the feedstock production areas and in the surrounding areas. We obtained a selection of satellite images from the Landsat satellite image archive. Please note that as the two study sites in Swaziland (RSSC and SWADE) are adjacent in the same region in the North-East, we could asses both projects from the same Landsat imagery.

The most recent images for each site were obtained for either 2014 or 2015, whilst images captured before the project was established dated from:

- 1975 for the industrial sugarcane plantation in Malawi (Illovo);
- 1976 for the industrial sugarcane plantation in Swaziland. Although RSSC started operations in its Mhlume Estate around 1958, it was not possible to collect satellite imagery prior to the establishment of this sugar estate, since satellite imagery was not routinely available in the 1950s. Instead, we used satellite images from 1976 and assumed that the previous land use of the area already occupied by sugarcane (~10000 ha) was similar to the surrounding land cover that was converted to sugarcane after 1976.
- 1998 for the smallholder-based sugarcane project in Swaziland (SWADE);
- 2007 for the industrial Jatropha plantation in Mozambique (Niqel).

The land use change that occurred in the smallholder Jatropha scheme in Malawi (BERL) could not be assessed through satellite images as land areas converted to Jatropha were quite small (few dozens of trees planted as boundary hedge) and scattered throughout the landscape. As BERL has '*standard operating procedures that stipulate that Jatropha should only be grown as a boundary crop around agricultural fields and homesteads*' [26], we assumed that the previous land use of these Jatropha areas was agricultural land.

Nevertheless, we obtained a Landsat satellite image of this site in 2014 and classified the land uses around the Mangochi area.

The land cover in each site was captured using the existing 40-year archive of open access Landsat satellite image data, through the USGS Earth Explorer portal. Spatial resolution of the satellite imagery was 60m for the 1970s images, and 30m for the rest of the images. More details on the imagery are provided in the supplementary material (Table S1). Imagery was atmospherically corrected using the Atmospheric and Radiometric Correction of Satellite Imagery (ARCSI) open-source software [27]. Band 6 (thermal infrared) was removed from the dataset, and the remaining six spectral bands were stacked together. Once the images had been pre-processed, we applied the SAGA 'cluster analysis for grids' routine using the 'Combined Minimum Distance' method across all six Landsat Bands, which resulted in an unsupervised classification with 15 classes. This number of classes was chosen as prior analyses showed that this captured the majority of variation across the imagery, without the number of classes becoming unwieldy. The 15 classes output from the SAGA routines were then amalgamated into up to eight classes based on our knowledge of the study sites (generated from scoping trips to each site in 2013 and 2014), and guided further through a visual assessment of associated Google Earth high-resolution images. A 5x5 majority filter was applied to imagery post-classification to remove isolated pixels.

The final classification includes the following land cover types: (i) the biofuel crop under study (sugarcane or Jatropha), (ii) forest (divided into high- and low- density forest in Swaziland and Malawi), (iii) bare land, (iv) agriculture other than the biofuel crop, (v) grassland, (vi) water and (vii) cloud or shadow. A final manual edit of the classes using our knowledge of the study sites tested the inherent robustness of the classifications, and that the classes linked spatially through the time-series in a meaningful way.

In each study site (except for BERL), we assessed the land use change occurred both within the plantation boundaries and in the surrounding areas. As the size of the surrounding areas analysed varied between study sites and was larger than the areas directly impacted by the project (Table S1, Fig. S1-S3), we applied the land use changes observed outside the project boundaries to an area equivalent to the project area. As a result, the land use change that occurred within the project areas can be compared to the land use change occurred in the surrounding areas. Given the very small size of the Jatropha hedges in the smallholder Jatropha scheme in Malawi (BERL), it was not possible to do this comparison for this study site.

2.3. Carbon stocks

We estimated the carbon stocks in AG and BG biomass, and SOC for each of the following land uses: (i) biofuel crop (i.e. sugarcane or Jatropha), (ii) forested areas, (iii) other agricultural land and (iv) grassland. Empirical data collected at the study sites were used to estimate the three carbon pools associated with biofuel crops and forested areas. To estimate the carbon stocks of agricultural areas and grasslands, we used empirical data collected through fieldwork, complemented with selected data derived from the literature. Fieldwork took place in September 2014 (BERL, Malawi), November 2014 (Niqel, Mozambique), June 2015 (Illovo, Malawi) and July 2015 (SWADE and RSSC, Swaziland).

As the smallholder sugarcane project (SWADE) and the industrial sugarcane plantation (RSSC) in Swaziland are adjacent in the same region (Fig. S3), they have analogous climatic and socio-ecological conditions, and the carbon stocks estimated for these two study sites are the same. Also for sugarcane, since the yields reported by both projects are very similar.

The carbon stocks associated with the smallholder Jatropha scheme in Malawi (BERL) could not be assessed due to lack of field data. However, as only two land uses were needed to be considered for this site - agricultural land (land use prior to Jatropha cultivation) and Jatropha (Section 2.2) -, we made assumptions on the carbon stocks associated with these two land uses. For agricultural land, we assumed that the carbon stocks would be similar to the carbon stocks estimated from agricultural fields in the other study site in Malawi (Illovo). This is to be expected as our observations from both study sites show that the main agricultural activity by a wide margin is maize grown under non-irrigated subsistence farming. For Jatropha, we assumed that the carbon stored during a 20-year rotation in BERL would be similar to the values estimated for Mozambique (Niqel), as both projects started at the same time (around 2008) and share similar climatic conditions (Section 2.3.1.1).

2.3.1. AG and BG carbon stocks

2.3.1.1. Jatropha

We estimated the current carbon stocks of the plantation in Mozambique by measuring the diameter of 40 randomly selected trees and estimating their biomass using allometric equations that relate stem diameter with biomass. Half of the trees were ~2 years old and the other half were ~6 years old.

To estimate the AG biomass of the ~2 years old Jatropha trees (7 cm < Diameter < 12 cm), we developed our own allometric relationship from destructive samples of 20 trees. We used the allometric equation obtained [AG Biomass = 0.036 * Diameter ^ 2.15; D < 15 cm] to convert tree diameters to tree biomass (see supplementary material for more information on the allometric model).

To estimate the AG biomass of the ~6 years old Jatropha trees (12 < Diameter < 21 cm), we could not develop our own allometric equation since the plantation managers did not allow us to cut such adult trees. We tested several allometric equations, but some overestimated Jatropha biomass and/or used < 3-year-old trees to develop the equation [26,28,29]. We decided to use Baumert's [30] allometric equation [AG Biomass = 0.016 * Diameter ^ 2.31; D < 21 cm], which was developed in Burkina Faso with adult trees with a diameter range similar to our trees in Mozambique.

Total carbon biomass per hectare was estimated by multiplying the calculated tree biomass (Mean ± SD: 4.8 ± 1.4 kg for ~2 year old trees; 10.1 ± 3.5 kg for ~6 year old trees) by tree density in the Jatropha plantation (1500 and 1667 trees/ha).

As explained in Section 2.3, the current carbon stocks associated with the Jatropha smallholder scheme in Malawi (BERL) were not directly measured. However, to assess the carbon impacts of land use change we did not use the current carbon stocks described above, but instead we used an estimation of the mean biomass stored in a 20 year rotation. We believe this is a better approach since Jatropha will accumulate biomass until it reaches the natural lifecycle of 20 years [20,21]. As we could not find any measured values on Jatropha plantations older than 6 years, we used the carbon values estimated by Achten et al. [21] to calculate average stocks of AG biomass in Jatropha plantations considering a 20-year period. These average values were used to estimate net changes in carbon stocks due to land conversion to Jatropha in both BERL (Malawi) and Niqel (Mozambique). Although tree density varies between both projects, it was not possible to take this into account as tree density (trees/hectare) was not specified in Achten et al. [21] estimations.

BG biomass was calculated considering a root: shoot ratio of 0.42 [28,31]. Jatropha biomass was assumed to have 42.5% carbon content [30].

To our knowledge, neither the smallholder scheme in Malawi nor the plantation in Mozambique is managed with regular pruning.

2.3.1.2. Sugarcane

In our study sites in Malawi and Swaziland, sugarcane is harvested every year during a nine-year period (on average). After the ninth harvest, sugarcane plants are uprooted and the land is left fallow for around six months. Afterwards, new sugarcane stems are planted and the cycle starts all over again. To enhance the comparability between sugarcane and Jatropha, we assumed for sugarcane the same rotation period (20 years) as Jatropha's typical lifecycle [20,21] (Section 2.3.1.1). Therefore, we considered that during a 20-year period, there are 19 years of sugarcane production (9+9+1) and one year that the land rests fallow (6 months + 6 months).

We obtained sugarcane yields (2010-2014) from each sugarcane area (RSSC-SWADE and Illovo), and considered yields as the wet biomass produced in non-fallow years.

We then estimated the mean biomass stored in a 20-year rotation, considering 19 years of annual production and one year without any production. Yields (i.e. wet biomass harvested) were converted into total dry AG biomass by calculating stalk dry weight (assuming that harvested stalks usually comprise ~30% of dry matter) and including the proportion of trash dry weight (total dry biomass entails ~35% of trash and ~65% stalk) [32,33]. BG biomass was calculated based on a root: shoot ratio of 0.15 [34,35]. Carbon was assumed to be 44% of the dry biomass [36,37].

2.3.1.3. Forested area

To estimate the carbon stored in forest biomass, 5-6 forested areas (Miombo woodlands in Mozambique/Malawi and savannah woodlands in Swaziland) were sampled in each study site (except for BERL, Section 2.3). In each forested area, 20-25 sites were randomly selected and circular plots of 10 m diameter were established (plots were separated by at least 20 m). In each plot, the diameter at breast height (DBH) of all trees with DBH > 5 cm was recorded. All forested areas were adjacent to Jatropha or sugarcane fields to have a good approximation of the previous forest that was converted to feedstock.

In Malawi and Mozambique, stocks of carbon in AG and BG biomass were estimated using Ryan et al. [38] allometric equations for miombo woodlands [AG: ln(stem biomass carbon, Kg) = 2.6 * ln(DBH) - 3.63] [BG: ln(root biomass carbon, Kg) = 2.26 * ln(DBH) - 3.37]. In Swaziland, biomass per tree was estimated using the allometric model developed by Nickless et al. [39] for broad-leafed South African trees, applying the correction factor suggested by Colgan et al. [40] [ln(stem biomass) = - 3.47 + ln(DBH) * 2.83 + 0.06]. As Nickless et al. [39] allometry cannot be applied for tree diameters greater than 33 cm, we applied a generic allometric model in such cases [41,42]. The carbon fraction in dry wood was considered to be 50% [43,44], and the root: shoot ratio 0.56 (if AG biomass < 20 t ha^{-1}) or 0.28 (if AG biomass > 20 t ha^{-1}) [45,46].

In Malawi and Swaziland, forested areas were divided into low- (AG biomass carbon < 10 t ha^{-1}) and high- (AG biomass carbon > 10 t ha^{-1}) density forest, according to the land cover classification (Section 2.2). In Mozambique, all forested areas sampled had AG biomass carbon > 10 t ha^{-1} and were thus classified as high-density forests.

2.3.1.4. Agricultural land

All land identified as 'other agricultural' land was assumed to be maize, the dominant staple crop in all study sites, and southern Africa in general [47]. Maize yield estimates were obtained through FAO latest reports on Crop & Food Assessments for Mozambique [48] and Swaziland [49]. Since these reports were not available for Malawi, maize yields were directly obtained from the Agriculture Development Office in Nkhotakota district (2014 yields). Maize yields were converted to AG carbon stocks assuming a harvest index of 53% and a carbon content of 45% in the dry matter [50]. BG biomass was calculated considering a root: shoot ratio of 0.19 [51].

2.3.1.5. Grassland

We estimated AG biomass in grasslands by averaging the biomass values reported for African grasslands (between 1 and 7 t ha^{-1}, from open to closed grasslands) [52]. BG biomass was calculated considering a root: shoot ratio of 1.89 [46], and the carbon mass fraction was assumed to be 47% of the dry biomass [45].

2.3.2. Soil organic carbon (SOC)

In each study country, SOC was measured in 5-6 Jatropha/sugarcane fields and 5-6 adjacent forests. In each forested area or feedstock field, three samples were analysed for total organic carbon through the Walkley & Black method [53]. Each of these samples was obtained by combining 4 subsamples from the upper 20 cm soil layer. In each sampled area, a core sampler was used to measure bulk density, which was needed to calculate SOC stocks in t ha^{-1}.

SOC in bareland, cropland and grassland was assumed to be 36%, 21.3% and 6.4% lower, respectively, than the SOC stocks reported in forested areas [54,55]. To estimate

SOC in mature Jatropha plantations, we assumed an increase of 20% compared to the SOC reported in the young Jatropha plantations in Mozambique (lower estimate extracted from Fig. 5.6 in Baumert [30]).

2.4. Carbon stock changes due to land use change in each study site

Monte Carlo simulations were used to assess the net changes in carbon stocks (including AG/BG carbon stocks and SOC) as a result of land conversion to sugarcane or Jatropha (considering a 20-year period). This approach incorporates the uncertainty associated with the estimates of carbon stocks and mitigates overconfident conclusions, as it is recommended in Chapter 3 of the IPCC Guidelines [45]. Input data to the Monte Carlo simulations were the area occupied by each land use prior and after each project started, and the distributions describing the carbon stored by each land use in each study site (for more information on the input data used to run these simulations see Table S2).

To parameterize each distribution, we followed IPCC guidelines for small data sets. If the coefficient of variation (standard deviation divided by the mean) was less than 0.3, we assumed a normal distribution; if higher than 0.3, we assumed a lognormal distribution [45]. Monte Carlo simulations proceeded by randomly sampling from each input distribution and computing the net carbon value as net carbon = current carbon stocks – previous carbon stocks. By repeating this process many times (n = 50000), we generated the distribution of net carbon values that can be expected given the estimates of carbon stocks and their associated uncertainty. Monte Carlo simulations were conducted using R, version 3.2.2 [56].

2.5. Carbon stock changes in biomass due to land use change under different scenarios

As a final step, we assessed how net carbon stocks change depending on the previous land use that is converted to biofuel crops (i.e. agricultural land, forest or a mix of both). For these simulations we only considered carbon stocks in biomass (AG and BG), as SOC highly influences the overall carbon stocks and it is highly variable both spatially and temporally (Section 3.2) [55,57–59].

To assess how net changes in biomass carbon stocks vary depending on the previous land use that is converted, we imposed a land use transition model on top of our Monte Carlo simulations. This model considered that a hypothetical area of 100 km^2 of forest or agricultural land is to be converted to sugarcane or Jatropha. We started considering that all 100 km^2 were agricultural land, and at each step (i.e. scenario) we transferred 40 ha of agricultural to forested land. In total, we completed 250 transfer steps, defining 250 different previous land use scenarios, with the final scenario being that all 100km^2 were forested land. For each individual scenario we ran Monte Carlo simulations (n = 10000 per scenario) to estimate net changes in biomass carbon stocks due to land conversion to sugarcane or Jatropha.

The biomass carbon stocks considered for these simulations were the highest estimates found for each land use in our study sites. Therefore, for forest, agriculture and sugarcane we took the carbon stocks estimated for Malawi, as these estimates were higher than in Mozambique and Swaziland (Section 3.2, Table 2). For Jatropha, we assumed average carbon values during a 20-year rotation. More information on the input data used to run these simulations can be found in Table S3.

3. Results and discussion

3.1. Land use change

Fig. 1 shows the previous and current land uses of the area currently occupied by the Jatropha and sugarcane projects studied. Results suggest that the previous land cover at the commercial sugarcane plantation in Malawi (Illovo) and at the commercial Jatropha plantation in Mozambique (Niqel) was mainly forested land. By contrast, in Swaziland, the previous land cover of both the commercial sugarcane plantation (RSSC) and the smallholder sugarcane scheme (SWADE) was a mixture of agricultural and forested land.

The land use change that occurred in the smallholder Jatropha project in Malawi was not directly assessed as it was not possible to distinguish Jatropha hedges in the satellite imagery due to their small size (Section 2.2; Fig. S4). However, information provided by the company that incentivised and assisted the smallholders to adopt Jatropha (BERL), and household surveys (performed in September 2014), allowed us to estimate that ~40000 Jatropha trees were planted throughout the Mangochi area (~800 farmers planted an average of ~50 trees each farmer). Assuming that each Jatropha tree occupies 2.1 m^2 (based on our own measurements in the study site), we estimated that Jatropha trees occupy ~8.5 ha spread across approximately ~60000 ha in the study area (see Fig. S4). As BERL only promoted Jatropha as a boundary crop around agricultural fields and homesteads [26], we assumed that the previous land use of the calculated ~8.5 ha was agricultural land. This is similar to what we observed in other areas of Malawi, where Jatropha is grown around agricultural fields using the same production model [60]. Overall, the land use change that occurred in this study site is minimal compared to the land use changes observed in the other study sites, and thus it cannot be shown in Fig. 1 as 8.5 ha would be imperceptible compared to the areas of the other study sites (1800-45000 ha).

<<Figure 1>>

Fig. 2 shows the land use change that occurred in the surrounding areas of each study site, in a comparable area to Fig. 1 (Section 2.2)[1]. The results suggest that by and large outside all project areas, forested land decreased while agricultural and bare land increased. Although it is very challenging to establish causality, land use change patterns occurred in the surroundings of biofuel projects can be potentially influenced by the projects themselves. This is because biofuel projects can displace farms that are subsequently allocated elsewhere in the area, or attract population due to direct employment and secondary job creation [61,62]. Both these mechanisms have been observed, for example, around the Jatropha plantation (Niqel) in Mozambique [60].

[1] The smallholder Jatropha project in Malawi (BERL) is not shown for the same reason as stated above

If Fig. 1 and Fig. 2 are compared, it can be clearly observed that the land use changes observed in the surroundings of the projects are minimal compared to the direct land use changes that occurred within the project boundaries. Figs. S1-S3 (supplementary material) provide a visual representation of the land use changes occurred in each study site.

<<Figure 2>>

3.2. Carbon stocks

Table 2 shows the estimated carbon stored in AG and BG biomass and SOC in each land use and for each country studied. It should be noted that while the same carbon stocks were estimated for the smallholder project (SWADE) and the industrial plantation (RSSC) in Swaziland, as they are adjacent in the same area (Section 2.3), their impact on carbon stocks will not be the same (Section 3.3), as the land converted to sugarcane differs (Fig. 1). The carbon stocks associated with the smallholder Jatropha scheme (BERL) in Malawi are not shown in the table because the carbon stocks associated with this study site were not directly measured (Section 2.3).

Overall, the values obtained are similar to those reported by other studies for miombo woodlands [38,63,64], South African savannahs [65,66], sugarcane in Brazil [67] and Jatropha [30,58,68].

Forested land was divided into low- and high-density forest in Swaziland and Malawi due to large differences in forest biomass. These differences are most probably caused by the unsustainable extraction of wood for energy purposes. While low-density forests appeared to be heavily cleared for firewood and charcoal production, high-density forests were much less exploited most likely because they had some kind of protection (e.g. sacred groves or formally protected forests). In Mozambique, we did not observe these large differences in forest density and all sampled forests in the study area were classified as high-density forest. Forests in the Mozambique study site were less exploited probably because of its much lower population density (24 people km^{-2} in Sofala region) compared to Malawi (71 people km^{-2} in Nkhotakota district) and Swaziland (52 people km^{-2} in Hohho and Lubombo districts) [69].

In each study site, the highest amounts of stored carbon were found in high-density forests, followed by sugarcane and Jatropha. Our data shows that carbon stocks in AG biomass are higher for sugarcane than for Jatropha, probably due to the high planting density of sugarcane and the low density of Jatropha wood [70]. If a 20-year rotation period is considered, sugarcane stores an average of ~21 t ha^{-1} of AG carbon, while Jatropha stores ~13 t ha^{-1} on average. It is important to highlight that while the sugarcane estimates reported here are based on field data, the values reported for Jatropha on the carbon stored during a 20-year rotation are only estimates. This is because we could not find any measured values on Jatropha plantations older than 6 years in southern Africa, given the short history of the crop and its widespread collapse across the region [5]. Therefore, these estimates are only indicative and will vary depending on climatic conditions [28] and management practices such as pruning [68].

<<Table 2>>

Although carbon stocks in AG biomass are higher for sugarcane than for Jatropha, when total carbon stocks (including SOC) are considered, Jatropha in Mozambique appears to have higher carbon stocks than sugarcane in Swaziland, due to the substantially lower values of SOC in Swaziland. Changes in SOC highly influence the overall carbon stocks not only for sugarcane and Jatropha, but for all land uses as SOC is generally the main carbon pool. This is consistent with other studies in the region [20,38]. The impact of SOC on the overall carbon stocks is even higher for land uses with little biomass, such as low-density forests, grasslands and agricultural land, where SOC represents more than three quarters of all the estimated carbon stocks. Finally, bareland is the land cover that stores the lowest amount of carbon, with carbon present mainly in the soil (Table S2 shows carbon stocks considered for bareland in each site).

3.3. Carbon stock change due to land use change

Fig. 3 represents in a boxplot the output distributions from the Monte Carlo simulations used to estimate the net changes in carbon stocks as a result of land conversion to sugarcane and Jatropha in each study site. Negative values on the Y-axis indicate that the model predicts carbon debts, while positive values indicate carbon gains. Overall, in the sugarcane study sites, most predicted values of carbon stock changes were positive, indicating carbon gains due to land use change. These carbon gains are the result of growing sugarcane on land previously covered by low-density forest and agriculture (Fig.1), land uses that were found to store less carbon than sugarcane (Table 2). To our knowledge, while some studies have assessed the carbon impacts of sugarcane production in southern Africa [23,71], an assessment like the one presented here on net changes in carbon stocks due to actual land conversion to sugarcane was still missing in southern Africa.

<<Figure 3>>

Conversely, the results obtained from the two Jatropha sites differ significantly. Whereas in the smallholder scheme in Malawi (BERL) most predicted values indicated carbon gains due to land use change, in the plantation in Mozambique (Niqel) more than 75% of the predicted values were negative, indicating a carbon debt due to land conversion. These contrasting results reflect the fact that these two projects were established in areas with very different previous land uses. While in Malawi Jatropha trees were planted in the edges of agricultural fields [26], in Mozambique high-density forest was cleared to grow Jatropha. Bailis and McCarthy [68] also found contrasting results on carbon impacts due to Jatropha conversion in India and Brazil, depending on the type of forest converted. In sub-Saharan Africa, some studies have estimated the potential impacts of Jatropha expansion and also found that carbon debts are likely to occur if miombo forest is converted to Jatropha, whereas carbon gains can be expected if cropland is converted [19–21].

Finally, Fig. 4 shows how net changes in biomass carbon stocks (current carbon stocks in biomass minus previous carbon stocks in biomass) vary depending on the previous land use (agriculture/forests) that is converted to either Jatropha or sugarcane. Negative values on the Y-axis indicate carbon debts, while positive values indicate carbon gains. The X-axis represents the previous land use scenario considered for each case. For instance, the scenario at X = 0 implies that the previous land contained 0% of high-density forest (thus all previous land use was agriculture), whereas the scenario at X=50 considers that the previous land contained 50% of high-density forest and 50% of agricultural land.

The Monte Carlo simulations show that, if a sugarcane or Jatropha plantation is planned to be located in our study sites, more forested land could potentially be converted into sugarcane (30-44% of forest) than into Jatropha (24-32%) without creating carbon debts (ranges represent the 25th and 75th percentile of the simulations). This difference between sugarcane and Jatropha is due to sugarcane storing (on average) more carbon in its biomass than Jatropha (Section 3.2). It is important to note that these results are only indicative and should not be extrapolated to other study sites. Carbon stocks in AG and BG biomass for sugarcane, Jatropha and forests can significantly vary between regions and management practices such as irrigation, plant trimming and forest harvesting [28,68,72,73], and these variations will likely create different outcomes for Fig. 4 in other study sites.

<<Figure 4>>

Even though the results shown in Fig. 4 should not be generalized to other regions, the simulations presented here provide a novel approach to identify a rough threshold of the extent to which carbon-rich landscapes (e.g. forested areas) can be converted to feedstock production without compromising the provision of carbon sequestration services. Understanding such thresholds can be particularly useful to inform land use decisions, especially for biofuel projects that aim to export feedstock/biofuels to international markets that require mandatory GHG emissions savings such as those outlined in the European Union Renewable Energy Directive 2009/28/EC [74]. Such simulations could complement (or even be integrated in) Environmental Impact Assessments (EIAs) or other toolkits that promote sustainable biofuel production and use, e.g. Bonsucro [75] and the Roundtable on Sustainable Biomaterials RSB [76].

3.4. Research gaps and limitations

The purpose of this paper is to assess changes in the provision of carbon sequestration services due to land conversion to feedstock in southern Africa. We compare the amount of carbon sequestration services provided by the present land use (i.e. Jatropha or sugarcane) to the amount provided by the previous land use (i.e. agriculture, forest, grasslands). The data obtained could be used as the land-use change component of a life-cycle assessment (LCA), but it is beyond the scope of the present study to perform a complete LCA. Therefore, in this paper we do not consider what is done with the biomass after it is harvested. In order to quantify the potential reduction in GHG emissions from biofuels, a subsequent LCA analyses would need to factor in not only the land-use change component, but also how often the biomass is harvested (i.e. more often in sugarcane and agricultural areas than in Jatropha and forested areas), and what is done with it once harvested.

Another limitation of this study, shared with the vast majority of the literature assessing the impacts of biofuel expansion on carbon stocks, is the degree of uncertainty associated with SOC estimates. SOC is highly variable both temporally and spatially, and it can also be affected and altered by several management practices that disturb the soil, such as soil tillage and fertilizer use [55,57–59]. However, due to the difficulty in obtaining data representative of this range of variability, most studies that assess the carbon impacts of land use change due to biofuel crops, including this one, have an inherent degree of uncertainty associated with SOC estimates [19,21,58,68]. Considering that SOC tends to be the main carbon pool in most land uses, further research on this area can significantly decrease the uncertainties associated with carbon stock studies.

4. Conclusions

Our study shows that variations in carbon stocks associated with direct land use change can significantly affect the provision of carbon sequestration services provided by biofuel landscapes. Such land use change effects need to be taken into account when assessing the potential reduction of greenhouse gases emissions from biofuels as they can significantly impact biofuel life cycle assessments.

Our results indicate that sugarcane landscapes tend to store more carbon in biomass (AG and BG) than Jatropha landscapes. However, as soil organic carbon (SOC) is generally the main carbon pool, the overall carbon stocks will depend on SOC. We also show that in all sugarcane study sites, both industrial plantations and smallholder schemes created carbon gains as the previous land use (low-density forest and agriculture) stored less carbon than sugarcane. By contrast, the two Jatropha sites appear to have diverging results. While in the smallholder scheme (BERL, Malawi) carbon gains are observed as Jatropha was planted in the edges of agricultural fields, carbon debts were created in the Jatropha plantation (Niqel, Mozambique) due to the conversion of high-density forest.

Although the findings reported here relate to specific study sites, our data provide, for the first time, a broader insight into how carbon impacts due to land use change vary between sugarcane and Jatropha systems across southern Africa. Finally, even though in this paper we only focus on a single ecosystem service (climate regulation), broader trade-offs between different ecosystems services need to be considered when assessing the impacts of biofuel projects.

Acknowledgements

This work was supported by a research grant from the Ecosystem Services for Poverty Alleviation Program (ESPA; NE/L001373/1). The ESPA program is funded by the UK

Department for International Development (DFID), the Economic and Social Research Council (ESRC) and the Natural Environment Research Council (NERC). The authors are grateful to valuable assistance from Francis X. Johnson, Paulo Lopes, Davies Luhanga, Mike Ogg, Cleo Sherry, Shakespear Mudombi and Victor Matsebula.

References

[1] A. Gasparatos, G. von Maltitz, F.X. Johnson, L. Lee, M. Mathai, J.A. Puppim de Oliveira, et al., Biofuels in sub-Sahara Africa: Drivers, impacts and priority policy areas, Renew. Sustain. Energy Rev. 45 (2015) 879–901. doi:10.1016/j.rser.2015.02.006.

[2] G. von Maltitz, K. Setzkorn, A typology of Southern African biofuel feedstock production projects, Biomass and Bioenergy 59 (2013) 33–49. doi:10.1016/j.biombioe.2012.11.024.

[3] W.M.J. Achten, L. Verchot, Y.J. Franken, E. Mathijs, V.P. Singh, R. Aerts, et al., Jatropha bio-diesel production and use, Biomass and Bioenergy 32 (2008) 1063–1084. doi:10.1016/j.biombioe.2008.03.003.

[4] K. Openshaw, A review of Jatropha curcas: An oil plant of unfulfilled promise, Biomass and Bioenergy 19 (2000) 1–15. doi:10.1016/S0961-9534(00)00019-2.

[5] G. von Maltitz, A. Gasparatos, C. Fabricius, The rise, fall and potential resilience benefits of Jatropha in Southern Africa, Sustainability 6 (2014) 3615–3643. doi:10.3390/su6063615.

[6] B. Batidzirai, F.X. Johnson, Energy security, agroindustrial development and international trade: The case of sugarcane in Southern Africa, in: A. Gasparatos, P. Stromberg (Eds.), Socio-Economic Environ. Impacts Biofuels Evid. from Dev. Nations, Cambridge University Press, London, 2012: p. 389.

[7] F.X. Johnson, S. Silveira, Pioneer countries in the transition to alternative transport fuels: Comparison of ethanol programmes and policies in Brazil, Malawi and Sweden, Environ. Innov. Soc. Transitions. 11 (2014) 1–24. doi:10.1016/j.eist.2013.08.001.

[8] J. Fargione, J. Hill, D. Tilman, S. Polasky, P. Hawthorne, Land clearing and the biofuel carbon debt, Science 319 (2008) 1235–1237. doi:10.1126/science.1152747.

[9] R. Righelato, D. Spracklen, Carbon mitigation by biofuels or by saving and restoring forests?, Science 317 (2007) 902. doi:10.1126/science.1141361.

[10] T. Searchinger, R. Heimlich, R. Houghton, F. Dong, A. Elobeid, J. Fabiosa, et al., Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change, Science 319 (2008) 1238–1240. doi:10.1126/science.1151861.

[11] MA, Millennium ecosystem assessment: biodiversity synthesis, Washington, DC: Island Press, 2005.

[12] TEEB, The Economics of Ecosystems and Biodiversity (TEEB) Ecological and Economic Foundations, Earthscan, London and Washington, 2010.

[13] A. Gasparatos, C. Romeu-Dalmau, G. von Maltitz, F. Johnson, C. Jumbe, C. Ochieng, et al., Operationalising the ecosystem services approach for biofuel landscapes, Biomass and Bioenergy, *This issue*.

[14] A. Gasparatos, P. Stromberg, K. Takeuchi, Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative, Agric. Ecosyst. Environ. 142 (2011) 111–128. doi:10.1016/j.agee.2011.04.020.

[15] C. Joly, B. Huntley, L. Verdade, V.H. Dale, G. Mace, B. Muok, et al., Biofuel impacts on biodiversity and ecosystem services, in: G.M. Souza, C. Joly (Eds.), Bioenergy Sustain. Bridg. Gaps, Paris: Scientific Committee on Problems of the Environment

(SCOPE), 2015: p. 779.

[16] M.A. Meyer, T. Chand, J.A. Priess, Comparing bioenergy production sites in the southeastern US regarding ecosystem service supply and demand, PLoS One. 10 (2015) e0116336. doi:10.1371/journal.pone.0116336.

[17] A. Gasparatos, G. von Maltitz, M. Mathai, J.A. Puppim de Oliveira, K.J. Willis, Biofuels in Africa: impacts on ecosystem services, biodiversity and human well-being, Yokohama: United Nations University Institute of Advanced Studies, 2012.

[18] W.M.J. Achten, L. V. Verchot, Implications of biodiesel-induced land-use changes for CO2 emissions: case studies in tropical America, Africa, and Southeast Asia, Ecol. Soc. 16 (2011). doi:10.5751/ES-04403-160414.

[19] H.A. Romijn, Land clearing and greenhouse gas emissions from Jatropha biofuels on African Miombo Woodlands, Energy Policy. 39 (2011) 5751–5762. doi:10.1016/j.enpol.2010.07.041.

[20] L. Rasmussen, K. Rasmussen, T. Bech Bruun, Impacts of Jatropha-based biodiesel production on above and below-ground carbon stocks: A case study from Mozambique, Energy Policy 51 (2012) 728–736. doi:10.1016/j.enpol.2012.09.029.

[21] W.M.J. Achten, a. Trabucco, W.H. Maes, L. V. Verchot, R. Aerts, E. Mathijs, et al., Global greenhouse gas implications of land conversion to biofuel crop cultivation in arid and semi-arid lands - Lessons learned from Jatropha, J. Arid Environ. 98 (2013) 135–145. doi:10.1016/j.jaridenv.2012.06.015.

[22] W.M.J. Achten, K. Dillen, A. Trabucco, B. Verbist, L. Messemaker, B. Muys, et al., The economics and greenhouse gas balance of land conversion to Jatropha: the case of Tanzania, GCB Bioenergy 7 (2015) 302–315. doi:10.1111/gcbb.12160.

[23] E. Dunkelberg, M. Finkbeiner, B. Hirschl, Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions, Biomass and Bioenergy 71 (2014) 37–45. doi:10.1016/j.biombioe.2013.10.006.

[24] I. Maltsoglou, T. Koizumi, E. Felix, The status of bioenergy development in developing countries, Glob. Food Sec. 2 (2013) 104–109. doi:10.1016/j.gfs.2013.04.002.

[25] MNRE, Ministry of Natural Resources & Energy, http://gov.sz.dedi337.nur4.host-h.net/index.php?option=com_content&view=article&id=480&Itemid=361 (accessed February 5, 2016).

[26] S.D. Makungwa, A. Chittock, D.L. Skole, G.Y. Kanyama-Phiri, I.H. Woodhouse, Allometry for biomass estimation in Jatropha trees planted as boundary hedge in farmers' fields, Forests 4 (2013) 218–233. doi:10.3390/f4020218.

[27] ARCSI, Atmospheric and radiometric correction of satellite imagery (ARCSI), (2015). http://rsgislib.org/arcsi/ (accessed February 5, 2016).

[28] W.J. Achten, W.H. Maes, B. Reubens, E. Mathijs, V.P. Singh, L. Verchot, et al., Biomass production and allocation in Jatropha curcas L. seedlings under different levels of drought stress, Biomass and Bioenergy. 34 (2010) 667–676. doi:10.1016/j.biombioe.2010.01.010.

[29] S.B. Ghezehei, J.G. Annandale, C.S. Everson, Shoot allometry of Jatropha curcas, South. For. 71 (2009) 279–286. doi:10.2989/SF.2009.71.4.5.1032.

[30] S. Baumert, Life cycle assessment of carbon and energy balances in Jatropha

production systems of Burkina Faso, Bonn University, 2014.

[31] G. Reinhardt, K. Becker, D. Chaudhary, J. Chikara, E. von Falkenstein, G. Francis, et al., Basic data for Jatropha production and use, IFEU, CSMCRI and University of Hohenheim, 2008. http://jatropha.pro/PDF bestanden/en_jatropha-database-june-2008[2].pdf.

[32] J.E. Irvine, Sugarcane, in: M. Swaminathan (Ed.), Symp. Potential Product. F. Crop. under Differ. Environ., International Rice Research Insitute, Laguna, Philippines, 1983: p. 526.

[33] G. Thompson, The production of biomass by sugarcane, Proc. South African Sugar Technol. Assoc. (1978) 180–187.

[34] M. Ebrahim, O. Zingsheim, M. El-Shourbagy, P. Moore, E. Komor, Growth and sugar storage in sugarcane grown at temperatures below and above optimum, J. Plant Physiol. 153 (1998) 593–602. doi:10.1016/S0176-1617(98)80209-5.

[35] K. Anderson-Teixeira, S. Davis, M. Masters, E. Delucia, Changes in soil organic carbon under biofuel crops, Glob. Chang. Biol. Bioenergy. 1 (2009) 75–96. doi:DOI 10.1111/j.1757-1707.2008.01001.x.

[36] A. Youkhana, S. Crow, J. Kiniry, M. Meki, R. Ogoshi, M. Nakahata, Above and belowground biomass and C dynamics under ratoon and plant crop practices for biofuel feedstock production in Hawaii, 2014. https://scisoc.confex.com/scisoc/2014am/webprogram/Paper88702.html.

[37] I. Vallis, W. Parton, B. Keating, A. Wood, Simulation of the effects of trash and N fertilizer management on soil organic matter levels and yields of sugarcane, Soil Tillage Res. 38 (1996) 115–132. doi:10.1016/0167-1987(96)01014-8.

[38] C.M. Ryan, M. Williams, J. Grace, Above- and belowground carbon stocks in a Miombo wooodland landscape of Mozambique, Biotropica. 43 (2011) 423–432. doi:10.1111.j.1744-7429.2010.00713.x.

[39] A. Nickless, R.J. Scholes, S. Archibald, A method for calculating the variance and confidence intervals for tree biomass estimates obtained from allometric equations, S. Afr. J. Sci. 107 (2011) 1–10. doi:10.4102/sajs.v107i5/6.356.

[40] M.S. Colgan, G.P. Asner, S.R. Levick, R.E. Martin, O.A. Chadwick, Topo-edaphic controls over woody plant biomass in South African savannas, Biogeosciences. 9 (2012) 1809–1821. doi:10.5194/bg-9-1809-2012.

[41] J. Jenkins, D. Chojnacky, L. Heath, R. Birdsey, National scale biomass estimates for United States tree species, For. Sci. 49 (2003) 12–32. papers2://publication/uuid/7B59F802-5540-47E9-911D-98E70B38771B.

[42] M.S. Colgan, G.P. Asner, T. Swemmer, Harvesting tree biomass at the stand level to assess the accuracy of field and airborne biomass estimation in savannas, Ecol. Appl. 23 (2013) 1170–1184. doi:10.1890/12-0922.1.

[43] J. Roy, B. Saugier, H. Mooney, Terrestrial Global Productivity, Academic Press, San Diego, CA., 2001.

[44] Y. Malhi, T.R. Baker, O.L. Phillips, S. Almeida, E. Alvarez, L. Arroyo, et al., The above-ground coarse wood productivity of 104 Neotropical forest plots, Glob. Chang. Biol. 10 (2004) 563–591. doi:10.1111/j.1529-8817.2003.00778.x.

[45] IPCC, 2006 IPCC Guidelines for national greenhouse gas inventories, (2006). doi:10.1016/j.phrs.2011.03.002.

[46] K. Mokany, R. Raison, A. Prokushkin, Critical analysis of root: shoot ratios in terrestrial biomes, Glob. Chang. Biol. 12 (2006) 84–96. doi:10.1111/j.1365-2486.2005.001043.x.

[47] J.E. Cairns, J. Hellin, K. Sonder, J.L. Araus, J.F. MacRobert, C. Thierfelder, et al., Adapting maize production to climate change in sub-Saharan Africa, Food Secur. 5 (2013) 345–360. doi:10.1007/s12571-013-0256-x.

[48] FAO, Special report. FAO/WFP crop and food security assessment mission to Mozambique, (2010). http://documents.wfp.org/stellent/groups/public/documents/ena/wfp231421.pdf (accessed February 5, 2016).

[49] FAO, Special report. FAO/WFP crop and food security assessment mission to Swaziland, (2015). http://documents.wfp.org/stellent/groups/public/documents/ena/wfp277084.pdf (accessed February 5, 2016).

[50] Z. Qin, Q. Zhuang, M. Chen, Impacts of land use change due to biofuel crops on carbon balance, bioenergy production, and agricultural yield, in the conterminous United States, GCB Bioenergy. 4 (2012) 277–288. doi:10.1111/j.1757-1707.2011.01129.x.

[51] W. Zhang, K. Liu, J. Wang, X. Shao, M. Xu, J. Li, et al., Relative contribution of maize and external manure amendment to soil carbon sequestration in a long-term intensive maize cropping system, Sci. Rep. 5 (2015) 1–12. doi:10.1038/srep10791.

[52] A. Baccini, N. Laporte, S.J. Goetz, M. Sun, H. Dong, A first map of tropical Africa's above-ground biomass derived from satellite imagery, Environ. Res. Lett. 3 (2008) 1–9. doi:10.1088/1748-9326/3/4/045011.

[53] A. Walkley, I. Black, An examination of Degtjareff method for determining soil organic matter, and proposed modification of the chromic acid tritation method, Soil Sci. 37 (1934) 29–38.

[54] Y. Zhang, J. Liu, X. Jia, S. Qin, Soil organic carbon accumulation in arid and semiarid areas after afforestation : a meta-analysis, Pol. J. Environ. Stud. 22 (2013) 611–620.

[55] A. Don, J. Schumacher, A. Freibauer, Impact of tropical land-use change on soil organic carbon stocks - a meta-analysis, Glob. Chang. Biol. 17 (2011) 1658–1670. doi:10.1111/j.1365-2486.2010.02336.x.

[56] R Core Team, R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, 2015. https://www.r-project.org/.

[57] B. Minasny, A.B. McBratney, B.P. Malone, I. Wheeler, Digital mapping of soil carbon, 2013. doi:10.1016/B978-0-12-405942-9.00001-3.

[58] J. Degerickx, J. Almeida, P.C.J. Moonen, L. Vervoort, B. Muys, W.M.J. Achten, Impact of land-use change to Jatropha bioenergy plantations on biomass and soil carbon stocks : a field study in Mali, GCB Bioenergy 8 (2016) 443–455. doi:10.1111/gcbb.12288.

[59] J. Almeida, J. Degerickx, W.M.J. Achten, B. Muys, Greenhouse gas emission timing in life cycle assessment and the global warming potential of perennial energy crops

warming potential of perennial energy crops, Carbon Manag. (2015). doi:10.1080/17583004.2015.1109179.

[60] G. von Maltitz, A. Gasparatos, C. Fabricius, A. Morris, K.J. Willis, Jatropha cultivation in Malawi and Mozambique: Ecosystem services tradeoffs and their effect on local human wellbeing and poverty alleviation, Ecol. Soc., *Revised and re-submitted.*

[61] S. Kim, B.E. Dale, Indirect land use change for biofuels: Testing predictions and improving analytical methodologies, Biomass and Bioenergy 35 (2011) 3235–3240. doi:10.1016/j.biombioe.2011.04.039.

[62] M. O'Hare, M. Delucchi, R. Edwards, U. Fritsche, H. Gibbs, T. Hertel, et al., Comment on "Indirect land use change for biofuels: Testing predictions and improving analytical methodologies" by Kim and Dale: statistical reliability and the definition of the indirect land use change (iLUC) issue, Biomass and Bioenergy 35 (2011) 4485–4487. doi:10.1016/j.biombioe.2011.08.004.

[63] J.M.B. Carreiras, J.B. Melo, M.J. Vasconcelos, Estimating the above-ground biomass in miombo savanna woodlands (Mozambique, East Africa) using L-band synthetic aperture radar data, Remote Sens. 5 (2013) 1524–1548. doi:10.3390/rs5041524.

[64] N.S. Ribeiro, C.N. Matos, I.R. Moura, R. a Washington-Allen, A.I. Ribeiro, Monitoring vegetation dynamics and carbon stock density in miombo woodlands, Carbon Balance Manag. 8 (2013) 11. doi:10.1186/1750-0680-8-11.

[65] C. Marunda, H. Bouda, Environmental services from the dry forests and woodlands of SubSaharan Africa, in: E. Chidumayo, D. Gumbo (Eds.), Dry For. Woodlands Africa Manag. Prod. Serv., 2010: p. 288.

[66] C.M. Shackleton, R.J. Scholes, Above ground woody community attributes, biomass and carbon stocks along a rainfall gradient in the savannas of the central lowveld, South Africa, South African J. Bot. 77 (2011) 184–192. doi:10.1016/j.sajb.2010.07.014.

[67] W. Amaral, J.P. Marinho, R. Tarasantchi, A. Beber, E. Giuliani, Chapter 5: Environmental sustainability of sugarcane ethanol in Brazil, in: P. Zuurbier, J. Vooren (Eds.), Sugarcane Ethanol Contrib. to Clim. Chang. Mitig. Environ., The Netherlands: Wageningen Academic Publishers, 2008: p. 256.

[68] R. Bailis, H. McCarthy, Carbon impacts of direct land use change in semiarid woodlands converted to biofuel plantations in India and Brazil, GCB Bioenergy 3 (2011) 449–460. doi:10.1111/j.1757-1707.2011.01100.x.

[69] GeoHive, Global population statistics, http://www.geohive.com/ (accessed February 9, 2016).

[70] W. Achten, Sustainability evaluation of biodiesel from Jatropha curcas L . A life cycle oriented study, Katholieke Universiteit Leuven, Belgium, 2010.

[71] L. Mashoko, C. Mbohwa, V.M. Thomas, LCA of the South African sugar industry, J. Environ. Plan. Manag. 53 (2010) 793–807. doi:10.1080/09640568.2010.488120.

[72] P. Ciais, M.J. Schelhaas, S. Zaehle, S.L. Piao, A. Cescatti, J. Liski, et al., Carbon accumulation in European forests, Nat. Geosci. 1 (2008) 425–429.

[73] H.K. Gibbs, M. Johnston, J. a Foley, T. Holloway, C. Monfreda, N. Ramankutty, et al., Carbon payback times for crop-based biofuel expansion in the tropics: the effects of changing yield and technology, Environ. Res. Lett. 3 (2008) 034001.

doi:10.1088/1748-9326/3/3/034001.

[74] EU, Directive 2009/28/EC, European Parliament, 2009. http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028.

[75] Bonsucro, Bonsucro guidance for the production standard, 2014. http://bonsucro.com/site/wp-content/uploads/2013/02/Guidance-for-the-Bonsucro-Production-Standard-v4.0.pdf.

[76] RSB, Guidance on consolidated RSB EU RED principles & criteria for sustainable biofuel production, 2013. doi:file:///C:/Users/dops0523/Dropbox/OXFORD-from-2015/REFERENCES/BIOFUELS/POLICIES-LandIssues/RSB-Guidance-2013.pdf.

Figure captions

Fig. 1. Previous and current land uses of the areas occupied by the Jatropha and sugarcane projects studied.

Fig. 2. Previous and current land uses of the areas surrounding the Jatropha and sugarcane projects studied.

Fig. 3. Net changes in carbon stocks (including AG/BG biomass and SOC) as a result of land conversion to sugarcane (light grey) or Jatropha (dark grey) in each study site. Each box represents the interquartile range (IQR; difference between the 25^{th} and 75^{th} percentiles), the thick black line is the median, and the top and bottom whiskers indicate the highest values within the upper range (75^{th} percentile + 1.5 * IQR) and the lowest values within the lower range (25^{th} percentiles - 1.5 * IQR).

Fig. 4. Net changes in carbon stocks due to land conversion to sugarcane and Jatropha under different previous land use scenarios. The X-axis represents the proportion of previous land considered to be high-density forest (the remainder is characterized as agricultural land). The thick line is the mean obtained for each scenario, while the shaded area indicates the 25^{th} and 75^{th} percentiles.

Table 1. Description of the study sites. Project names stand for: BERL (Bio Energy Resources Ltd.); RSSC (Royal Swaziland Sugar Corporation Ltd.); SWADE (Swaziland Water and Agricultural Development Enterprise); EthCo (Ethanol Company Limited).

Table 2. Estimated carbon stocks in aboveground (AG) and belowground (BG) biomass, and soil organic carbon (SOC) for each land use in Malawi, Swaziland and Mozambique (Mean ± SD).