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The Biofuel Debate – Status Quo and Research Needs to Meet Multiple Goals of Food, Fuel and Ecosystem Services in the Tropics and Subtropics

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Abstract

The current biofuel debate is characterized by concerns about the environmental effects of large-scale biofuel plantations, controversies about GMO-based feedstocks and the recent global food crisis. Predictions for the development of the biofuel sector are either departing from the supply-side or the demand-side, but are mostly based on modelling efforts with an unclear experimental basis and only broadly defined economic settings. Results vary widely and tend to undervalue technical progress in processing efficiency or management-related increases in biomass yields. Moreover, calculations often neglect the impact of climate change, the need for irrigation and processing water, for soil fertility maintenance and the importance of socio-economic issues. Against these shortcomings and in view of several decades to centuries of Ecosystem Carbon Payback Times of most biofuel plantations, their future as a large-scale replacement for hydrocarbons will strongly depend on improved matter conversion efficiencies and successful prevention mechanisms for conflicts over land use.

Keywords: Carbon fixation, Ecological Carbon Payback Time (ECPT), Land ownership, Marginal lands, Water use

1 Introduction

To curb the consequences of the global rise in $\mathrm{CO_2}$-levels and other greenhouse gases resulting from the burning of hydrocarbons and of high crude oil prices worldwide, within the last decade large-scale efforts have been undertaken to better use and further explore the potential of plant-based biofuels in partly replacing fossil energy carriers. Rising food prices culminating in 2007/2008 with widespread social unrest in poor countries of Africa and SE-Asia have reminded political decision makers and scientists of an apparently underestimated dimension of the biofuel debate. Existing concerns about the environmental effects of large-scale biofuel plantations such as sugar cane or soybean in

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Brazil and corn in the United States in combination with controversies about the use of GMO-approaches to increase production efficiencies were suddenly amended by the awareness of rapidly disappearing food stocks. To what degree this scarcity was only temporary, related to speculation and regional crop failure and may thus be overcome by increased investments in agricultural primary production to raise yield levels, or whether it is the consequence of a still growing world population combined with a change in consumption patterns (higher demand of livestock products) is still under debate. However, there now is ample evidence that in many cases biofuel plants do not grow for free on wastelands but directly or indirectly compete with food crops for the same resources such as land, water and nutrients. Focussing on tropical and subtropical countries, this paper tries to briefly summarize the *status quo* of the biofuel discussion and to raise questions for further discussion and definition of research priorities.

2 The contribution of biofuels to alleviate energy scarcity and reduce C-emissions: resource-focused and demand-driven assessments

The available reports on the potential of plant-based biofuels distinguish between resource-focused (supply-side) and demand-driven assessments (demand-side). Thereby the former papers focus on the extent of the total energy resources base and the competition between the different use(r)s of theses resources, such as starch for fuel production *versus* starch for food, or fuel (biomass) production *versus* conservation of soil carbon stocks (BERNDES *et al.*, 2003, Figure 1). The latter papers, in contrast, evaluate the competitiveness of biomass-based electricity and biofuels with fossile fuels, regardless of which type of biofuels are used. Most of these analyses are based on modelling efforts with an unclear experimental basis and only vaguely efined economic settings. Thereby the final outcomes vary widely and in most cases do not take into account technical progress in processing efficiency or management-related increases in biomass yields. In their evaluation of 17 such demand- and supply-side scenario studies BERNDES *et al.* (2003) forecasted a bioenergy potential of 47 - 450 $\times 10^{18}$J (EJ) yr^{-1} for the year 2050. For this time period HOOGWIJK *et al.* (2005), in their IPCC report-based[1] study, predicted that the largest contribution to biofuel energy (130 - 410 EJ yr^{-1}) will come from plants growing on 'abandoned' agricultural land (HOOGWIJK *et al.*, 2003) whereby, alternative uses of and possible conflicts from access rights to such lands are not considered.

Most of these scenario studies focus on forest plantations (pine trees and eucalypts) as the source of biofuel that widely vary in total surface area, followed by dung and cereal residues (BERNDES *et al.*, 2003). In this context it is assumed that 500 Mio ha of fuelwood plantations can be successfully established by 2050. In this the use of conventional plant breading and genetic engineering techniques to increase biomass production and conversion efficiencies to ethanol (e.g. metabolic engineering to increase lignocellulosic biomass biosynthesis) is thought to play a major role (SHOSEYOV *et al.*, 2003; YUAN *et al.*, 2008). It is evident that most of these estimates concerning future forest plantations are (overly) optimistic, emphasising technical feasibilities and neglect-

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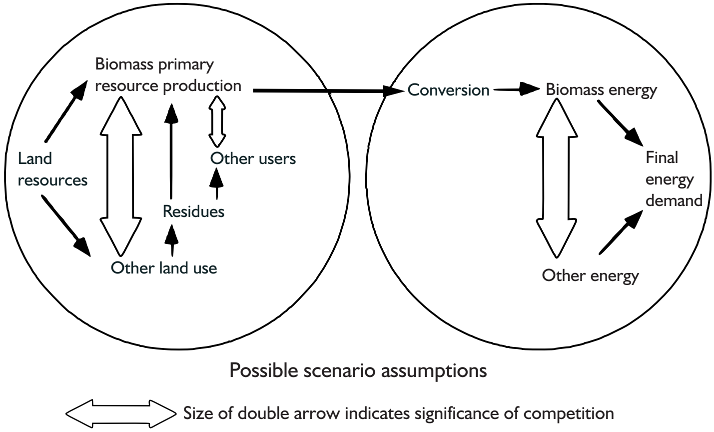
[1] IPCC Intergovernmental Panel on Climate Change; http://www.ipcc.ch/ipccreports/index.htm

ing socio-economic issues such as land use conflicts, timber forest expansions and the effects of climate change, forest conservation efforts and food-first policies.

Another potential and often overlooked constraint to plant-based biofuel production is the large-scale availability of irrigation water, as it is unlikely that all of the above mentioned plantations of trees or crops can indeed be productive on rainfed, low-fertility waste land (Berndes, 2002). In this context it is important to note that total water use per unit of biofuel energy gained not only comprises water required to fulfil evapotranspiration demands during plant production but also for processing steps such as fermentation and waste removal in ethanol production (Frings *et al.*, 1992) or evaporative cooling in power plants.

Less resource-driven and therefore perhaps more reliable seem the estimates of lignocellulose conversion based on crop residues which might reach 270 EJ yr^{-1} by 2100. This would correspond to 75% of the global commercial primary energy consumption in 2000 (Berndes *et al.*, 2003), but major technological breakthroughs are required to make lignocellulose conversion to ethanol economically feasible and operational at the required scale.

Figure 1: Diagram of the difference of demand-driven and resource-focused (supply side) assessments of the potential role of plant-based biofuels. Source: Berndes *et al.* (2003)



3 The likely impact of new technologies on global biofuel production

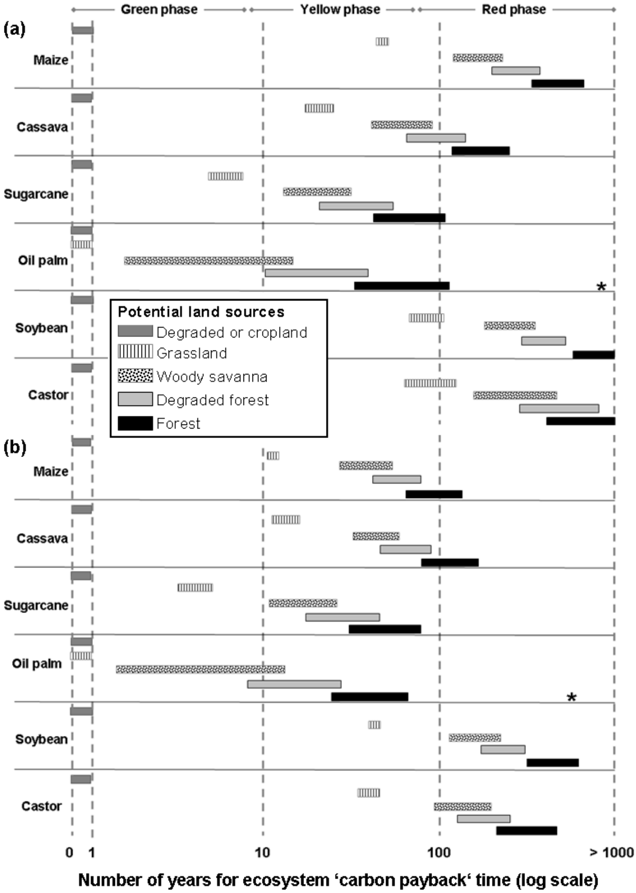
At present biofuels are produced on three pathways or 'platforms' that are ethanol, biodiesel and biogas. Estimated net energy balances vary from 150 - 550 GJ ha^{-1} yr^{-1} for lignocellulosic feedstocks such as poplar (*Populus* spp.), miscanthus (*Miscanthus sinensis*) or switchgrass (*Panicum virgatum* L.), from 10 - 300 GJ ha^{-1} yr^{-1} for ethanol production from maize (*Zea mays* L.), sugarcane (*Saccharum officinarum*), sugar beet (*Beta vulgaris* L.) or sweet sorghum (*Sorghum* L.) but are only -20 - 0 GJ ha^{-1} yr^{-1} for biodiesel production from soybean (*Glycine max* (L.) Merr.), canola (*Brassica napus* L.)

or sunflower (*Helianthus annuus* L.) (YUAN *et al.*, 2008). Among the latter, only sweet sorghum, which is fairly heat and drought tolerant, allows for dual purpose use (grain for food and stover for ethanol production). However, given the much higher biomass yields of switchgrass (10 - 25 t ha^{-1} yr^{-1}) and hybrid miscanthus (7 - 38 t ha^{-1} yr^{-1}; DANALATOS *et al.* (2007) which are even superior to those of poplar and only have a few months of lag time rather than years before harvesting, these two grasses appear to be very promising as biofuel crops. Given its perennial nature, miscanthus has even been used to decrease soil erosion and purify water, and it also contributed to increased diversity of small mammals, birds and invertebrates (SAMSON *et al.*, 2005; HILL *et al.*, 2006; TILMAN *et al.*, 2006; SEMERE and SLATER, 2007a,b). However, future industrial processing of both C_4-grasses for biofuel depends to a large degree on the success of breeding efforts to overcome recalcitrance (particularly due to lignin) and the effective decrease and/or breakdown of lignin. In this context successful genetic manipulation of enzymatic in planta breakdown processes in maize has received particular attention (BISWAS *et al.*, 2006) as well as genetically induced dwarfing (PENG *et al.*, 1997) and increased biomass production by delayed flowering (SALEHI *et al.*, 2005).

4 Food-fuel-ecosystem services: research questions from a system's perspective

One of the approaches to compare the effects of plant biofuel production with non-fuel plant growth and thus an important attempt to evaluate biofuel plant effects on landuse systems is the concept of Ecosystem Carbon Payback Time (ECPT). This consists in calculating the number of years it takes for the biofuel C savings from avoided fossil fuel combustion to offset the carbon losses in ecosystems used to grow those biofuels (FARGIONE *et al.*, 2008). There is evidence that the cultivation of biofuel plants on natural ecosystems such as rainforest areas or drained peatlands may release 17 - 420 times more CO_2 than is saved by the economization of fossil fuel (SEARCHINGER *et al.*, 2008). Based on geographically explicit crop yield data coupled with soil carbon stock data (MONFREDA *et al.*, 2008; RAMANKUTTY *et al.*, 2008), GIBBS *et al.* (2008) showed that decades to millennia of biofuel production would be required to compensate for C losses from cleared tropical rainforests with C stocks of $\sim$200 t C ha^{-1} (as compared to dry tropical forests with $\sim$100 t C ha^{-1}), using even the most effective plant species and processing techniques (maize, cassava or soybean 300 - 1500 yrs and oil palms 30 - 120 yrs on non-peat soils and $>$ 900 yrs in SE Asian peatlands; Figure 2). Depending on C stocks and mineralization patterns even the compensation of C losses on agricultural soils used for biofuel plantations may require several decades. Only the conversion of already degraded lands with low soil C stocks and limited C fixation into biofuel plantations may provide quick C payback, even if to achieve this irrigation and nutrient applications may become necessary (GIBBS *et al.*, 2008). It is obvious that ECPT values also depend on the biomass yields of the introduced biofuel plants; therefore paypack times for many African soils are much longer than elsewhere in the world, due to the predominance of very old, highly leached land surfaces with low productivity. These calculations only slightly change if future needs to partly rely on petroleum sources such as tar sands are considered, of which carbon balances are 17 - 30% lower than of crude oil (BERGERSON and KEITH, 2006; BRANDT and FARRELL, 2007).

Figure 2: Diagram of the ecosystem carbon payback time (ECPT) for potential biofuel crop expansion pathways across the tropics (modified after Yuan *et al.*, 2008). The bars represent the range of ECPT across the humid, seasonal and dry tropics for different combinations of land sources and biofuel feedstock crops. The green, yellow and red column descriptors represent a stop light - where green stands for 'go' in replacing degraded lands, yellow for 'caution' in replacing grasslands, woody savannas and red for 'stop' replacing forests for biofuel crop expansion.
(a) Shows the payback period for potential biofuel production based on crop yields of 2000 as reported in Monfreda *et al.* (2008). Note that '*' indicates the 918 year payback time if oil palm expands into peat forests. (b) Shows the potential payback period if all crops achieved the top 10% global yields through gradual or abrupt improvements in agricultural management or technology. Yield increases for crops such as maize, castor and rice have the largest impact on ECPT because these crops were substantially below global 90th percentile yields, while sugarcane, soybeans and oil palm were already high yielding so the change has a smaller impact. Note that '*' indicates the 587 year payback time if oil palm expands into peat forests.



Irrespective of ECPT calculations great care should be taken when planning to use large surfaces of 'abandoned land' or 'wasteland' for the production of biofuel plants. Not only does such land often have severe physical or chemical growth constraints for growing biofuel plants, but it may also be exposed to insecurity of tenure and competing uses for its naturally produced biomass by pastoralists whose flocks exploit such open grasslands but are not adequately considered in national and international assessments.

Further neglected constraints for the widespread cultivation of biofuel plants are scale-dependent, such as latent conflicts between large biofuel farmers and small tenants with their subsistence crops.

5 Conclusions

In the wake of increasing competition between biofuel plants and food crops for land, water and ultimately nutrients, the political future of biofuels as a large scale replacement for hydrocarbons will strongly depend on the availability of highly efficient processes for matter conversion into fuel, in particular for the lignocellulosic pathway. Also important will be effective mechanisms to avoid or reconcile conflicts of interest with alternative use(r)s for the land dedicated to biofuel plantations, mainly to avoid competition with plant or livestock-based (subsistence) food production. Finally, small ECPTs are needed to readily obtain positive C balances with biofuel plants as compared to the burning of hydrocarbons and to minimize the generally negative effects of biofuel plantations on (i) natural and agro-biodiversity, (ii) farmers' right to farm their own land for subsistence and (iii) ecosystem services such as carbon sequestration, availability of clean water, prevention of erosion and other effects of multi-dimensional landscapes.

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