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Short Rotation Forestry (SRF) versus rapeseed plantations: Insights from soil respiration and combustion heat per area

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Abstract

Bioenergy crops may be an important contributor to mitigating global warming risks. A comparison between willow and poplar Short Rotation Forestry and rapeseed cultivation was designed to evaluate the ratio between soil respiration and the combustion heat obtained from the extracted products per hectare. A manual dynamic closed chamber system was applied to measure CO_2 emissions at the SRF and rapeseed sites during the growing season. Our results show that poplar and willow SRF has a very low ratio compared to rapeseed. We thus recommend poplar and willow SRF as renewable sources for bioenergy over the currently prevalent rapeseed production.

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Keywords: Soil respiration; manual dynamic closed chamber; SEMACH-FG; bioenergy crops; climate change mitigation

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Nomenclature

ha	10^4 m^2
t	10^3 kg
d.w.	dry weight
yr	year
MJ	10^6 joules
PAR	Photosynthetically active radiation
eq	equivalent

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1. Introduction

Fossil fuels are major contributors to the energy sector, despite their negative effects on the environment and their shortcoming as non-renewable resources. Bioenergy crops are being used to substitute fossil fuels in order to reduce greenhouse gas emissions and to mitigate global warming risks, in addition to other interests such as energy security [1, 2]. Many studies calculating the energy efficiency of biofuel from different bioenergy crops [3-10] did not include the flow of carbon associated with soil respiration. Alternatively it was assumed that the combustion-related CO_2-emissions are balanced by the amount taken up by plant growth. Carbon costs of the different activities, from field preparation to harvest, manufacturing and consumption materials (agro-chemicals) and machines, as well human labour, were included in the above-cited studies, however.

At present, energy and greenhouse gas-based life cycle assessment (LCA) of using bioenergy crops is lacking empirical data about soil GHG emissions and the soil carbon pool [11]. Thus, any LCA without consideration of these parameters will provide unreliable results on biofuel capability to save GHG as compared to fossil fuels. We focused on two bioenergy crops, rapeseed and SRF cultures. Rapeseed (*Brassica napus* L.) is an important and common bioenergy crop and considered the main feedstock for biofuel in Europe. Short Rotation Forestry (SRF) plantations consist of cultures of fast growing and high-yield clones of willow (*Salix sp.*) and poplar (*Populus sp.*). In Germany, more than 2 million hectares were under bioenergy crop cultivation in 2012; with more than 40% of this area occupied by rapeseed [12]. SRF occupies only about 4,000–5,000 ha with increasing tendency – an emerging crop [13].

Rapeseed crops require large quantities of nitrogen, and consequently receive higher rates of N-fertilizers than other annual crops [14]. The average amount of nitrogen added annually to rapeseed fields in the UK is 180–190 kg ha^{-1}; a maximum of 270 kg ha^{-1} was applied in 1983 [15]. Rapeseed is considered a sensitive crop to low pH values. Thus, liming is important to improve soil conditions by adding calcium carbonate or magnesium carbonate, which may additionally increase soil CO_2 emissions. SRF are less demanding than other bioenergy crops, e.g., the biomass productivity of non-fertilized willow SRF does not significantly differ from those receiving medium and high levels of N-fertilizers. Furthermore, the production of non-fertilized SRF showed the highest energy use efficiency as compared with other annual and perennial bioenergy crops [16].

The energy output from SRF products (woody biomass) and rapeseed products (rapeseed oil and cake) were compared in this study. In general, rapeseed straw is not used in energy production, and may be considered as field residue left on the soil surface [16]. Thus, rapeseed straw was not included in our calculations, similar to the neglect of leaf litter at the SRF site. About 2.5 t straw (d.w.) ha^{-1} yr^{-1} are produced at rapeseed fields [17] versus ca. 7.4 t leaf litter ha^{-1} on average over a four-year rotation at a willow SRF site (ca. 1.85 t ha^{-1} yr^{-1}; [18]). The aim of this study is a comparison between the cumulative seasonal CO_2 soil emissions per energy unit (MJ kg^{-1}) obtained from one hectare to assess the efficiency of the two sources of bioenergy. In addition, the CO_2 savings resulting from different land use has been estimated.

2. Materials and Methods

2.1. Site description

A 2-hectare site of willow and poplar SRF was established in 2005 by the Saxon State Agency for Environment, Agriculture and Geology (LfULG) on an arsenic (As) and other trace metal-contaminated soil in Krummenhennersdorf (~ 8 km N of Freiberg/Saxony; 50°58′ N 13° 20′ E; ca. 350 m asl). Two different poplar cultivars (Populus sp.), H 275 and Max 3, and the three willow (Salix sp.) cultivars Tora, Sven and Jorr with high planting densities (ca. 12,000 plant ha^{-1}) were studied. The rapeseed field was located only a few meters away from the SRF site (Figure 1).

Fig. 1. Left: Satellite view of Freiberg and the experimental site; Right: SRF and rapeseed fields

2.2. Field CO_2 flux measurements

One week before starting the measurements, ten PVC rings were placed at the SRF site and another three at the rapeseed site. Soil emissions were measured at each ring biweekly from April to October 2014 with a manual dynamic closed chamber system (SEMACH-FG; [19]). CO_2-fluxes were calculated by linear regression of the concentration versus time. For the SRF site, each plant type was represented by two measuring points. At each point, three individual measurements were done each time. The average emission rate was calculated from the average of the two points.

2.3. Environmental variables

Average monthly temperature and precipitation data were obtained from monthly statistics [20] (Figure 2). In addition, various meteorological parameters were registered during each measurement (soil temperature and soil moisture content, air pressure, air temperature and relative humidity, as well as PAR) through built-in SEMACH-FG sensors.

2.4. Calculations

The emitted amounts of carbon dioxide (kg ha^{-1}) from soils at the SRF and rapeseed sites were calculated for the entire observation period (April–October 2014). Combustion heat values (MJ kg^{-1}) for willow and poplar, as well average harvested biomass (oven dry tons ha^{-1} y^{-1}) from two rotations (harvested in 2008 and 2010) were calculated for each clone based on data by Dietzsch [21]. Average productivity and combustion heat values for rapeseed were obtained from Wcislo [22]. The CO_2 emission-energy ratio was calculated by dividing the cumulative seasonal CO_2 emitted from soil per hectare [kg CO_2 ha^{-1}] by the energy value obtained from each crop per hectare [MJ ha^{-1}] eq. 1.

$$= \frac{\mathrm{CE}}{\mathrm{productivity} \times \mathrm{combustion\ heat\ value}} \qquad (1)$$

3. Results and Discussion

During cold months (October to April), soil CO_2 emissions are generally rather low, because of low temperatures and resulting suppressed soil microbial activity (data not shown). Yet, minimum emission rates of CO_2 during the growing season were measured in June, in parallel to minimum differences between CO_2 emission at the SRF and the rapeseed field (Figure 2). The main reason behind this decrease in respiration rate was the low precipitation in June, even if temperature was relatively high (Figure 3).

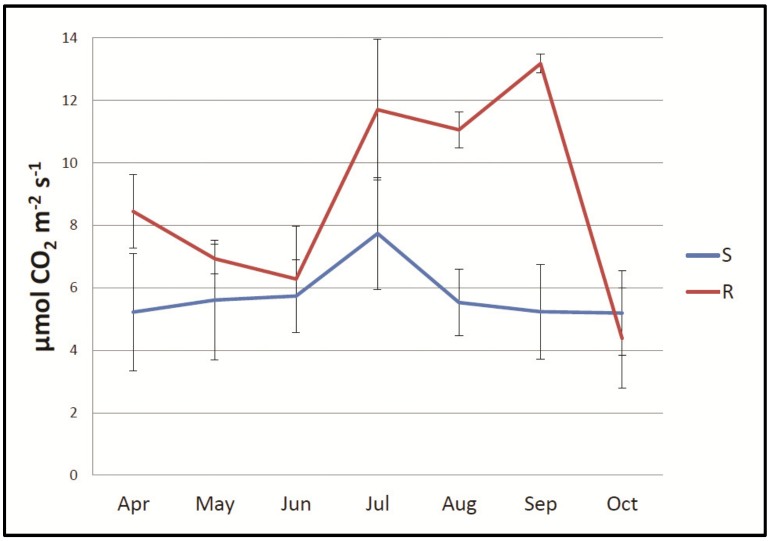

Fig. 2. CO_2 emission rates from soils under willow and poplar SRF (S) and rapeseed (R) plantations during the growing season 2014. Error bars represent two standard deviations.

3.1. Cumulative seasonal CO_2 emission (CE)

In order to compare the amount of CO_2 emitted from soil at different sites, soil CO_2 emission rates were transformed into cumulative emissions (kg CO_2 ha^{-1}) for the entire measuring period (April–October). The CE calculation was based on eq. 2 (after Li et al. [23]):

$$= \sum[(Fa + Fb) \times 5 \times 10^{-6} \times t \times 24] \quad (2)$$

The unit of CE is (t CO_2 ha^{-1}), Fa and Fb are the measured emission rates (mg CO_2 m^{-2} h^{-1}) for the same site at two subsequent days, and t is the number of days between the two measurements. Due to limited diurnal soil temperature fluctuations, it was assumed that the measured emission rate is the same for the entire day.

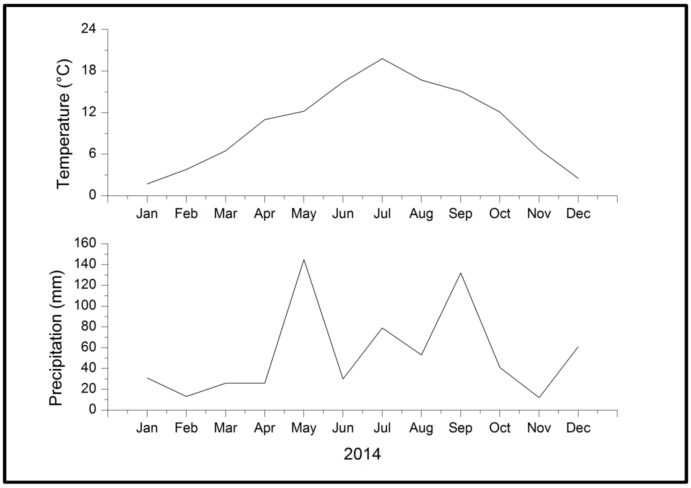

Fig. 3. Mean monthly precipitation and air temperatures at the SRF and rapeseed sites

Figure 4 shows a comparison between the cumulative seasonal emissions of CO_2 from the SRF and rapeseed soils. Fall and winter months are not included in this comparison, because soil respiration reaches its minimum under cold conditions and is close to no difference between the two sites (data not shown). The seasonal CO_2 emissions from the SRF site accumulate to 63% of the rapeseed site. Thus, about 24 t CO_2 can be saved annually per hectare, if the land was under SRF plantation instead of rapeseed. The normal lifetime of a SRF plantation is between 20–25 years before replanting new cuttings. Accordingly, around 480–600 t of CO_2 ha^{-1} can be saved during this period.

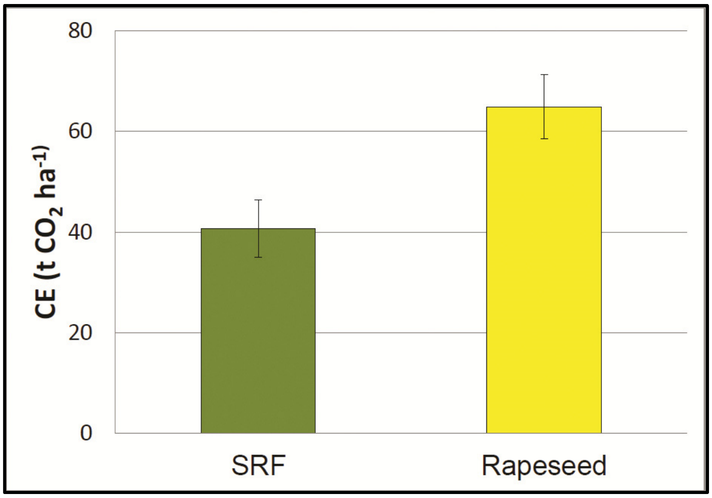

Fig. 4. Average cumulative CO_2 emission from the SRF and rapeseed sites (April–October 2014)

3.2. Output energy

The output energy was determined by multiplying the end product yield (DM woodchips/ rapeseed oil) by its caloric value. To estimate the ratio for willow and poplar woodchips, combustion heat values of 18.34 and 18.44 MJ kg^{-1} respectively were used [20]. Yet, average productivity and combustion heat value (1478.5±118.17 kg oil mass ha^{-1} and 38.9±0.54 MJ kg^{-1} respectively) were calculated from 14 different rapeseed cultivars [21]. Rapeseed cake is used to feed animals. Thus, metabolizable energy (ME) was used to estimate the contribution of rapeseed cake to the output energy with a value of 13.71 MJ kg^{-1} [24, 25]. Rapeseed mass will be allocated to its co-products rapeseed oil and cake; the allocation is assumed to be 40 and 60%, respectively.

3.3. $CO_{2(soil\ respiration)}$ / Energy ratio

The ratio of $CO_{2\ (soil\ respiration)}$ / Energy acts as an efficiency indicator for the extracted energy in terms of carbon dioxide; CO_2 emitted from soil divided by energy output. It appears to be a very helpful indicator to compare between different bioenergy crops, because it evaluates different elements; CO_2 emission from soils, combustion heat value of the products, and land area used for biomass production. In this case, energy ratio was estimated between the cumulative seasonal CO_2 emission as by-product of soil respiration (kg CO_2) to produce specific energy-crop and its combustion heat obtained from different forms of the extracted biomass (wood pellets and oil) per hectare (MJ ha^{-1}).

The average ratio between the emitted quantities of carbon dioxide from soil and the combustion heat obtained from the extracted products per hectare are shown in table 1. Clone H275 (poplar) has the lowest ratio, being the best clone from the energy extraction and CO_2 emission point of view, followed by Sven, Max 3, Jorr and Tora. In general, poplars showed lower average ratios than willows (157.8±12 and 199.9±31.3 kg CO_2 GJ^{-1} respectively).

The key message is that SRF has a lower average ratio than rapeseed (183.1±38.7 and 738.0 respectively). Short Rotation Forestry is about 400% more efficient than rapeseed (Figure 5).

Table 1. $CO_{2\ (\text{soil respiration})}$ emission-energy ratio

Plant	**Tora (Willow)**	**Sven (Willow)**	**Jorr (Willow)**	**H 275 (Poplar)**	**Max 3 (Poplar)**	**Rapeseed**
Soil CO_2 emission (kg CO_2 ha^{-1})	51,846.9	38,295.8	38,569.3	35,341.3	39,610.7	64,871.8
Production (kg ha^{-1}, L ha^{-1})	11,750	12,700	10,800	13,150	12,650	1,478.5 (oil) 2,217.7 (cake)
Combustion heat values (MJ kg^{-1})	18.34	18.34	18.34	18.44	18.44	38.9 (oil) 13.71 (ME-cake)
Combustion heat (GJ ha^{-1})	215.0	232.9	198.1	242.5	233.3	57.5 (oil) 30.4 (cake) 87.9 (total)
Ratio (kg CO_2 GJ^{-1})	240.6	164.4	194.7	145.8	169.8	738.0
Relative to rapeseed (%)	32.6	22.3	26.4	19.8	23.0	100.0

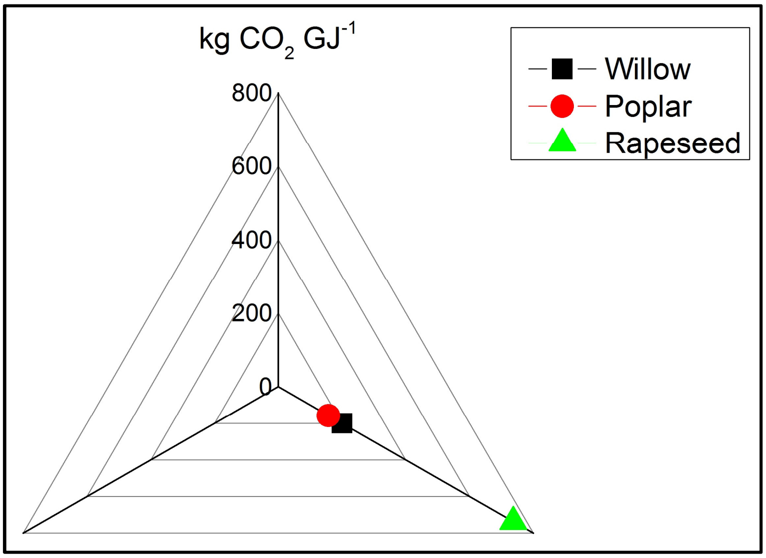

Fig. 5. $CO_{2\ (\text{soil respiration})}$ / Energy ratio for willow, poplar SRF and rapeseed

3.4. Global-warming potential (GWP)

It is possible to include other major GHGs to the estimation, namely N_2O and CH_4, using their global-warming potential (GWP). Thus, CO_2-eq will be calculated instead of CO_2. Nitrous oxide and CH_4 have 298 and 25 times higher GWP than CO_2, respectively, on a time horizon of 100 years [26]. Drewer et al. [27] reported that CH_4 emissions were very low and insignificant from SRF and rapeseed fields. Other authors like Hellebrand and Scholz [28] mentioned that the annual CH_4 emission at non-fertilized poplar and willow plantations were negative (atmospheric methane was degraded in the soil) and ranged between 0.25 and 1.00 kg CH_4 ha^{-1}. This value is relatively small and equal to -6.25 to -25 kg CO_2-eq. Therefore, CH_4 will be neglected in our calculations. The key parameter controlling N_2O emissions from soil is nitrogen availability. An exponential relation exists between Nfertilization and N_2O emission. Perennial bioenergy crops such as SRFs have higher nitrogen-use efficiency; they require less fertilizer and emit 40–99% less N_2O than conventional bioenergy crops such as rapeseed. Furthermore, rapeseed plants emit more N_2O than other cereal crops during the growing season and rapeseed soils show higher postharvest emissions than during the growing season because of their residues [14,29].

In our calculation of CO_2-eq, a value of 2.26 kg N_2O-N ha^{-1} yr^{-1} was used. This is the annual emission at a rapeseed field receiving a standard rate of N-fertilizers (200 kg N ha^{-1} yr^{-1}), as given by Walter et al. [14] from 43 sites. That value is equal to 1,058.3 kg CO_2-eq. For SRF, Zona et al. [30] measured N_2O emission during the second year after establishing a SRF on former fertilized-agricultural land. They reported 0.42±0.17 Mg CO_2-eq ha^{-1}, which was used in our calculation and is equal to 429 kg CO_2-eq ha^{-1}. For new results with CO_2-eq using the GWP see table 2.

Table 2. Greenhouse gas emissions and net global warming potential from soils under SRF and rapeseed cultivations

Plant	Tora (Willow)	Sven (Willow)	Jorr (Willow)	H 275 (Poplar)	Max 3 (Poplar)	Rapeseed
Soil GHG emissions (kg CO_2-eq ha^{-1})	51,846.9	38,295.8	38,569.3	35,341.3	39,610.7	64,871.8
Ratio (kg CO_2-eq GJ^{-1})	243.1	166.3	196.9	147.5	171.6	750.1
Relative to rapeseed (%)	32.4	22.2	26.2	19.7	22.9	100.0

4. Conclusions and Recommendations

GHG emissions from soils need to be calculated when estimating the energy efficiency of biofuels or when applying LCA for bioenergy crops. Moreover, using real values obtained from field experiments may decrease the uncertainty of estimating GHG-savings, because there are different parameters affecting soil emissions. Our results are in good agreement with those of other researchers [2, 31], who mentioned that the energy efficiency of biofuel derived from rapeseed in the European countries is low, although empirical data for soil emission were not included in their calculations. Felten et al. [4] compared the ability of annual GHGs savings between different bioenergy crops. Results showed that rapeseed used for biodiesel production was the lowest, followed by maize and Miscanthus (3.2±0.38, 6.3±0.56 and 22.3±0.13 Mg CO_2-eq ha^{-1}), respectively.

Based on results of the GWP of CO_2 and N_2O emissions at the SRF and rapeseed fields, CO_2 is stronger than the other GHGs and can easily alter the CO_2-eq/energy ratio. Thus it is important to avoid activities that enhance CO_2 emissions. Methane (CH_4) and N_2O were relatively insignificant (unless the cultivations were on former wetland or very carbon-rich soils), compared to CO_2. The contribution of N_2O to GWP was 1.63% in the rapeseed and 1.07±0.13% in the SRF. We recommend including real data for soil CO_2 emission for energy efficiency calculations and LCA, as well to use SRF as a source of bioenergy.

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