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Research paper

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

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A B S T R A C T

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.

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 bio-ethanol) [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

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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].

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 (~10,000 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

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