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Biofuels and Ecosystem Carbon Balance Under Global Change

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1. Introduction

Terrestrial ecosystems are estimated to contain 3000 Pg of organic carbon (C) of which more than two thirds are stored in soils (Jobbágy and Jackson 2000). Total soil organic carbon (SOC) consists of different C pools with intrinsic turnover rates ranging from less than a year to thousands of years (Amundson 2001). The processes that drive the cycling of soil C are C inputs from net primary productivity (NPP=GPP-ecosystem respiration) and outputs through C decomposition (Fig. 1). New organic matter is the product of NPP which is transferred to soils in the form of litter and presents the largest C input to soils. Carbon output to the atmosphere is mainly driven by soil respiration (consisting of autotrophic and heterotrophic respiration) which is the second largest driver of C in the global C cycle (Fig. 1). Annually, soils release 98 ± 12 Pg C to the atmosphere which has increased yearly by 0.1 Pg C between 1989-2008 (Bond-Lamberty and Thomson 2010) and which yearly exceeds the current rate of fossil fuel combustion by a factor of 10. These large numbers show that even slight changes in the soil C and soil C cycling are highly relevant to the global C cycle mainly because of their potential to sequester or release CO_2 (Trumbore 1997). C sequestration denotes the transfer of C from atmospheric CO_2 into long-lived pools (e.g. woody biomass, recalcitrant soil C pools) without reemitting it immediately.

Although the soil is a dynamic system C input and output need to be balanced in order to keep the SOC pool at equilibrium (Fig. 2a). If C input is smaller than C output a depletion of the SOC pool occurs which can result in large releases of CO_2 to the atmosphere (Fig. 2b). On the other hand, if C input to the soil exceeds C output additional SOC can be sequestered in soils. SOC is not only an important C sink within the terrestrial C budget it also strongly influences soil fertility and soil quality which in return is needed for plant growth (Lal 2004; Cruse et al. 2010).

Global change denotes all human-caused changes to the atmosphere, hydrosphere, pedosphere and biosphere (Körner 2003). The increasing CO_2 concentration in the atmosphere is one of the most drastic global change components that directly affect plants and the ecosystems they live in (IPCC 2007). Secondary effects of higher CO_2 concentrations are climate warming causing tertiary effects such as extended growing seasons, shifts in species composition and alterations in precipitation patterns. Elevated CO_2 directly affects plants through photosynthesis and as photosynthesis at the current level of CO_2 concentration is not yet CO_2-saturated there is leeway for more carbon fixation and with it the possibility of more C storage in terrestrial ecosystems. On the other hand climate warming affects almost all aspects of carbon cycling and enhanced C fluxes potentially feed back to the atmosphere causing the so called positive feedback to climate change (Luo 2007).

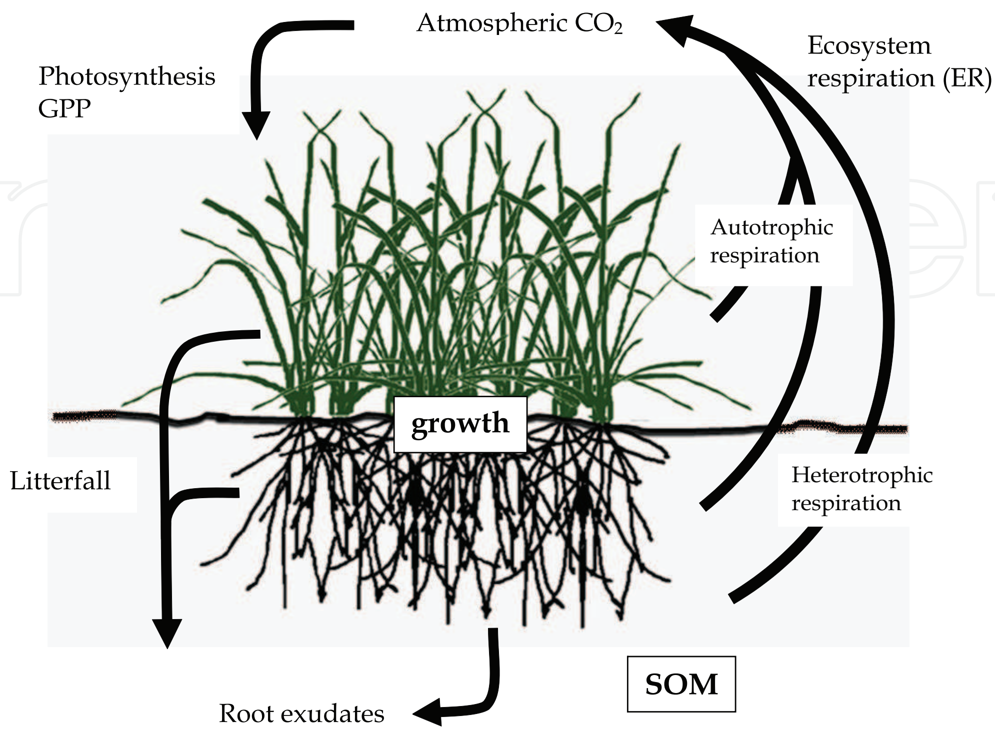

Fig. 1. Schematic diagram of terrestrial ecosystem C processes. GPP, gross primary production, SOM, soil organic matter

Identifying possible strategies for mitigating climate change by reducing increases in atmospheric CO_2 has put a strong focus on growing biofuel feedstock for alternative energy. Biofuels are generated through the combustion of biomass, usually grain or cellulosic-based feedstock. Biofuel feedstock production can help offset C emissions from fossil fuels but continuous biomass harvesting involves the removal of large quantities of C inducing a disequilibrium in the ecosystem's C balance (Fig. 2b; Luo and Weng 2011). There is thus an urgent need to investigate the impacts of biofuel feedstock harvesting on an ecosystem's C balance and its feedback to climate change (Luo et al. 2009)

This chapter focuses on key issues related to biofuel feedstock harvesting and ecosystem C balance under global change.

2. Terrestrial ecosystem C cycle

Carbon enters a terrestrial ecosystem through photosynthetic uptake (GPP=gross primary production) and is either incorporated into biomass, respired through ecosystem respiration (ER=autotrophic + heterotrophic respiration) or secreted into the soil via litter and root exudates (Fig. 1; Chapin et al. 2009). The main terrestrial ecosystem C cycling processes are photosynthesis and C decomposition and hence are the main components to calculate net ecosystem productivity (NEP=GPP-ER). Once C has entered the plant system it is allocated to above- and belowground tissues with the partitioning being strongly dependent on nutrient availability. The partitioning of C allocation within the plant influences how much C goes into aboveground biomass (leaves, stems) and how much enters the soil (coarse and fine roots). Belowground primary productivity can account for up to 33% of the annual net primary productivity (Jackson et al. 1997; Norby et al. 2004) which assigns roots an important role in the net ecosystem C balance. Dead plant material from above- and belowground litter is decomposed by microorganisms releasing CO_2 to the atmosphere and providing energy for microbial biomass growth. Microbial biomass together with organic residuals of dead plant material and dead microbes form the soil organic matter (SOM, Luo and Zhou 2006) of which carbon represents 50% by weight. C decomposition from short- and long-lived C pools is one of the most important factors in regulating terrestrial ecosystem C cycles.

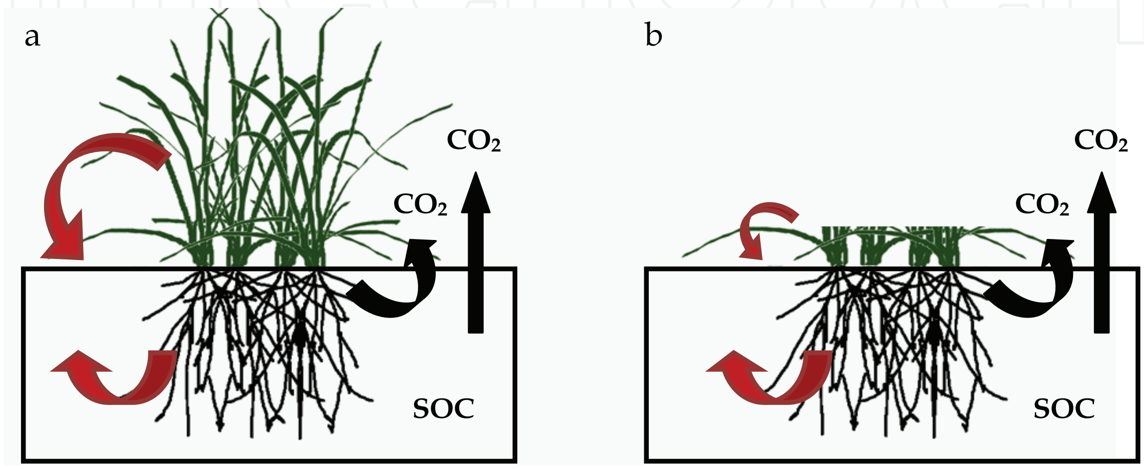

Fig. 2. Soil C dynamics for a) a natural grassland and b) a harvested field for biofuel feedstock. Red arrows represent C input to the soil and black arrows C output

3. Global change and C processes

Global change is one of the most important issues that this century is going to face. Global atmospheric CO_2 concentrations gradually increased from pre-industrial concentrations of 280 ppm to 390 ppm in 2011 (Mauna Loa, Hawaii; Tans 2011) and continue to increase, the main causes being deforestation, land use change and the burning of fossil-fuels (IPCC 2007). As a consequence to the increasing CO_2 and other green house gas concentrations in the atmosphere, global temperatures have increased by 0.74°C over the last century and predictions for the end of this century suggest a further increase in temperatures by another 1.1°C - 6.4°C (IPCC 2007). Temperature affects almost all chemical and biological processes (Shaver et al. 2000) and increasing global temperatures will likely enhance C fluxes between pools. As primary productivity and C decomposition are directly affected by changes in temperature ecosystem C uptake will be highly influenced by global warming. One of the major uncertainties of global warming is a possible positive feedback between the global carbon cycle and climate change but interactions among processes and fluxes are most uncertain making predictions difficult (Shaver et al. 2000; Luo 2007). Global change also includes altered precipitation regimes as a direct result to climate warming with a higher frequency in extreme events (rainfall extreme, drought) being very likely (IPCC 2007). Furthermore, human activities have increased the rate and magnitude of N deposition (Galloway et al. 2004) and since N availability strongly influence C processes future ecosystem C sequestration largely depends on N availability (Luo et al. 2004; Luo et al. 2006; Field et al. 2007). Global change includes various factors and their multiple interactions have smaller or larger impacts on ecosystem C processes and understanding those interactive effects on ecosystem processes becomes crucial in predicting possible carbon-climate feedbacks (Luo et al. 2008).

3.1 Impacts of global change on C processes

C influx through photosynthesis is stimulated by increased CO_2 concentrations (Curtis and Wang 1998; Norby et al. 1999; Ainsworth and Long 2005) often leading to increasing biomass growth but results are highly variable between species and plant age (Norby et al. 1999; Körner et al. 2005). Higher CO_2 concentrations could also induce higher C sequestration in soils (Jastrow et al. 2005; Lichter et al. 2005) but results strongly varied with CO_2 experimental facility, ecosystem type and N treatment (Luo et al. 2006). Highest C sequestration rates in soils were found in studies with N fertilization (Hungate et al. 2009) and most likely reflect effects of elevated CO_2 and N on plant growth as well as interactions between CO_2 and N on soil C decomposition (Reich et al. 2006). Increased soil C efflux under elevated CO_2 was reported from most CO_2-enrichment studies which was attributed to additional substrate from greater plant growth under elevated CO_2 available to soil microorganisms (Zak et al. 2000).

Increasing temperatures affect most biochemical processes such as C influx and C decomposition. Results are highly variable and range from no change, increases and decreases in photosynthesis, plant growth, primary production and soil respiration (Luo 2007). Generally, C decomposition reacts more to higher temperatures (Melillo et al. 2002; Zhou et al. 2007) than does C influx although the response of increasing soil C decomposition to warming attenuates over time (Rustad et al. 2001). The overall response of C decomposition to climate warming could be a net release of CO_2 from soils which might result in a positive feedback between C cycles and climate warming within this century (Friedlingstein et al. 2006). Furthermore, climate warming affects regulatory mechanisms of ecosystem C processes such as increased length of growing season, changes in water dynamics, species composition and nutrient availability (Luo 2007).

Precipitation patterns are changing in its frequency and intensity as a consequence of climate warming. Increased precipitation mostly increases C uptake via photosynthesis as well as increases soil respiration (Zhou et al. 2009). Drier conditions as they occur during heat waves reduce gross primary productivity and result in large net releases of CO_2 (Ciais et al. 2005; Arnone et al. 2008). This net release in CO_2 can offset C sequestration from previous years and turn ecosystems into C sources which will then contribute to a positive carbon-climate feedback. Besides the direct effects of increasing or decreasing water availability there are indirect effects of water availability through other climate change factors. Elevated CO_2 usually leads to less water loss through stomata (Medlyn et al. 2001; Leuzinger and Körner 2007) whereas a warmer climate increases evaporation leading to more negative water balances in the soil. As primary production in many ecosystems is largely limited by water availability any changes in precipitation will have substantial impacts on ecosystem C dynamics (Heimann and Reichstein 2008).

Nitrogen is one of the most limiting nutrients for plant growth (Vitousek and Howarth 1991) and N fertilization is widely used to improve plant productivity. N addition can increase plant growth by 30-50% although there are large differences between plant functional types and biomes (LeBauer and Treseder 2008; Xia and Wan 2008). Interactions between C and N cycles are important as N has the potential to sequester C when plant growth is not restricted by the lack of available N. Aboveground biomass is more stimulated by additional N availability than belowground biomass reducing C input to the soil (Lu et al. 2011). Litter quality usually increases with N addition which enhances decomposition of this high-quality litter (Knorr et al. 2005) causing less accumulation of C in the soil. Results on soil C storage under N addition are controversial and likely vary between natural ecosystems and agricultural ecosystems (Pregitzer et al. 2008; Liu and Greaver 2010; Lu et al. 2011). As climate change is a multi-factor process we need to investigate interactions between those climate change factors and expect dynamics that we cannot investigate by only looking at one factor.

4. Impacts of biofuel feedstock harvesting on C cycles

4.1 Biomass removal and SOC

Crop and plant residues (usually deriving from corn, barley, oat, sorghum, soybean, sunflower and wheat) are considered to be free products for biofuel production as they are left behind after harvest and seem not be of any use (Lal 2004). Plant residues are high-cellulosic feedstock (high concentration of cellulose and hemicelluloses) which are suitable for ethanol production but are not in direct competition to food compared to starch-rich biomass from grain. Complete biomass removal might impact soil quality, SOC content and soil water content more than a partial removal. The amount of corn stover (referring to all aboveground plant material such as stalk, leaves, cobs and husk) residue that can be removed without endangering SOC contents of soils was estimated to be 25% of total removal (Blanco-Canqui and Lal 2007). If more than 25% of corn stover was removed soils showed decreasing SOC contents.

Most biofuel feedstock derives from monocultures such as corn, soybeans, switchgrass or sugarcane and is grown on fertile soils. However, studies have shown that more bioenergy can be produced from switch-grass mixtures or high-diversity grasslands than from monocultures (Tilman et al. 2006; Wang et al. 2010). Studies have shown that even though aboveground biomass of high-diversity grasslands was removed annually soils still sequestered carbon. The full life-cycle of these high-diversity grasslands results in a net sequestration of atmospheric CO_2, which makes these high-diversity grasslands so called carbon negative biofuels.

The partitioning of C allocation within the plant influences how much C goes into harvestable biomass and how much enters the soil. Depending on the vegetation type of the biofuel feedstock C allocation strongly varies and influences the amount of C stored in soils. Root architecture and their vertical distribution contribute to soil C maintenance with less C stored in deeper soil layers. Deep soil layers though store the highest amounts of highly stable organic C compounds and are less affected by freshly added litter input. It was suggested that in the absence of fresh organic carbon input the stability of organic compounds in deep soil layers is maintained as the available energy required to breakdown recalcitrant SOC is not provided (Fontaine et al. 2007). Therefore biomass removal for biofuel production could protect deep soil recalcitrant C pools from decomposition.

Root systems play as much a role in the build-up and maintenance of SOC as does the amount of residue removed. Especially graminoids (to which most biofuel crops belong to) have larger ratios of belowground biomass to aboveground biomass and therefore allocate more C through belowground biomass to the soil than through aboveground biomass which gives them a higher C sequestration potential (De Deyn et al. 2008). It was even suggested that belowground biomass is more important for C sequestration than aboveground biomass as studies showed that changes in SOC pools positively correlated with the quantity of belowground biomass input but not with input of aboveground biomass (Russell et al. 2009; Lu et al. 2011). Balesdent and Balabane (1996) measured root-derived C in maize cultivated soils and found that although the shoot to root ratio was only 0.5 root-derived C was 1.5 times higher than aboveground-derived C (from stalks and leaves). Furthermore, root litter of grasses is of lower quality and therefore less easily decomposable compared to aboveground litter due to lower N but higher lignin concentration (Vivanco and Austin 2006). This higher recalcitrance of plant litter slows down the litter decay process and increases the amount of C stored in the soil (Sartori et al. 2006; Johnson et al. 2007).

4.2 Biofuel feedstock harvest and global change

The sustainability of biofuel feedstock harvest under global change needs to be evaluated in order to quantify changes in the net ecosystem C balance as well as assess a possible positive feedback to climate change. Biofuel feedstock harvest and the coherent changes in the C balance can be evaluated from experimental studies that use clipping or biomass harvesting to remove aboveground biomass (Luo et al. 2009). One study that combined the effects of climate warming and biomass feedstock harvesting on ecosystem C dynamics was conducted in the Southern Great Plains, USA, which is considered to be a major region for biofuel feedstock production (Luo et al. 2009). Temperatures were increased by 2°C and biomass was clipped annually. On average, data of nine years showed increased net primary productivity (NPP) under warming and even higher values in the combination treatment of warming and clipping. Although warming increased soil respiration rates clipping showed a decreasing trend in soil respiration. Yearly biomass removal reduced the C input to soils which was clearly demonstrated by higher losses of soil C in the clipped plots compared to the unclipped plots (Fig. 3). In both clipped treatments losses in soil C after nine years were more than twice as high as they were for the unclipped plots. Additionally, warming enhanced soil C loss resulting in the highest loss of soil C under clipping and warming treatment (Fig. 3). These results clearly show that biofuel feedstock harvest in combination with warmer temperatures results in the highest loss in soil C.

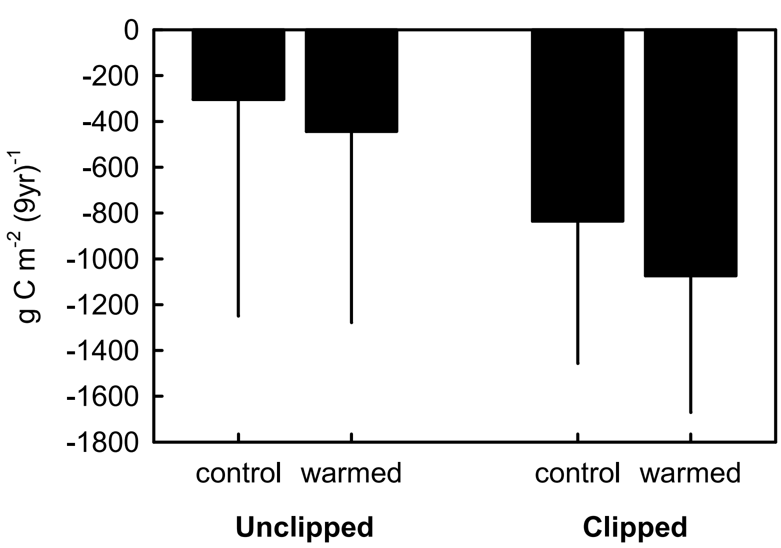

Fig. 3. Change in soil C content between 1999-2008. Values are means of 5 plots ± 1 se

4.3 Clipping-induced erosion under global change

Changes in land use through alteration of land coverage and disturbance of soil structure result in changes in soil moisture which can induce higher soil erosion rates (Lal 2004). Generally, plant coverage protects the soil from soil erosion by intercepting rainfall and runoff. Plant cover, plant height, rooting characteristics and other plant related parameters are important factors in reducing soil erosion rates (Wilhelm et al. 2007; Johnson et al. 2010). If aboveground biomass is removed for biofuel feedstock harvest more bare ground will increase temperatures as well as surface runoff and thus accelerate soil erosion (Schlesinger et al. 1990; Zuazo and Pleguezuelo 2008). Cover and type of vegetation can therefore affect soil erosion and potentially lead to a net source of C by soil erosion induced loss of SOC.

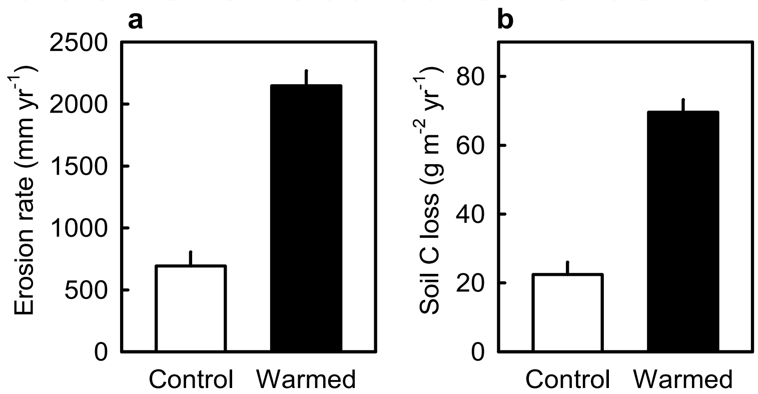

Fig. 4. a) Yearly erosion rate in the clipped subplots, b) yearly soil C loss in the clipped subplots. Values are means of 16 measurements per treatment ± SD. Redrawn with permission from *Global Change Biology Bioenergy*, Xue et al. 2011

It is well known that biomass removal on a continuous basis results in increased soil erosion but it is not well known how a warmer climate might amplify C loss from soils through erosion. The only study, we are aware of, that combines the effects of biomass removal and climate warming on soil erosion rates was conducted in a tallgrass prairie in the Southern Great Plains, USA (Xue et al. 2011). In a multiyear experiment (since 1999) grassland was warmed (+2°C) on a whole ecosystem-level and half the plots were clipped in order to mimic biofuel feedstock harvest. One side effect of warming was a reduction in soil moisture which was even greater in the clipped plots. Clipping-induced relative soil erosion rate was threefold increased under the warming scenario (Fig. 4a). These high erosion rates resulted in high losses of SOC (Fig. 4b). The stronger response to the warming treatment in the clipped plots was ascribed to lower soil moisture in the clipped plots as evaporation from the soil surface was increased when biomass was removed. Some of the consequences of higher erosion rates are reduced soil fertility, degraded soil structure and reduced SOC, all being enhanced by biomass removal. The soil that is most affected by erosional processes is the SOC-rich upper soil level making erosion a net source of C to the atmosphere (e.g. Lal 2003).

5. Interactive effects of biofuel feedstock harvesting and global change

5.1 Biofuel feedstock harvesting and NECB

Soils and their C stocks will be affected by land use change and by manipulations in the substrate supply but more importantly changes in the soil C budget will potentially affect the net ecosystem C balance (Fargione et al. 2008; Sanderson 2008; Luo et al. 2009) and consequentially contribute to the overall terrestrial C-cycle feedback.

Ecosystems can function as C sources or C sinks and their role in the global C cycle becomes even more important with global change as ecosystems either release or absorb atmospheric CO_2 and with it enhance or mitigate climate warming (Chapin et al. 2006). Net ecosystem production (NEP) is a measure of gross primary productivity (GPP) minus ecosystem respiration and mostly coincides with the net ecosystem C balance (NECB) unless C in other forms than CO_2 or dissolved organic C moves in or out of the system (Chapin et al. 2006; Lovett et al. 2006). Therefore, NECB is the net estimate of C accumulation (positive NECB) or C loss (negative NECB) in any system. If an ecosystem's net C balance is positive the ecosystem functions as a C sink by sequestering C. In contrast, a negative NECB implies C release to the atmosphere and any ecosystem showing a negative balance functions as a C source. NECB can be applied on short-term or long-term scales and to any spatial scale which makes it a very useful parameter for cross-scale comparisons (Chapin et al. 2006). To fully estimate the impact of biofuel feedstock removal on ecosystems under global change the net ecosystem C balance needs to be calculated to estimate a feedback of biomass removal to climate change. So far there are not many studies that measure the impacts of biofuel feedstock harvest on the net ecosystem C balance under global change. Nevertheless this is important as biofuels are supposed to help mitigate climate change by reducing CO_2 release from fossil fuels. But if biofuel feedstock harvest has large negative impacts on the net ecosystem C balance this mitigation strategy might not help reduce CO_2 release to the atmosphere.

5.2 NECB under elevated CO_2

Elevated atmospheric CO_2 generally increases above- as well as belowground biomass and also enhances soil C storage although the extent to which C is stored in soils is largely dependent on N availability (Luo et al. 2006). Belowground biomass often shows a higher response to elevated CO_2 therefore increasing C input to soils (Luo et al. 2006). C accumulation in plant and soil pools reflects increased C input into ecosystems that usually decreases litter quality and with it decomposability. Decreasing decomposability also derives from increased mycorrhizal growth under elevated CO_2 that enhances physical protection through formation of intra-aggregate or organomineral complexes to protect organic matter from microbial decomposition (Rillig 2004). Large fractions of the C accrued in soils under elevated CO_2 derive from increased belowground biomass growth which is not affected by biomass removal. Nevertheless there are some factors that need to be considered when making predictions about net ecosystem C balances for biofuel feedstock harvest under elevated CO_2. It is not yet clear whether there will be a down-regulation of CO_2 stimulation of photosynthesis and with it in plant growth and other C processes under persistent CO_2 stimulation (Long et al. 2004;). Photosynthetic acclimation was alleviated in grassland when plants were harvested but only under high N availability (Ainsworth et al. 2003). Low N conditions resulted in some acclimation of photosynthetic capacity. It seems that all responses of C processes under elevated CO_2 are strongly dependent on N availability. However, when only considering the global change factor elevated CO_2, biofuel feedstock harvest might still allow for C sequestration in soils resulting in a positive net ecosystem C balance.

5.3 NECB under climate warming

Unlike elevated CO_2 that primarily influences C uptake through photosynthesis warming affects almost all chemical and biological processes. Furthermore, warming involves some secondary effects on ecosystems such as extended growing seasons, change in species composition and drier conditions. Hence, it is not surprising that ecosystem warming experiments have produced inconsistent results regarding plant growth, soil respiration and net ecosystem production. Nevertheless the most important biomass fraction for C sequestration under biofuel feedstock harvest is the belowground biomass which was positively stimulated under warming and harvesting scenarios (Luo et al. 2009). This positive interaction was ascribed to over-compensatory mechanisms of plant physiological processes to biomass removal (Owensby et al. 2006). As belowground biomass growth is enhanced under warmer conditions the C loss through biomass removal might be less important for the net ecosystem C balance than the gain in C through increased belowground biomass. On the other hand continuous biomass removal increases soil erosion rates (Xue et al. 2011) which is accompanied by high losses of soil C. Even higher erosion rates occur when biomass removal takes place under warmer conditions as the soil dries out more easily leaving unstable soil structures favoring soil erosion. Therefore, biomass harvesting of natural grassland (Luo et al. 2009) in combination with warming resulted in a more negative net ecosystem C balance than for the warming treatment alone (Fig. 5). The more negative C balance is mainly due to high soil C losses (Fig. 4) as C input to soils was smaller than the C lost through CO_2 release and soil erosion. Thus, over-compensatory belowground biomass growth was not enough to offset soil C loss under warming and clipping. This long-term experiment shows that growing biofuel feedstock for harvesting under climate warming puts an additionally strain on the ecosystem C balance and does not help to sequester more C in order to reduce CO_2 release to the atmosphere.

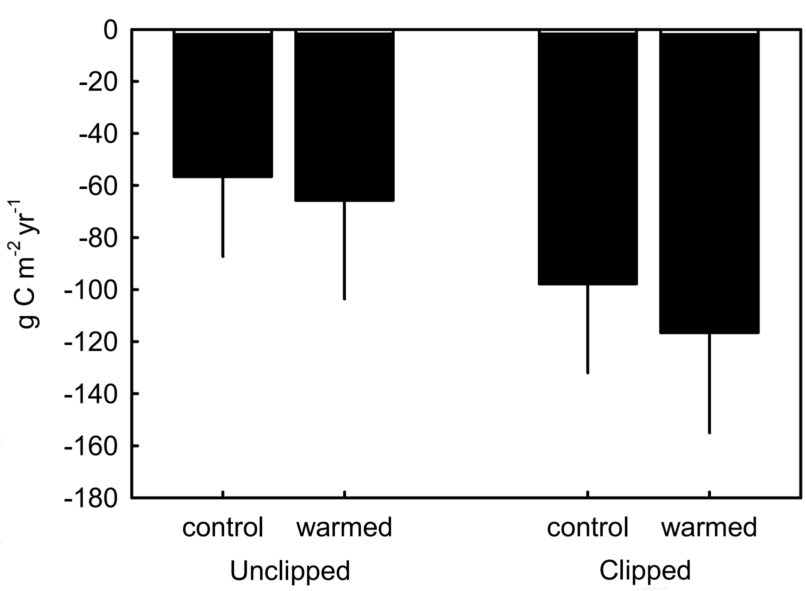

Fig. 5. Net ecosystem C balance calculated per year for the period of 2000-2008. Values are means of 6 plots ± 1 se

5.4 NECB and change in precipitation

Changes in precipitation as a consequence of global change include more frequent extreme precipitation and drought events which likely have large effects on ecosystem processes (Weltzin et al. 2003). Precipitation is an important factor in shaping ecosystem C dynamics as aboveground biomass and soil respiration linearly increase with mean annual precipitation but belowground biomass and soil C content remain rather constant (Zhou et al. 2009). As was shown for the Southern Great Plains in the USA no change in belowground C allocation is more important to the net ecosystem C balance than higher aboveground plant growth since this higher aboveground litter input was compensated by higher litter decomposition. A more positive net ecosystem C balance therefore seems plausible under wetter conditions. On the other hand warming induced drought suppresses net primary productivity and turns ecosystems into net sources of carbon dioxide (Ciais et al. 2005; Arnone et al. 2008). If additionally biomass is removed the net ecosystem C balance could become even more negative contributing more to a positive carbon-climate feedback.

5.5 NECB and N addition

N addition strongly influences ecosystem C processes through photosynthesis and biomass production and therefore has large impacts on the net ecosystem C balance. Generally N addition increases C input to soil through increased aboveground litter input (Liu and Greaver 2010). With higher N availability plants invest less C into belowground biomass as roots can more easily acquire N. Furthermore, higher N availability strongly influences the shoot to root ratio and root litter flux to soil decreases (Liu and Greaver 2010). If additionally C from aboveground biomass is not returned to soil due to biofuel feedstock harvest total C input to the soil will decrease and a negative net ecosystem C balance is very likely.

6. Conclusion

Growing biofuels for alternative energy can help mitigate increasing atmospheric CO_2 concentration; however continuous biofuel feedstock harvest will influence the whole ecosystem C balance possibly resulting in a positive feedback to climate change. Ecosystem C processes are strongly influenced by global change factors and their interactive effects are very complex and not yet well understood. An overall response of biomass feedstock removal on the net ecosystem C balance under global change is therefore still speculative but we know that global change factors that enhance root biomass have a more positive effect on the net ecosystem C balance when biomass is continuously removed than factors that enhance aboveground biomass. Increased CO_2 concentration in the atmosphere has the potential to increase belowground C storage especially when N and other nutrients are not limiting. Climate warming on the other hand seems to reduce soil C storage as C decomposition and C losses through soil erosion under biofuel feedstock harvest are higher. Responses to changes in precipitation are very variable but drier conditions result in a more negative ecosystem C balance if biomass is continuously removed. This effect could be neutralized again under elevated CO_2 as stomatal conductance and evapotranspiration decline thus decreasing the plant water use. N availability is a crucial factor for optimized plant growth and C storage but high N addition can also reduce belowground biomass and thus C input to soils. If additionally all biomass is removed there will be an even smaller C input into soil. One way to alleviate strong impacts of biomass harvest on C-cycling might be to harvest at a later time as harvesting after plant senescence showed to reduce C and N losses although biomass yield might be slightly lower (Heaton et al. 2009; Niu et al. 2010).
In conclusion, this chapter showed that biofuel harvesting has large impacts on the net ecosystem C balance which are likely enhanced under global change. More information on interactive effects of multiple global change factors is still needed to fully estimate the impacts of biofuel feedstock harvest on net ecosystem C balance and any possible feedback to climate change.

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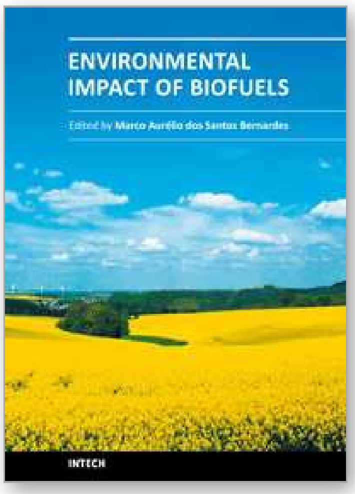

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This book aspires to be a comprehensive summary of current biofuels issues and thereby contribute to the understanding of this important topic. Readers will find themes including biofuels development efforts, their implications for the food industry, current and future biofuels crops, the successful Brazilian ethanol program, insights of the first, second, third and fourth biofuel generations, advanced biofuel production techniques, related waste treatment, emissions and environmental impacts, water consumption, produced allergens and toxins. Additionally, the biofuel policy discussion is expected to be continuing in the foreseeable future and the reading of the biofuels features dealt with in this book, are recommended for anyone interested in understanding this diverse and developing theme.

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