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BIOMASS & BIOENERGY

Short Communication

Neglected carbon pools and fluxes in the soil balance of short-rotation woody biomass crops

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ARTICLE INFO

Article history:
Received 29 August 2014
Received in revised form
25 November 2014
Accepted 4 December 2014
Available online

Keywords:
Bioenergy crop
Populus sp.
Weeds
Harvesting
Belowground biomass
DOC

ABSTRACT

The cultivation of dedicated bioenergy crops is being stimulated because of their potential to replace fossil fuels and to maintain or to sequester carbon (C) in the soil, and thus help to mitigate the rising atmospheric CO_2 levels. There are, however, still a lot of inaccuracies with regard to the dynamics of C in the soil, and thus with the potential to sequester soil C in these bioenergy crops. Using experimental data observed at the intensively monitored short-rotation woody crops (SRWC) plantation of the POPFULL project, we demonstrate that frequently neglected C pools and fluxes can be of crucial importance for the soil C balance. We highlight three specific cases. First, C inputs into the soil due to weed roots may equal or exceed those due to poplar fine roots, especially during the establishment phase of the plantation. Secondly, harvesting influences the dynamics of above- and belowground C inputs, as well as the soil environment. Large amounts of C are stored in the belowground woody biomass, which represents a long-term C pool. Thirdly, spatial differences related to the planting design are an important source of error in the upscaling of soil variables. We call upon researchers to consider and measure these neglected C pools and fluxes.

1. Uncertainties associated with the soil carbon balance of short-rotation woody crops

Agriculture for food production and forestry for timber production have been human activities since millennia. Historic improvements in technical, mechanical, biological and management processes have led to higher food and timber yields, and to a more efficient production. In contrast to traditional agriculture and forestry, the cultivation of crops for the production of biofuels is of a more recent nature [1]. The culture of biomass for biofuels still represents a small proportion of both the agricultural and the energy sectors, and it is only applied at a small scale. In this contribution we focus on the soil carbon (C) balance of short-rotation woody crops (SRWC) for the production of bioenergy. Some management practices are still under development due to the relatively recent introduction of SRWC (since the 1970's). For example, appropriate and sustainable weed management remains a major

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http://dx.doi.org/10.1016/j.biombioe.2014.12.002
0961-9534/

issue, especially during the establishment years of any SRWC culture. SRWC cultivation is now fully mechanised, from soil preparation, planting and management till harvesting. Most mechanization comes from agricultural machinery that has been adapted for SRWC, and so it is somewhere in between forestry and conventional agriculture.

Bioenergy is being stimulated because of their potential to replace fossil fuels and to maintain or sequester carbon (C) in the soil. These features might help to mitigate the rising atmospheric CO_2 levels, and thus global climate changes. The soil C, or the soil organic matter, is an essential component of soil fertility. To maintain – or to increase – soil C levels the soil depends on the input of crop residues. In bioenergy crops most of the organic C aboveground is removed for the production of biofuels. So the question remains: how can we reconcile the competing demands for organic C products for biofuels with the C for soil fertility and for sequestration? [2]. In SRWC the weed management and the harvesting operation affect the C cycle by affecting productivity, C inputs into the soil from weeds, from harvest losses. As for conventional agricultural crops [3], the efficiency of SRWCs for soil C sequestration is highly uncertain [4].

The C mass balance approach is a suitable and frequently used technique for understanding C cycling and for proposing management options for increasing C sequestration. This approach accounts for the balance of all C inputs into and all C outputs out of the soil. The soil C mass balance approach also allows to evaluate whether a system is losing or gaining C, and to identify the main fluxes. Although all C fluxes should be considered, only the most evident inputs and losses are generally considered in the soil C balance [5]. This limits our understanding of the dynamics of the soil C of SRWCs.

In this communication (i) we describe and we quantify the impact of different management processes on the soil C balance of an SRWC; and (ii) we identify the principal sources of error associated with the quantification of the soil C balance. We illustrate and document our analyses and suggestions with experimental data observed at the intensively studied SRWC plantation of the POPFULL project (http://uahost.uantwerpen.be/popfull/).

2. Study case

The operational POPFULL site is a large-scale (18.4 ha) SRWC plantation of twelve poplar (*Populus* sp.) and three willow (*Salix* sp.) genotypes planted in April 2010 in monoclonal blocks in a double-row planting scheme. The distance between the narrow rows was 75 cm and that of the wide rows was 150 cm. The distance between trees within a row was 110 cm, yielding an overall density of 8000 trees per ha. The plantation in East-Flanders (Belgium) was managed in two-year rotation cycles, for two rotations (four years in total; 2010–2014). Manual and chemical weed control was applied during the first rotation, and during the first year after coppice. Neither fertilization nor irrigation was applied during the entire lifetime of the plantation. Table 1 provides a synoptic summary of the documented results from the plantation.

3. Management processes affecting the C balance

3.1. *Presence of weeds*

In agricultural crops and in SRWC plantations, spontaneous annual vegetations below the canopy are considered unwanted [6]. This explains perhaps why weed production is rarely reported in studies on C balances. Weeds do have an important function within any agro-ecosystem. Aboveground, weeds compete for light [7] and belowground they compete for water and nutrients [8]. Weeds, however, also provide a high annual input of C into the soil, especially in the first rotation [Fig. 1; 9]. In our plantation weed root biomass and root productivity during the first rotation were more than two times higher than those of the fine roots of the poplar crop [9]. Aboveground, these weeds reached up to 1.5 m height and accumulated up to 300 g C m^{-2} in biomass. The planting of annual ‘cover crops’ in periods of non-growth has been proposed as one of the most promising strategies to offset the

Table 1 – Range of carbon fluxes for the quantification of the soil C balance and their sensitivity to the use of different genotypes, former land uses, planting scheme and harvesting machines. Values rounded to the nearest unit. [Values adapted from 9, 18, 24] SRWC = short rotation woody crop; DOC = dissolved organic carbon. POPFULL project (http://uahost.uantwerpen.be/popfull/). Sensitivity expressed as change in the mean: (–) not applicable, (*) 1–5%, (**) 5–30%, (***) >30%.

Flux of C	Range ($g\ C\ m^{-2}\ y^{-1}$)	Sensitivity			
		Genotype	Former land-use	Planting scheme	Harvesting machine
Litterfall	70–175	**	*	*	–
Harvest losses[a]	1–145	***	***	–	***
Weed aboveground biomass	170–290	**	***	–	–
Weed belowground biomass	15–26	**	***	*	–
Tree fine roots	3–30	***	***	**	–
DOC	7	**	*	–	–
Pool of C	($g\ C\ m^{-2}$)				
Aboveground biomass	1820–2950	**	*	–	–
Root biomass	180–360	**	*	**	–

[a] Only for the year of harvest. For the annual value, the number should be divided by the length of the rotation (two years).

Fig. 1 – Winter weeds during the second year of a short rotation woody crop (SRWC). Photo taken on 12 April 2011 at the POPFULL field plantation.

removal of C inputs from bioenergy crops [2]. Moreover, the weed root mass can influence the nutrient cycle of the system [10]. Annual weeds may thus have an impact on the establishment of the SRWC crop [8] and on its productivity [11], but they also play a relevant ecological role.

The assessment of aboveground productivity in fast-turnover plants, such as annual weeds, is rather easy. Harvesting the aboveground biomass is the most frequently used technique. It is fast and simple, and it requires few resources [12]. In contrast, the belowground biomass is not a directly observable characteristic and the estimation of belowground production is more complex. The determination of the annual belowground productivity is much easier in annual species than in woody plants. In annual weeds all belowground plant organs are produced yearly and the productivity can be estimated by directly sampling the belowground mass [13]. The most straightforward approach is to estimate belowground productivity using aboveground biomass data and a root:shoot ratio. As the soil C balance is very sensitive to the inputs from weeds [14] it is worth to quantify both above- and belowground biomass.

3.2. *Effects of harvesting*

Harvesting represents the highest costs for biomass yield [15–17]. The harvest efficiency should therefore be increased to reduce overall costs and to increase the competitiveness of biomass with other energy sources. Measurements on the POPFULL SRWC reflected that between 77.4% and 94.5% of the potentially harvestable biomass was actually harvested [18], compared to 64% for a switchgrass biofuel plantation [19]. Harvest losses include shoots and stems that are not harvested, as well as materials that are left at the site. This means that a large portion of the produced biomass was left at the site and this represented a high C input to the soil (Fig. 2). We observed that overall the inputs from harvest losses were as high as the fine root inputs [9]. With higher aboveground biomass production the C inputs from the harvest losses proportionally increased. This observation demonstrates that the harvesting operation has an effect on the C balance of the culture and should be properly quantified.

3.3. *Effect of plant spacing design*

High-density SRWC plantations often use a double-row planting design [20–22], which affects biomass production

Fig. 2 – Harvest losses. Cut biomass that was supposed to have been harvested, but remained on the field was considered as harvest losses and thus a C input to the soil. Photo taken one day after the first harvest of a short rotation woody coppice (SRWC) culture (February 2012).

and spatial distribution of C fluxes. In the double-row POPFULL plantation, fluxes of C in terms of litter-fall, root production and soil respiration measured in narrow rows and wide rows had different means and a different standard deviation [9,23,24]. Therefore, the samples had to be considered as belonging to different statistical populations, and each data set had to be processed separately. Large quantities of C were sequestered in the root biomass, with 173 g C m^{-2} in the narrow rows and 127 g C m^{-2} in the wide rows. Those spatial differences corresponded to the higher soil respiration measured in the narrow rows with respect to the wide rows [23]. Understanding the planting density and spacing as factors of variability helps to reduce uncertainties in quantifying the soil C balance.

3.4. *Additional environmental factors*

Concerning the impact of the dissolved organic C (DOC) and the hydrological cycle on the soil C balance, we found low levels of DOC in the water table [24]. Evapotranspiration rates of poplar SRWC are a bit higher than those of arable crops [25,26]. But this slightly higher water consumption is largely compensated by the higher groundwater quality achieved with the low-disturbance crop management of SRWC as compared to arable crops [27]. A similar comparison with regard to plant diversity indicates an increase of diversity if SRWC is planted in areas that are dominated by agriculture. Biodiversity in SRWCs is higher than in agricultural crops, but lower than in natural undisturbed sites, as has been demonstrated for invertebrates [28] and birds [29]. In short, SRWCs offer additional environmental services as compared to the culture of annual energy crops.

4. Final considerations and take-home messages

Across their full life cycle, biofuels can be C neutral (no net effect on atmospheric CO_2 and other greenhouse gases, GHG), C negative (a net reduction in GHG), or C positive (a net increase in GHG, or a source). This depends on how much CO_2 and other greenhouse gases – expressed as CO_2 equivalents – are removed from or released into the atmosphere during crop growth as well as on how much fossil CO_2 is released during management and transport [30,31]. Bioenergy production is expected to increase exponentially and biomass-for-energy will probably be harvested at larger scales in the future. The implications of the removal of this biomass on soil C pools and fluxes deserve attention. It has been recognized that SRWC cultivation on marginal lands can be a better alternative than bioenergy sources from agricultural crops [2,30]. Our results help to identify whether SRWC can be a C neutral source of energy. Our preliminary results showed a small C increase in the soil of an SRWC due to the large input of C by the weeds and the harvest losses.

. C inputs due to weed roots may equal or exceed those due to poplar fine roots, especially during the establishment phases of the plantation. Harvesting influenced the dynamics of above- and belowground C inputs, as well as the soil environment. Leaching of DOC represented a negligible component of the C balance.

In the selection of the appropriate SRWC management, the choice of the suitable genotype, the process of weeding and the efficiency of the harvesting process are all important for the soil C sequestration. Some C fluxes as weed inputs, harvesting losses and DOC are hardly considered in soil C balances. These C balance-related processes are usually considered negligible and difficult to quantify or to measure. We here demonstrated that they cannot be neglected and that they can be as important as other C fluxes (Table 1). The quantification of the soil C balance of SRWCs for bioenergy is necessary to evaluate its C sequestration potential.

Acknowledgements

This work was supported by the European Research Council under the European Commission's Seventh Framework Programme (FP7/2007-2013) as ERC Advanced Grant agreement # 233366 (POPFULL), as well as by the Flemish Hercules Foundation as Infrastructure contract ZW09-06. Further funding was provided by the Flemish Methusalem Programme and by the Research Council of the University of Antwerp. GB was supported by the Erasmus-Mundus External Cooperation, Consortium EADIC – Window Lot 16 financed by the European Union Mobility Programme # 2009-1655/001-001. We gratefully acknowledge the excellent technical, logistic and field support of the entire POPFULL team, especially Laura Broeckx and Melanie Verlinden for sharing data, and Nadine Calluy for laboratory analyses.

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