Is short rotation forestry biomass sustainable?

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Declaration

I hereby declare that I completed this work without any improper help from a third party and without using any aids other than those cited. All ideas derived directly or indirectly from other sources are identified as such. In the selection and use of materials and in the writing of the manuscript I received support from the following persons:

Prof. Dr. Jörg Matschullat -- advisory role

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This thesis has not previously been published in the same or a similar form in Germany or abroad.

10.06.2016 *Kamal Zurba*
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Date, signature

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Abstract

Despite the negative effects of fossil fuels on the environment, these remain as the primary contributors to the energy sector. In order to mitigate global warming risks, many countries aim at reducing greenhouse gas emissions. Bioenergy crops are being used as a substitute for fossil fuels and short rotation forestry is a prime example.

In order to examine the sustainability of energy crops for fuel, typical European short rotation forestry (SRF) biomass, willow (*Salix* spp.) and poplar (*Populus* spp.) are examined and compared to rapeseed (*Brassica napus* L.) in respect to various aspects of soil respiration and combustion heat obtained from the extracted products per hectare.

Various approaches are used to look at an As-contaminated site not only in the field but also in a soil-column experiment that examines the fate of trace elements in SRF soils, and in an analysis using MICMAC to describe the driving factors for SRF crop production. Based on the cause-effect chain, the impacts of land-use change and occupation on ecosystem quality are assessed when land-use is changed from degraded land (grassland) to willow and poplar SRF.

A manual opaque dynamic closed chamber system (SEMACH-FG) was utilized to measure CO_2 emissions at a willow/poplar short rotation forest in Krummenhennersdorf, Germany during the years 2013 and 2014, and at a rapeseed site in 2014.

Short rotation forest soils showed higher CO_2 emission rates during the growing season than the dormant season – with a CO_2 release of 5.62±1.81 m^{-2} s^{-1} for willows and 5.08±1.37 µmol CO_2 m^{-2} s^{-1} for poplars in the growing season. However, during the dormant season the soil sites with willow emitted 2.54±0.81 µmol CO_2 m^{-2} s^{-1} and with poplar 2.07±0.56 µmol CO_2 m^{-2} s^{-1}. The highest emission rates for the studied plantations were observed in July for both years 2013 and 2014, during which the highest air and soil temperatures were recorded.

Correlations between soil emission of CO_2 and some meteorological parameters and leaf characteristics were investigated for the years 2013 and 2014. For example, for the willow clone (Jorr) and poplar clone (Max 3), high correlations were found for each between their soil emission of CO_2 and both soil temperature and moisture

content. Fitted models can explain about 77 and 75% of the results for Jorr and Max 3 clones, respectively. Moreover, a model of leaf area (LA) can explain about 68.6% of soil CO_2 emission for H275. Estimated models can be used as a gap-filling method, when field data is not available.

The ratio between soil respiration and the combustion heat calculated from the extracted products per hectare was evaluated and compared for the study's willow, poplar and rapeseed crops. The results show that poplar and willow SRF has a very low ratio of 183 kg CO_2 GJ^{-1} compared to rapeseed, 738 kg CO_2 GJ^{-1}.

The soil-column experiment showed that by continuing the SRF plantation at the As-contaminated site, remediation would need only about 3% of the time needed if the site was left as a fallow field.

In order to understand the complex willow and poplar short rotation forestry production system, 50 key variables were identified and prioritized to describe the system as a step to enhance the success of such potentially sustainable projects. The MICMAC approach was used in order to find the direct and the indirect relationships between those parameters and to classify them into different clusters depending on their driving force and interdependency. From this, it can be summarized that in order to enhance the success of a SRF system, decision makers should be focussing on: ensuring a developed wood-fuel market, increasing farmers' experience/training, improving subsidy regulations and recommending a proper harvesting year cycle.

Finally, the impacts of land-use change and occupation on the ecosystem quality were assessed. Results show that establishing SRF plantations on degraded lands improved the ecosystem structural quality (ESQ) by about 43% and ecosystem functional quality (EFQ) by about 12%.

Based on overall results, poplar and willow SRF biomass can be recommended as renewable and sustainable sources for bioenergy.

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List of Abbreviations

a.s.l.	above sea level
ABC	annual bioenergy crops
AT	air temperature
Bd	biodiversity
Bp	biomass production
CE	cumulative emission
CEC	cation exchange capacity
CNS	carbon, nitrogen and sulphur
d.w.	dry weight
EFQ	ecosystem functional quality
eq	equivalent
ESQ	ecosystem structural quality
ET	evapotranspiration rate
F	forestland
GHG	greenhouse gas
GPP	gross primary production
ha	hectare = 10^4 m^2
K_d	solid–liquid partition coefficients or Distribution coefficients
Kf	soil hydraulic conductivity
LAI	leaf area index
MDI	matrix of direct influences
MICMAC	cross-impact matrix multiplication applied to classification
MII	matrix of indirect influences
MJ	10^6 joules
NPP	net primary production
PAR	photosynthetically active radiation
PEL	percentage of electrolyte leakage
PNV	potential natural vegetation
PVC	polyvinyl chloride
Ra	autotrophic respiration
Rh	heterotrophic respiration

List of Abbreviations ...continued

RMSE	root mean square error
S	species richness
SEMACH-FG	soil emission manual chamber-Freiberg
Sf	soil fertility
SLA	specific leaf area
SM	soil moisture content
SOC	soil organic content
SOM	soil organic matter
SRC	short rotation coppice
SRF	short rotation forestry
SRWC	short rotation willow coppice
Ss	soil structure
ST	soil temperature
t	metric ton 10^3 kg
TAB	total aboveground biomass
Vs	vegetation structure
Wb	on-site water balance
yr	year

1. Background

1.1. General introduction

It is very important to understand the movement of carbon among its four main reservoirs: the atmosphere, the terrestrial biosphere, the oceans and fossil carbon (Schimel 1995). Between the years 1750 and 2011, the atmospheric CO_2 concentration rose from 278 to 391 ppm as a result of human activities (IPCC 2013). Accordingly, over one century, the average global temperature increased by 1ºC above the preindustrial level, with an associated increase in extreme weather events and other environmental problems (Harnay and Rème 2012). Furthermore, the balance of energy on our planet has been disturbed. Most of this imbalanced energy is going into the oceans. Deep sea and sea surface water temperatures are rising. Moreover, the anthropogenic carbon uptake by oceans causes a decrease in the pH of surface waters, in addition to global change of the water cycle (Talley et al. 2015).

Scientists and policy makers are worried about how our limited non-renewable resources can meet the increasing demand for energy and about the emissions of greenhouse gases GHGs (Karp and Shield 2008). Transport is responsible for about 25% of European GHG emissions (Linares and Pérez-Arriaga 2013). Many legislative and technical steps have been taken to reduce fossil fuel use, such as carbon taxes and improving energy efficiency, even though the researchers Harnay and Rème (2012) point out that new vehicle technologies may be more influential than the carbon tax system.

In response to the Kyoto Protocol (1997), the EU committed itself to reduce its anthropogenic carbon dioxide equivalent emissions of GHGs by 8% in the period 2008–2012 as compared to 1990 levels (UN 1998). Later, the EU set new targets for 2020 to achieve 20% lower GHG emissions as compared to 1990, 20% greater energy efficiency and 20% renewable energy (EP 2010). Such commitments have led to a search for new renewable energy sources (EEA 2008).

The increasing concern about renewable energy is driven by many factors, such as energy security, climate change (Karp and Shield 2008) and the limited global supply of fossil fuel (de Neergaard et al. 2002). Bioenergy crops are renewable sources for energy because they absorb atmospheric CO_2 and transfer C into the soil. This

C-sequestration is considered a tool to rehabilitate the environment (Gupta et al. 2009; Sainju et al. 2008).

Yet, not all bioenergy crops are produced in the most sustainable way. Sustainability depends on many factors, such as feedstock type, management and location. For example, extracting feedstock from savanna or peatlands may have even higher GHG emissions than fossil fuel. Thus, more investigations and assessments should be done to select the proper crop (FAO 2008; Johnson 2009; McKechnie et al. 2011).

This chapter aims to introduce and describe the system of Short Rotation Forestry (SRF) as a sustainable source of woody biomass for energy, first by describing the concept of Soil Organic Carbon (SOC), where atmospheric carbon is captured and stored in soil, and the opposite process where carbon is lost from soil to the atmosphere through soil respiration. Moving to the bioenergy sector, some energy ratios for main bioenergy crops and how the energy input changes with different activities are discussed that provide examples to illustrate the distribution of energy throughout the production system. After that, basic concepts about willow and poplar SRF are presented, including a general description of this plantation, productivity and main factors that affect it. Since establishing SRF on degraded and marginal lands is recommended, this topic is examined together with results of many studies.

Most importantly, the supply of woody biomass from SRF for energy has been reported to be sustainable. Thus, the general concept of sustainability is addressed, and specific benefits of adopting SRF as a tool to mitigate climate change are provided; these include social, economic and environmental impacts. Finally, the main challenges of SRF are described. The objectives of this study are at the end of this chapter.

1.2. Soil organic carbon (SOC)

Plants play an important role in the carbon cycle. They absorb atmospheric CO_2 and transfer C into the soil. This C-sequestration is considered a tool to rehabilitate the environment. Soil, the second largest store of C after the oceans, has the ability to significantly alter the atmospheric CO_2 concentration, depending on many factors, including land management practices (European Commission 2011; Gupta et al. 2009).

Converting cropland to forest will increase mean soil organic carbon (Poeplau and Don 2013). In one study, cultivation of land was responsible for the loss of about 50% and 30% of the initial organic carbon soil content in the top 20 and 100 cm of soil, respectively, over a 30–50 year period (Post and Kwon 2000).

Carbon sequestration in soil is affected by multiple factors; these include changes in the inflow of organic matter to soil, changes in the organic decomposition rate, field activities that may alter soil's physical properties and enhance the loss of organic matter (e.g., tillage), and vertical changes in the organic matter within the soil profile (Post and Kwon 2000).

Typical estimations of global SOC consider the top meter of the soil horizon. Yet, Jobbágy and Jackson (2000) estimated the vertical distribution and storage of SOC to a 3-m depth. The amounts of organic carbon stored in the second and the third meter are about 34% of that in the first meter in the boreal forests, 57% in croplands, 86% in the deserts. Globally, total amount of SOC stored in the first meter is about 1502 Pg and distributed as 41, 23, 16, 11 and 9% in the layers of 0–20, 20–40, 40–60, 60–80 and 80–100 cm depth, respectively (Figure 1). Additional amounts of C are stored in the second and the third meter of about 491 and 351 Pg, respectively (Pg = petagram = 10^{15} g = 1 billion ton).

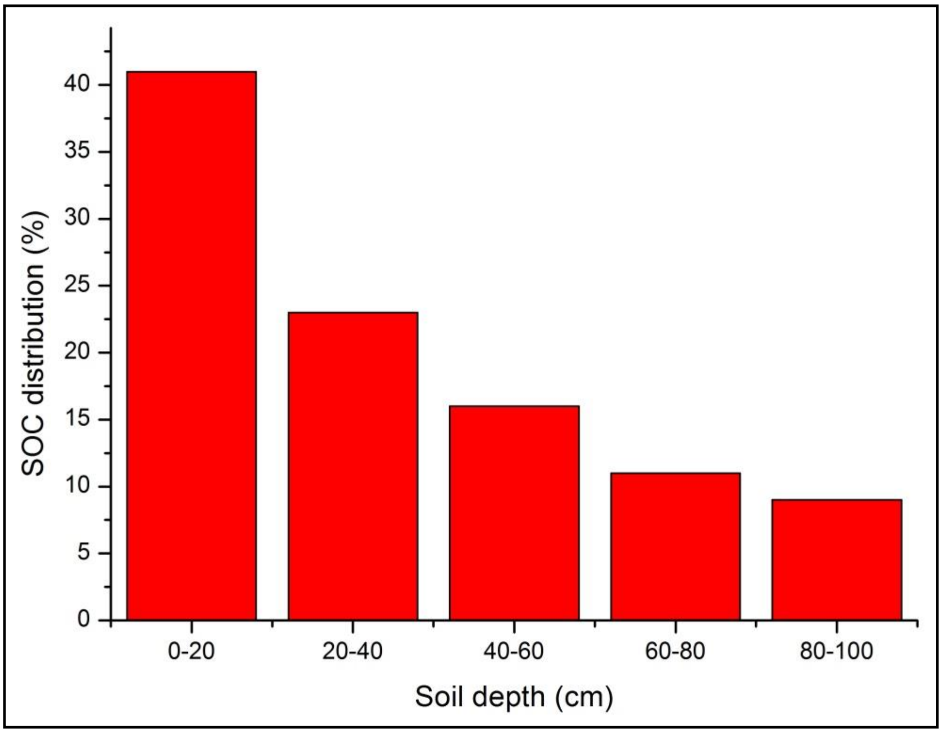


Figure 1. Vertical distribution of soil organic carbon (SOC) in the top meter of a soil profile as estimated by Jobbágy and Jackson (2000)

1.3. Soil respiration

Soil respiration is a process that releases carbon dioxide from soil. This emission comes mainly from root respiration (autotrophic) and decomposition of organic matter by soil organisms (heterotrophic). A smaller component of soil respiration comes from abiotic factors such as carbonate reactions (Rochette et al. 1997; Rustad et al. 2000). Soil respiration is the largest emitter of CO_2 from the terrestrial ecosystem to the atmosphere (Subke and Bahn 2010). It is affected by many parameters, the most important of which are soil temperature and moisture, soil properties (C:N ratio, pH, texture and structure), air pressure and land use (Luo and Zhou 2006).

Generally, natural fluxes of CO_2 between the biosphere and atmosphere are controlled by the ratio of net primary production (NPP) to gross primary production (GPP). When plants fix atmospheric carbon in their biomass, part of the fixed carbon will be consumed by plants themselves to provide energy required for their growth, and released again as CO_2 to the atmosphere through autotrophic respiration (R_A). However, global warming and climate change may alter this ratio and affect the ecosystem's behaviour to act as a source or a sink for CO_2 (Box 2004). For example, it is expected that global warming will significantly affect the boreal ecosystems, which store about 10–20% of the terrestrial SOC. This amount of organic carbon is susceptible to mineralization and subsequently increase atmospheric CO_2 concentration (Allison and Treseder 2011; Jobbágy and Jackson 2000). In addition to different abiotic factors, tillage and harvesting can disturb the ecosystem and alter the soil respiration rate *Rs* (Shabaga et al. 2015).

As mentioned previously, many biotic and abiotic factors are involved in the soil respiration process and make it complex, making common methodologies to describe the actual reaction of soil respiration to temperature changes hard to obtain (Subke and Bahn 2010). In spite of this fact, the relation between soil respiration and soil temperature is generally explained by exponential function (Zhang et al. 2015). However, the relationship with soil moisture content is different than soil temperature. A general description was suggested by Zhang et al. (2015): maximum soil respiration is achieved at an optimum soil moisture content, which is about 0.25 m^3 m^3 under desert ecosystem (Figure 2).

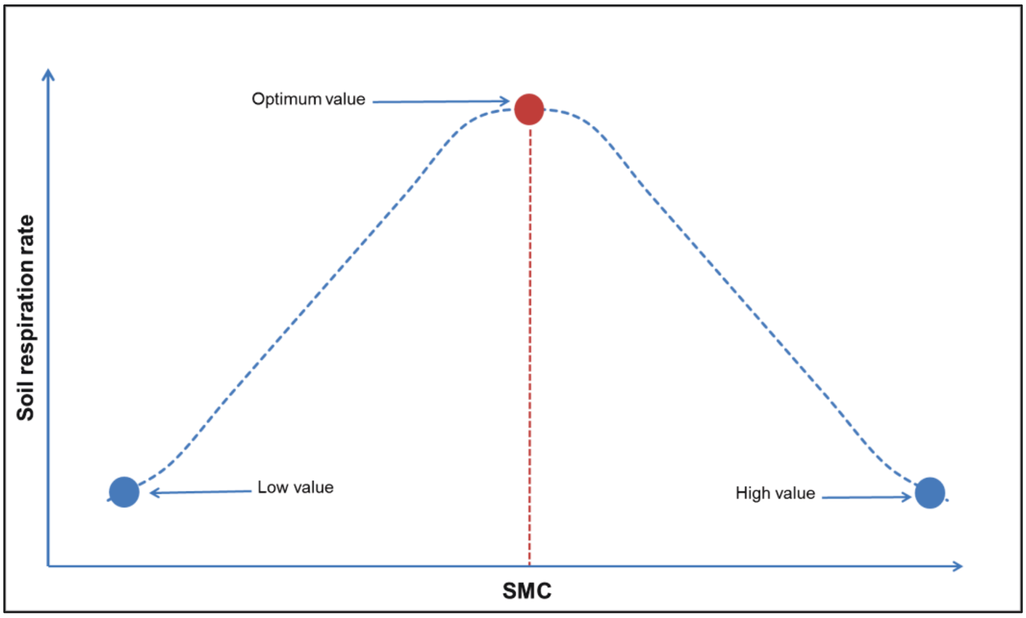


Figure 2. General relationship between soil respiration rate and soil moisture content (***SMC***) as suggested by Zhang et al. (2015)

The measurement of soil respiration started in the 1830s and aimed to test soil fertility. Since then, different techniques have been developed, from alkali trap closed chambers using NaOH or KOH to the most recent developed portable CO_2 analysers (Luo and Zhou 2006; Rochette et al. 1997). The most common devices to measure trace GHGs utilize chamber techniques, mainly closed static and dynamic chambers (Denmead 2008; Oertel et al. 2016).

1.4. Energy and bioenergy crops

The search for alternatives to fossil fuel has increased as a result of the 1970's oil crisis. Sweden, for example, decided to replace part of its imported fossil fuel with local wood fuel (Hoffmann and Weih 2005; Perttu 1998). The environmental impacts of bioenergy feedstock production would be less than that of conventional fuel (Roedl 2010). Comparative life cycle assessment (LCA) is normally used to assess and to compare different energy sources, though most studies have focused on GHG emissions and less on other impacts such as acidification and solid wastes (Djomo et al. 2011).

Bioenergy crops can be seen as a CO_2-neutral energy source because the fixed amount of atmospheric CO_2 consumed during plant growth by the photosynthetic process is emitted during combustion (Sáez et al. 1998). The most commonly grown crops are maize (*Zea mays*) and wheat (*Triticum spp.*), which are the major feedstocks for bioenergy. Additional bioenergy crops include sugarcane (*Saccharum officinarum*, a perennial grass that needs to be renewed after 5 years to keep productivity stable), other perennial C4 grasses such as switchgrass (*Panicum virgatum*) and different species of *Miscanthus* (Karp and Shield 2008), as well as woody plants under SRF plantations.

Willow and poplar are the most used plants in SRF in Europe because the climatic conditions are favorable for tree growth (Dimitriou and Fištrek 2014), furthermore, they can be used for the fiber industry (Perttu 1998).

Fossil fuel power plants have several negative impacts on the environment and human health, for example, acid rain caused by sulfur dioxide, declining air quality (e.g., ozone concentrations, emission of CO_2, SO_2, NO_x and Hg), smog formation, and finally their contribution to global warming (Heller et al. 2004). Useable energy such as electricity and heat can be transformed from the extracted woody biomass, making it an attractive renewable source for energy (Walle et al. 2007). Woody biomass can be used in the production of heat and power in different ways such as combustion and gasification. Furthermore, it is mostly produced locally (Volk et al. 2004) and offers environmental advantages when used as fuel feedstock over fossil fuel (Kopp et al. 2001).

Agrochemicals such as fertilizers and pesticides have high energy equivalent values (based on their lifecycle: manufacturing, packaging, shipping and application), for example, nitrogen, phosphate and potash fertilizers have values of 78.2, 17.5 and 13.8 MJ kg^{-1}, respectively (Helsel 1992), and even higher values for herbicides: 288 MJ kg^{-1} (Green 1987). Thus, applying a low-input management regime for bioenergy crops will significantly increase the energy efficiency of such crops (Nassi O Di Nasso et al. 2010).

Djomo et al. (2011) in their review, found that the energy ratios (ER) for willow and poplar SRF were 13–79 and 3–16 for the cradle-to-farm gate and the cradle-to-plant, respectively. This wide range is a result of variations in the yield, management practices, as well the technology used to generate electricity, e.g., gasification has higher conversion efficiency than direct combustion of the biomass. Harvesting and fertilization are strongly responsible for raising the energy input value. Furthermore, willow and poplar were slightly different from each other in their ER but not significantly.

Despite the low productivity of poplar clones studied by Dillen et al. (2013), the energy ratio for cradle-to-farm gate ER_{farm} was 29.8. Higher values were estimated by Heller at al. (2004) and Nassi O Di Nasso et al. (2010) for willow and poplar SRF plantations with values of 55 and 60.8, respectively. A value of 39 was estimated for *Miscanthus* (Angelini et al. 2009).

The input and output energy of a poplar SRF grown on degraded land under a low-energy input management system was estimated by Dillen et al. (2013); the site was kept without the addition of fertilizers, irrigation or fungicides for 16 years and produced 4 harvests. The results demonstrated that the total energy input in the form of woody chips was 49.3 GJ ha^{-1} while energy output in the form of electricity produced through gasification was 546.5 GJ ha^{-1} (1469.1 GJ ha^{-1} at the farm gate). Of that input energy, 30% was due to weed control (chemical and mechanical weeding), harvesting and chipping accounted for about 26.8%, and the conversion of biomass into electricity utilized about 23.8%. Finally, the production of the cuttings, planting and transportation of woody chips to power plants (50 km) were responsible for about 10% of the total energy costs (Figure 3).

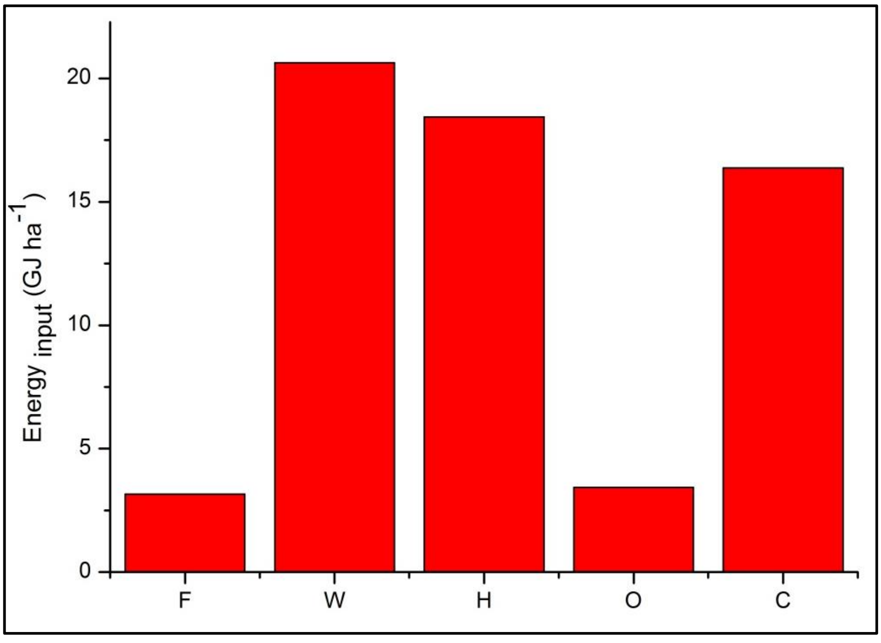


Figure 3. Detailed breakdown of energy inputs over 16 years to a poplar SRF with 4 harvests due to: ***F***: Field preparation; ***W***: Weed control (chemical and mechanical); ***H***: Harvesting and chipping; ***O***: Other factors (planting materials, transport of biomass) ***C***: Converting biomass into electricity. Data used from Dillen et al. (2013)

Yet, contradictory data can be found, such as that of Wilnhammer et al. (2015) that described a scenario for wood energy analysis for Germany for the period 2010–2035. Their scenario showed that an increase of using 35% of woods for energy, combined with a decline of 31% in the material-based wood products may enhance global warming because other alternatives will be used such as non-wood building materials. For this reason, importing wood to fill the gap in the energy sector is better than using conventional materials by other sectors.

1.5. Willow and poplar short rotation forestry

Trees under SRF are single-stemmed or multi-stemmed trees (Sims et al. 2001). Other terms used by researchers to specify the type of SRF include "Short rotation coppice" (SRC) or "short-rotation woody crops" (SRWC) – these refer to fast-growing trees used to produce wood biomass for energy (Dimitriou and Fištrek 2014; Djomo et al. 2011; Hoffmann and Weih 2005; Pacaldo et al. 2014). Such types of plantations have been used in Sweden since the 1970s (Lockwell et al. 2012).

Many genetically improved plants are cultivated under short-rotation systems, such as willow (*Salix* spp.) and hybrid poplar (*Populus* spp.), these plants are fast growing, high-yield crops and are asexually produced (Volk et al. 2004). Willow has abundant species, which helps hybridization to find new varieties with better characteristics (Karp and Shield 2008).

In spring, cuttings are thickly planted in double rows (density ranging between 10,000 to 20,000 trees ha^{-1}) and once rooted coppiced in winter (cut down near ground level in order to force the regrowth of many new shoots). Later, each tree will have between 6–15 new stools as multiple stems. Harvesting is repeated every 2–10 years (2–3 years is the average rotation length) using chipping machines. Rotation length depends on many factors, such as soil status and goal dimensions of the harvested wood production. A single plantation remains in the field for 20–30 years (7–8 harvests), minimizing establishing costs. Trees reach a height of 5–8 meters within 3 years of each harvest (Dimitriou and Fištrek 2014; Kahle et al. 2010; Kopp et al. 2001; Volk et al. 2004).

This multiple-harvest technique enables willow and poplar plantations to compete in the energy market (Kopp et al. 2001). Cutting on short cycles (average 3 years) makes it possible to cultivate plants under dense plantation and extract higher biomass (Dillen et al. 2013). Furthermore, the consumed non-renewable energy to produce one tonne of wood fuel from SRF decreases as rotation length increases, from 1.0 to 0.45 MJ for one and two-year rotations, respectively, and 0.31 MJ for three-year harvesting intervals (Nassi O Di Nasso et al. 2010).

Yet, under dense plantation and long cutting intervals, high mortality and invasive fungal infections are expected (Sims et al. 2001). Willow and poplar trees under SRF plantation have very few roots below 1.3 m and about 70% of their roots are less than 1 mm in diameter. At the beginning of the growing season, the stored carbohydrates in roots are used to support new stool growth. Thus, the length of coppice rotation limits root size but not the number of fine roots (Crow and Houston 2004).

SRF can be irrigated with treated wastewater. This has been successful in Enköping, Sweden, where 75 ha of willow SRF are irrigated annually with 200,000 m^3 of treated wastewater during the growing season when precipitation is not sufficient. SRF can also be fertilized with a mixture of sewage sludge and wood ash to offer a balanced fertilizer of N, P and K (Dimitriou and Aronsson 2005).

Crop yield is affected by several factors: plant variety, site properties (e.g., climate, slope and soil chemical and physical properties), crop management, sensitivity to leaf rust attacks and frost (Aronsson et al. 2014; Dimitriou et al. 2011). Differences in the management regimes and system boundaries make it difficult to directly compare SRF productivity between studies (Dillen et al. 2013). These factors are discussed in more detail below.

Metrological parameters play a large role in the rate of yield, particularly precipitation during the growing season and air temperature. Biomass production is affected positively by the number of growing days (daily mean temperature ≥ 5 ^{o}C (Kopp et al. 2001). A heavy reduction in yield is observed when plants are highly susceptibility to leaf rust (Dillen et al. 2013) because temperature and rainfall can impact the effects of fungus.

Productivity is significantly affected by the interaction between clone production and rotation (Dillen et al. 2013). Nassi O Di Nasso et al. (2010) found that harvesting intervals have significant influence on productivity. For example, harvesting poplar plantations every 3 years was better than every 1–2 years. Furthermore, there is a positive correlation between the number of stools and biomass; high stool numbers correspond with high biomass production (Dillen et al. 2013).

There is no consensus among researchers concerning fertilization. Some researchers mention that SRF yields increase significantly with fertilization (e.g., Aronsson et al. 2014). Others found that fertilizing with N, P and K annually did not affect productivity of willow and polar SRF but rather reduced the period to reach maximum production and increased mortality (e.g., Kahle et al. 2007; Kopp et al. 2001).

In general, different average yields of willow and poplar SRF were reported by authors as appear in Table 1.

Table 1. Productivity of willow and poplar under SRF plantation in tonnes of DM ha^{-1} $year^{-1}$

Productivity	Reference
7.7	Mola-Yudego et al. (2015)
11.5	Djomo et al. (2011)
13.6	Heller et al. (2004)
4.3–10.5	Dillen et al. (2013)
6–12	Dimitriou and Aronsson (2005)
8–12	Faaij (2013)

1.6. Degraded lands

Degraded lands, caused by natural processes and human activities, cover about 15% of the Earth's land mass (ca. 1964 million ha). The reasons for degradation can be classified into four categories listed in descending order: water erosion, wind erosion, chemical and physical deterioration, and most degraded lands fall under the first two categories (Faaij 2013). Depending on the extent of degradation, these lands can be further classified into: severely, moderately or lightly degraded soils (Gibbs and Salmon 2015).

Kerckhoffs and Renquist (2013) defined marginal lands as lands "which provide (on average) suboptimal growing conditions for major food or feed crops in the relevant climatic zone". The term marginality is often used by researchers to describe lands from biophysical or/and economic point of view, but not quantitatively defined, making it unclear.

Moreover, lands are classified based on rankings relative to the ideal one (Richards et al. 2014). In the same way, degraded land is very widely defined; it may include different types of exhausted land, i.e. abandoned (Takimoto et al. 2009), or soils that are desertified, salinized, compacted or eroded (Gibbs and Salmon 2015). In addition, marginality of land is dynamic and may change depending on different physical factors, such as techniques applied in the field or other economic factors (FAO 1999).

Land availability plays a crucial role in meeting the future world energy demand that is increasing rapidly (Faaij 2013). Contaminated soils inhibit food production and may yield potential risks for human and animal health (Maxted et al. 2007). Marginal lands can be used to establish perennial bioenergy crops (Karp and Shield 2008). Such areas may be suitable, however, for short rotation forestry (SRF) because it can be established on a broad range of land-use areas that include marginal lands (Broeckx et al. 2012), to produce biomass for energy purposes – and to bring about a longer term remediation of soils with moderate trace element contamination, e.g. Cd (Dimitriou and Fištrek 2014), or at least prevent further soil deterioration. In addition, fields can be left without adding agrochemicals, making the system low-energy input (Dillen et al. 2013).

Thus, SRF may support efforts to decrease conflicts between food and energy crops by reducing the competition on arable lands. Such forestry can also restore slightly contaminated soils to be suitable for growing food crops (Maxted et al. 2007). The risks of negative impacts on human health and environment will be also minimized, e.g., Cd concentrations decreased 12% in the topsoil after 10–20 years under willow SRF (Dimitriou et al. 2012b). In addition to increasing farm income (Witters et al. 2009) by extracting biomass for energy, even if woody biomass contains high concentrations of heavy metals, removing them from ash is not difficult from a technical point of view (Dimitriou and Aronsson 2005).

Different energy crops, maize (*Zea mays*), rapeseed (*Brassica* sp.), willow (*Salix* spp.) and poplar (*Populus* spp.), were established on soil contaminated with Cd, Pb and Zn and compared (Witters et al. 2009). These crops were ranked according to income (economic return) and phytoremediation scenarios. Each scenario has its own goal: farmer income and site remediation. Compared to other energy crop options, results showed that SRF is suitable for phytoremediation, however, maize and rapeseed are more suitable for attaining income. Hence, it would be difficult for farmers to adopt SRF as an option to remediate contaminated sites unless it is financially supported. Without subsidies, farmers will choose other crops able to fulfill their needs such as maize and rapeseed because SRF does not provide them with sustainable income.

On the other hand, some challenges may be introduced as a result of using marginal lands for bioenergy crop production, such as reductions in productivity (Li et al. 2010) which may reach to 30–45% when planting bioenergy crops on severely degraded lands (Faaij 2013). Moreover, there may be higher costs required for transportation of the harvest if such lands are far away from energy plants (Li et al. 2010).

In general, establishing willow and poplar in SRF on a low to moderately contaminated soils with trace elements is recommended because it is cheap and an environmentally friendly method to remediate sites (Witters et al. 2009).

1.7. SRF: A sustainable biomass production system

Sustainability is an important topic at institutional and governmental levels (Romero and Linares 2014), as well as when talking about energy issues. In most cases, using wood fuel from willow and poplar short rotation forestry is sustainable because it has the potential of reducing GHG emissions and has other environmental, economic and social benefits (Witters et al. 2009). Yet, sustainability is not a simple issue and requires complicated approaches when dealing with its components (Romero and Linares 2014) because it is based on human values, which should be compatible with environmental, economic and social aspects (Volk et al. 2004).

It is rare to find researchers who connect ecosystem service with the psychology of human behaviour (Hicks et al. 2015). Thus, the following short introduction may provide useful insights into understanding the basics of the sustainability from psychological point of view.

Values are used to describe human needs; they deliver standards for individuals and society to direct different affairs, such as actions and choices. Generally, people classify things into either two contradictory categories, e.g., true and false, and their selection is based on their values. Societies show extremely different patterns of values. These values acquired by learning and experience play a main role in developing them, hence, the relation between values and behaviour increases with time. Selected actions by humans are influenced by their values (Williams 1979).

Humans have both sustaining and non-sustaining values; the later can negatively affect the ecosystem. As an example, the sustaining value (equity) lies between personal well-being and the well-being of others, this value can transform to a non-sustaining value (selfishness) if personal well-being of others is ignored (Twomey et al. 2010), to overcome these challenges, values support sustainability shall be grasped.

Furthermore, areas that lie between opposite values can create trade-offs that are responsible for guiding people's behavior, i.e. willingness to change and traditionalism (stability) make the process more complicated (Hicks et al. 2015).

Change towards sustainability requires essential changes to different social, economic and environmental aspects (Twomey et al. 2010). However, human values are changeable over time (Hicks et al. 2015). Despite existing challenges, policy makers are able to change the development into more sustainable way.

By extracting wood fuel in a sustainable way from SRF, many benefits (externalities) will be gained by the society, economy and environment (Dimitriou and Fištrek 2014; Sáez et al. 1998). These provided benefits are the reason behind considering SRF as promising crop energy and paying a lot of attention to develop it (Mola-Yudego et al. 2015).

1.7.1. Socio-economic benefits

Various economic and social advantages will be generated when SRF is used as a renewable source for energy, such as, enhancing industry and developing regions, creating direct/indirect jobs, and strengthening the energy security at the regional level (Domac et al. 2005; Sáez et al. 1998). Moreover, these socio-economic benefits are considered key driving forces behind the increase of bioenergy share at the local, regional and national levels (Domac et al. 2005).

1.7.2. Environmental benefits

Air

Establishing more SRF can cause a significant reduction of atmospheric carbon (Walle et al. 2007) because the net contribution of SRF to the atmospheric CO_2 is slightly negative. SRF considered a net uptake of atmospheric CO_2 (Perttu 1998).

By comparing the emissions of CO_2, SO_2 and NO_x from heating plants using willow woods and others using fossil oil, emissions from the different steps of each chain (e.g., cultivation, fertilizer use and transport) were considered. SRF allows for a reduction of 80% in CO_2 and SO_2 emissions. At the same time, an increase of 10% in NO_x was reported by Perttu (1998) and a reduction in NO_x emissions was reported by Heller et al. (2004).

Using willow and poplar biomass for energy, e.g., as co-firing to generate electricity can reduce 90–99% of the GHG emissions in comparison to coal. Their GHG emissions are 24 times lower than coal (Djomo et al. 2011; Styles and Jones 2007). The emission reductions included SO_2 and NO_x because wood has less sulfur content and higher moisture content and volatility than coal (Heller at al. 2004).

Water

A scientific controversy on the impacts of SRF on water exists, involving more doubts surrounding water consumption than water quality. In general, SRF has higher evapotranspiration than croplands but less than forestlands. Many studies have estimated the evapotranspiration of SRF. Due to the variation in soil properties and climatic parameters, a broad range of values have been reported by Dimitriou and Fištrek (2014).

To achieve the European Union water policy goals, the intensive farming shall be reduced (EEA 2008). Yet, fertile lands are limited in Europe and the demand of biofuels is increasing. Consequently, this puts greater pressure on fertile lands to produce bioenergy crops rather than crops for food – this pressure on land use is normally linked with water quality deterioration because of the intensive farming practices.

In comparison with croplands, SRF is considered to be a low-energy input system, with limited use of the agrochemicals such as pesticides in fields, and a positive influence on groundwater quality (Dimitriou and Fištrek 2014). For example, the average amount of N-fertilizer recommended for cereals is ca. 120–140 ha^{-1} $year^{-1}$ (Dimitriou et al. 2012a) and for rapeseed the recommended amount is about 180–190 kg ha^{-1} $year^{-1}$ (Berry et al. 2014), while it is about 70–80 kg ha^{-1} $year^{-1}$ for SRF in case a fertilizing regime is applied.

The leakage of nutrients and other agrochemicals from the soil is less at SRF sites than conventional agriculture sites because SRF utilizes nutrients in an efficient way with minimum leaching to groundwater (Dimitriou and Fištrek 2014). Short rotation forests have an excellent and well-developed root system and trees remain for a prolonged periods in soil (Perttu 1998).

In conclusion, it is highly recommended to establish SRF in regions where groundwater has a high risk of being contaminated due to N-leaching (Dimitriou et al. 2012a).

Soil

Soil organic matter is the part of the soil composed of different plant, animal and microbial breakdown residues and involves many complex processes – physical, chemical and biological (Post and Kwon 2000).

SRF can improve the physical and chemical quality of soil by increasing its organic matter content. It can improve the soil structure, infiltration rate, water storage, holding capacity, aggregate stability, thus minimizing the risks of losing nutrients through surface runoff, and having higher soil biota than conventional farming due to the no-till practice at SRF sites. For these reasons, it is highly recommended to establish SRF in areas with high risk of erosion (Dimitriou and Fištrek 2014; Kahle et al. 2007; Mann and Tolbert 2000).

In fields under willow and poplar SRF plantations for 12 years and without fertilization, C_{org} increased from 7.5±0.2 to 11.05±0.65 g kg^{-1} due to the annual accumulation of the litter. Due to the no-tillage practise, the total nitrogen increased from 0.90±0.04 to 1.06±0.03 g kg^{-1}. As a result, C/N ratio increased from 8.4±0.1 to 10.4±0.3, and soil bulk density decreased from 1.59±0.06 to 1.43±0.04 g cm^{-3}. Its porosity increased from 40.05±2.25 to 46.15±1.35 %, whereas soil pH did not change significantly. Although phosphorus and potassium concentrations were depleted in the soil, plants were provided with their needs sufficiently (Kahle et al. 2007).

Lockwell et al. (2012) for example, compared the changes of soil organic carbon (SOC) when converting abandoned alfalfa fields to high-density SRF (using 18,000 willow cuttings per hectare) in southern Quebec, Canada. Their results show that SRF did not change the total soil organic carbon (TSOC). Instead, SRF changed the distribution of the organic carbon within soil profile. Yet, these results do not represent a long-term situation because measurements were conducted after 9 years of establishing the SRF. In order to demonstrate an effect on the soil carbon stock, a comparison would need to be made after 20–25 years of establishing the SRF site, which is the typical life-span of such plantation as suggested Post and Kwon (2000) suggestion, long-term studies are needed when estimation about soil carbon sequestration is needed.

Soils under willow SRF and conventional annual crops for periods of 10–20 years were compared (Dimitriou et al. 2012b). Results showed that soils at SRF sites had 9% higher organic carbon in the topsoil and 27% higher in subsoil.

A non-fertilized poplar SRF filed in central Germany was compared with winter wheat that received 120 kg N ha^{-1} annually. Results showed that soil carbon sequestration increased more in soil under SRF than under winter wheat, with soil C_{org} values of 18.6 for SRF and 8.1 g kg^{-1} for wheat, C/N ratio values of 11 for SRF and 9.6 for wheat were measured (Baum et al. 2013).

Other example from a non-fertilized site under willow and poplar SRF was compared with a neighbouring fertilized field under conventional annual crops (winter wheat, winter barely, oat, winter rape, grass, clover, lupine and maize). In this case, the results show that soil at both sites did not differ significantly (Kahle et al. 2010).

1.7.3. Biodiversity

As long as SRF is not established in regions that have high ecological value such as wetlands and swamps, it can promote biodiversity by providing habitats and protecting places for living things such as plants and animals (Dimitriou and Fištrek 2014; Sage 1998). Such SRF sites show a higher diversity of breeding birds than areas with conventional crops (Londo et al. 2005). The dense canopy of SRF reduces the sunlight reaching the soil surface, which in turn increases the ground-layer species of insects and plants such as shade tolerant herbs and grasses (Dimitriou and Fištrek 2014; Sage 1998).

Improving the habitat quality (air, water and soil) where human and biota are living will subsequently improve their health and protect them (Dimitriou and Fištrek 2014).

1.8. Challenges

In the future, there is a positive prospect of increasing areas under SRF in Europe, even on agricultural lands close to power and energy supply stations, because local feedstocks are favorable (Dimitriou and Fištrek 2014). Yet, there are many challenges in developing this sector, which can be summarized as follows:

- One of the critical barriers to using biomass as renewable energy source is its cost, (Sáez et al. 1998). Hence, financial incentives are needed for this sector to encourage farmers to establish new SRF sites because biomass is still considered as a rural source and non-commercial product, and this idea has to be changed.
- Providing enough biomass feedstock on a global level, eliminating competition against food production and ensuring product sustainability (Linares and Pérez-Arriaga 2013).
- Challenges may arise from the use of degraded lands due to the additional costs for site preparation (Dillen et al. 2013).
- Disease and pest occurrences are major factors that may alter the sustainability of bioenergy crops because they directly affect their productivity (Karp and Shield 2008).
- Additional research is needed on the feasibility of establishing SRF on marginal and degraded lands (Faaij 2013).
- During combustion or gasification the woody biomass, problems may arise if the biomass has a high content of alkali metals. Moreover, wood moisture content is an important factor with thermal conversion processes because heating values of woody biomass decreases as its moisture content increases (Karp and Shield 2008).
- Scaling up from chamber measurement to ecosystem, regional and/or global level is the main challenge (Rustad et al. 2000).

1.9. Objectives of this study

The aim of this study is:

1. To study soil respiration under different biomass production systems, SRF and rapeseed, and to elucidate existing correlations between soil respiration and other soil, climatic and plant parameters.
2. To conduct 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: willow/poplar SRF and rapeseed. In addition, to estimate the CO_2 savings resulting from different land uses.
3. To investigate the fate of trace elements and heavy metals in soil when soil is unvegetated and fed with rainwater using a soil column test.
4. To investigate driving factors for a willow and poplar short rotation forestry (SRF) production system and evaluate the strength of relationship between these factors using the MICMAC approach. This will involve the visualization of direct and indirect relationships to better understand their role in the system.
5. To assess the impacts on the ecosystem quality when SRF plantations are established on degraded lands, based on the cause-effect chain principle.

2. Methodology

2.1. Site Description

In 2005, the Saxon State Agency for Environment, Agriculture and Geology (LfULG) established a willow and poplar short rotation forest at a 2-hectare site located on arsenic (As)-contaminated land in Krummenhennersdorf (about 8 km north of Freiberg/Saxony; 50°58′N 13°20′E; ca. 350 m a.s.l.). The site's soil contained an average of 128±18 mg As kg^{-1} (Kumpiene et al. 2014) and other trace metals (see the geochemical survey map of Saxony for topsoil, Figure 4).

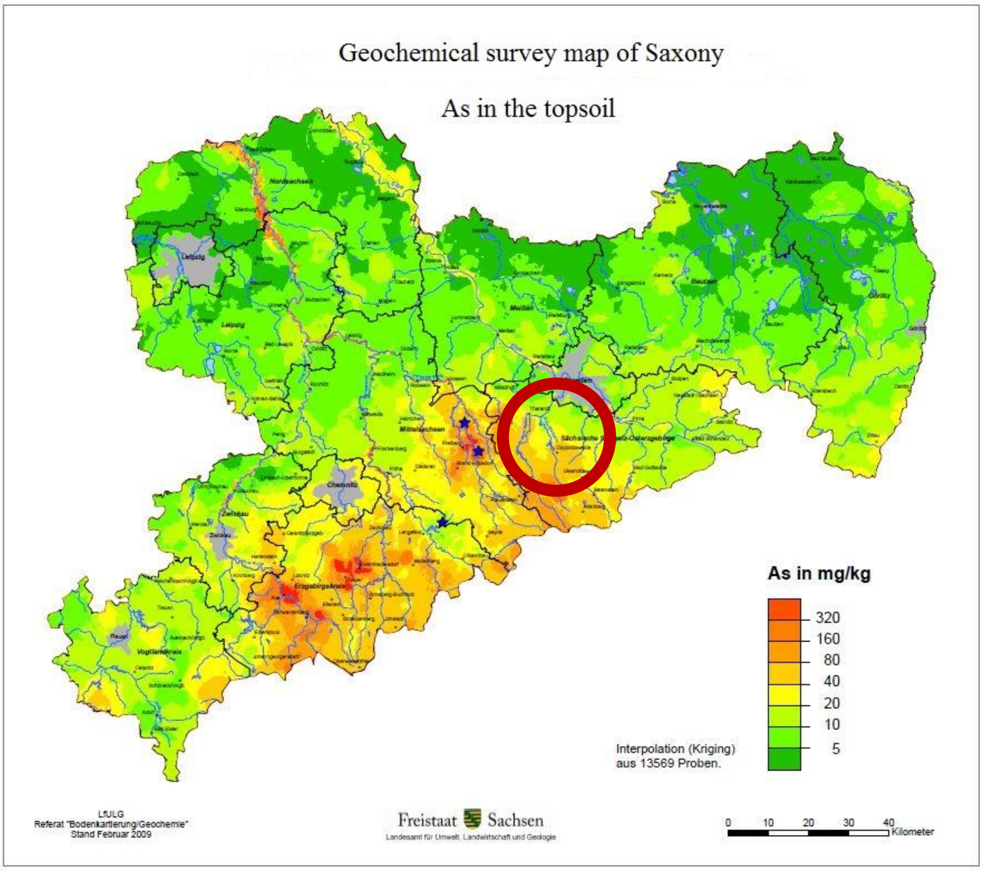


Figure 4. Geochemical survey map of Saxony for Arsenic (As) in the topsoil (after LfULG 2009)

This SRF site is located in an area that has a history of mining and metallurgical industry, especially lead (Pb), silver (Ag) and zinc (Zn). Less than one kilometer from the SRF site is situated an approximately 140-meter high chimney, the Halsbrücker Esse, which was built in 1889 (Figure 5) and was at that time the tallest in Europe. The purpose of building such tall chimney was to disperse the emissions over a wide area instead of loading the pollutants in a small area, thereby avoiding legal claims against the metallurgical plant. Thus, damaging emissions were distributed over an area of about 300 km^2 around this chimney (Andersen 2006).

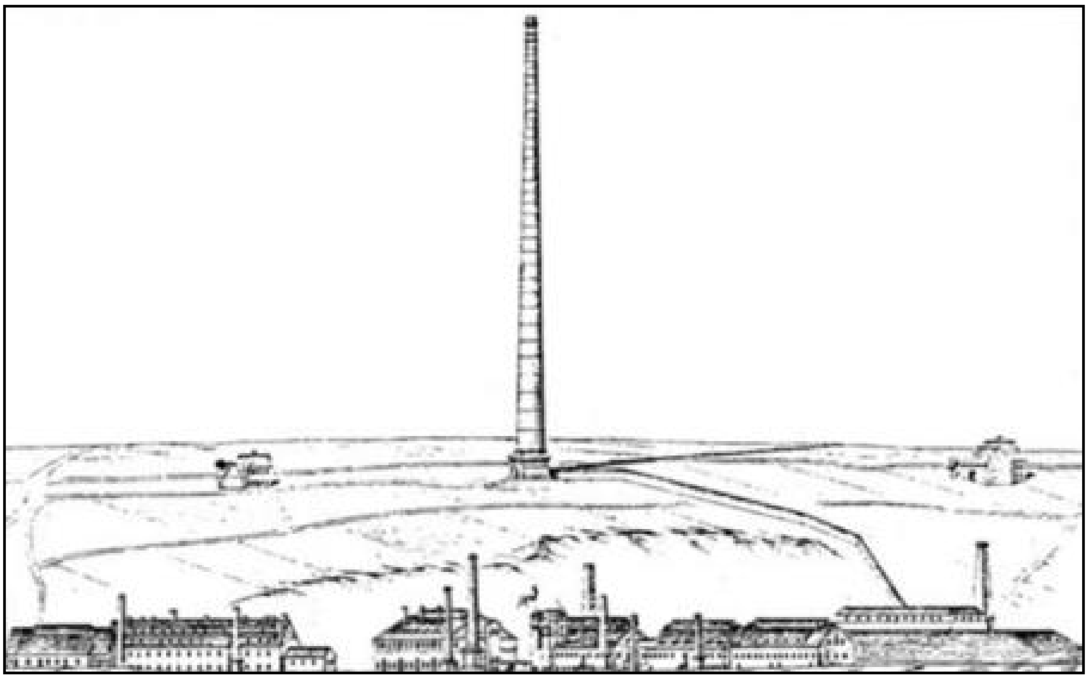


Figure 5. The chimney, Halsbrücker Esse, at Halsbrücke in 1889 (Andersen 2006)

The site was cultivated with different clones of poplar (*Populus sp*. H 275 and Max 3) and willow (*Salix sp*. Tora, Sven and Jorr) in a double row system with a high planting density at about 11,850 trees ha^{-1} (Figure 6).

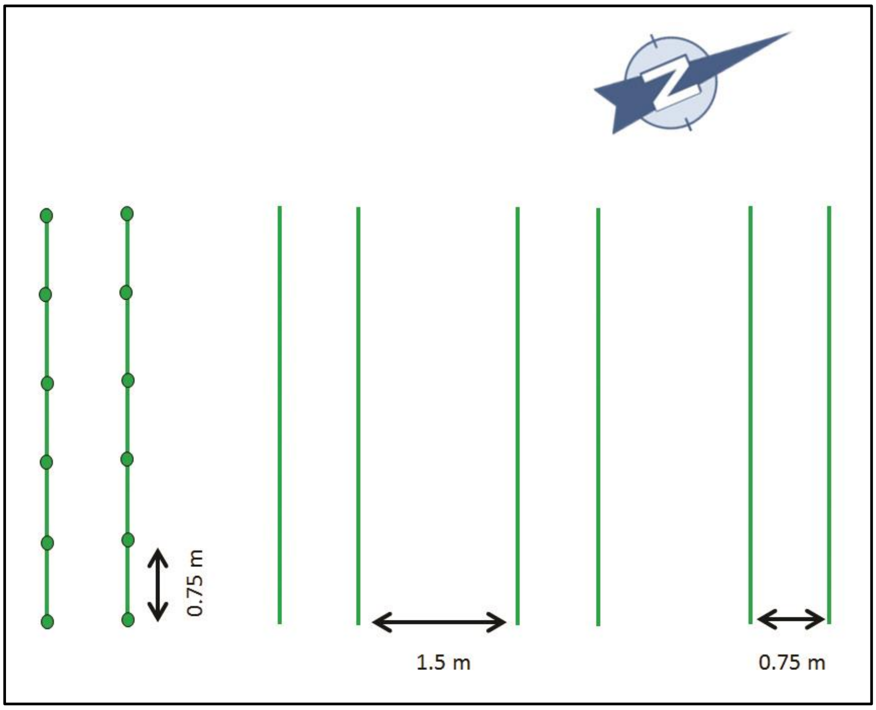


Figure 6. Plant spacing of the double row system at the SRF site

The annual average rainfall is 820 mm and the mean annual average temperature is 7.2°C. The soil is silt loam in texture (Figure 7) and classified as average quality, ackerzahl 45. (Ackerzahl is a soil quality index used to rate fields in Germany that ranges between 1= very bad and 120=excellent.) The soil is not deep, has a pH value of 5.7 and contains 2.5% humus in the top 30-cm layer (Röhricht and Kiesewalter 2008), with an average cation exchange capacity (CEC) of 10.7±0.6. The site has a gentle slope of about 5% towards the southwest and 2–3% towards the northwest.

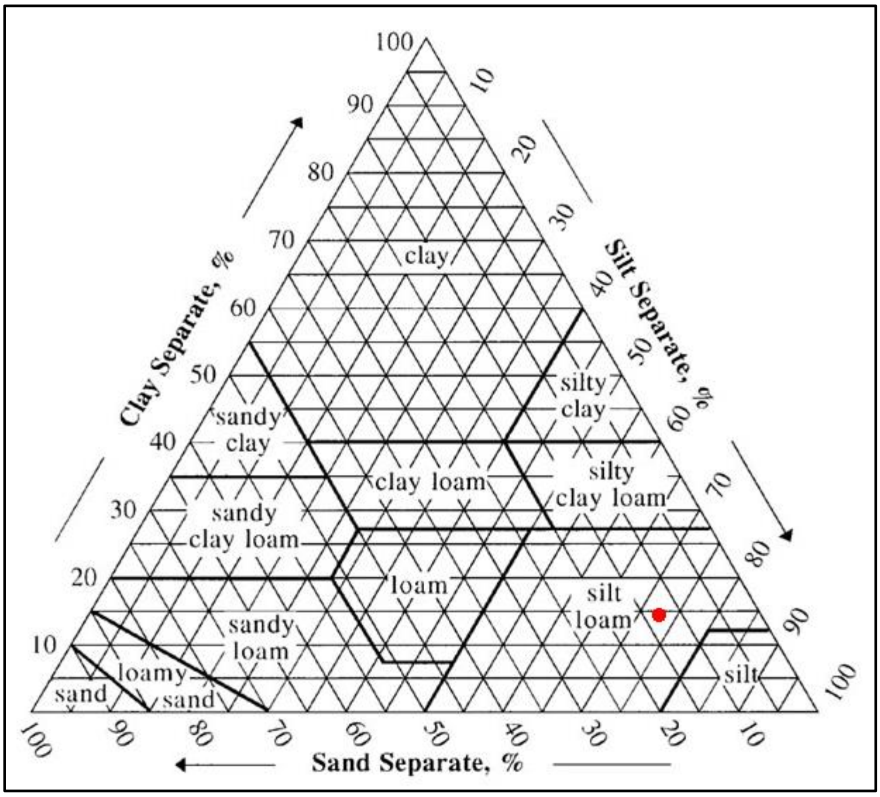


Figure 7. Soil texture at the SRF site, the diagram was generated through the website of the United States Department of Agriculture (http://www.nrcs.usda.gov/)

The adjacent rapeseed field (about 12-hectare site located at a few meters to the north of the short rotation forest) and a grassland site surrounding the SRF site (about 1000 m^2) have almost the same site conditions and are examined in parallel in this work's study area (Figure 8).

Figure 8. Study site at Krummenhennersdorf, Germany that includes a short rotation forest and rapeseed field

2.2. Environmental variables

Average monthly temperature and precipitation data were obtained from monthly statistics available online at (wetter.com). Various parameters were registered during each measurement:

- Soil temperature and soil moisture content by inserting sensors into soil at a depth of about 10 cm, (Th2-f UMS© and EC-5-k Decagon©, respectively),
- Photosynthetically active radiation (PAR) below the canopy at about 50 cm above the soil surface (SQ-215 Apogee Instruments©) and
- Air pressure, air temperature and relative humidity through the built-in SEMACH-FG sensors as described in section 2.3.1 (144SC0811BARO Sensor Technics©, PT1000 Pollin© and DKRF 4001-P Driesen©, respectively).

2.3. Measuring CO_2 emissions

2.3.1. Soil emission of CO_2

Soil emissions were measured monthly in 2013 and biweekly from April to December in 2014 with a manual opaque dynamic closed chamber system (SEMACH-FG). This system consists of a transparent cylindrical chamber (acrylic glass, volume 15.87 L) to trap emitted CO_2 from the soil surface. An infra-red CO_2 sensor (Vaisala GMP343) inside the chamber logs the concentrations. Within the chamber air is contained, homogenized with a small fan, and sensors measure the parameters of volumetric water content (EC-5-k Decagon©) and soil temperature (Th2-f UMS©). In addition, air temperature, air pressure and relative humidity inside and outside the chamber, as well as photosynthetic active radiation (PAR) are measured. The chamber is connected to a portable computer to collect and store the data (Figure 9).

Figure 9. Manual soil respiration measuring system (SEMACH-FG). *Top*: PVC collar; *Lower-left*: gas collection chamber; *Lower-right*: registration and steering unit.

CO_2 was registered by placing the chamber on collars (diameter 25 cm) that were inserted in the soil at up to 5-cm depths one week prior to measurement. These collars contain an inner rubber ring that has two main purposes: it gives the chamber a tight fit to contain gas released from the soil (preventing leakage) and also ensures a stable positioning of the chamber (Rochette et al. 1997). Each measurement lasted

for a short time, followed by a 5-min interval with the chamber open to restore ambient conditions inside the chamber. The measuring period was shortened to three minutes to avoid the negative effect of placing the chamber on soil surface, i.e. changing soil environment (Rochette et al. 1997). The CO_2 flux was calculated with linear regression of the concentration in ppm_v versus time. The last 120 seconds were used to calculate the slope of the CO_2 accumulation inside the chamber.
Soil emission rate was calculated based on the following formula:

$$FCO_2 = \frac{\Delta VCO_2 * V_{ch} * P_{ch} * 100}{60 * R * (T_{ch} + 273.15) * A_{ch}}$$

where FCO_2 is the emission rate in µmol CO_2 m^{-2} s^{-1},
V_{Ch} is the volume of chamber (m^3),
ΔCO_2 is the mixing ratio of the CO_2 inside the chamber (ppm_v min^{-1}),
P_{Ch} is the air pressure inside the chamber (mbar),
R is the universal gas constant (KJ mol^{-1} K^{-1}),
T_{Ch} is the air temperature inside the chamber (°C) and
A_{ch} is the chamber cross-sectional area (m^2).

At the willow and poplar SRF site, each plant type was represented by two measuring points (10 collars at SRF site), and by three measuring points at the rapeseed site. Collars were inserted at randomly selected points at both sites because the soil emission rate does not significantly differ in areas either between two double rows or within a double row (Pacaldo et al. 2014). At each sampling point, three individual measurements were taken each time. The average emission rate was calculated from the average of the two points.

2.3.2. Sensitivity of soil respiration to temperature (Q_{10})

Q_{10} is used as an indicator of temperature sensitivity to soil respiration, as well, it is an important parameter in different ecosystem models (Xu and Qi 2001). Furthermore, our calculations are based on van ’t Hoff equation, which is the most common one as described by Davidson et al. (2006):

$$F = \propto e^{\beta T}$$

$$Q_{10} = e^{\beta \times 10}$$

where F is the emission rate (µmol CO_2 m^{-2} s^{-1}),
α and β are fitted parameters, and
T is the soil temperature in (°C) at depth of 10 cm.

Correlation between soil temperature and soil respiration was fitted to obtain regression coefficients (α and β) for each clone, then average Q_{10} values were estimated for willow and poplar clones.

2.4. Willow and poplar leaf traits

From each plant type, two healthy, fully expanded leaves from each of five individual plants were collected per month as described by Cornelissen et al. (2003). Leaves were scanned to measure leaf size by using image analysis software. Leaves were dried in the oven at 80 °C for 48 h, then dry mass were weighed to calculate the Specific Leaf Area (SLA).

2.4.1. Measuring leaf area

Collected leaves were scanned using (Zeutschel OS 12000 HQ) scanner. Four pieces of 1 cm^2 papers were cut with known sizes and scanned within each leaf. Then, images were processed to count pixels and converting them into area unit with Adobe Photoshop 7.0 ME software (Figure 10), by averaging number of pixels per cm^2, Leaf Area (LA) was estimated using the following equation:

$$\text{Leaf Area } (cm^2) = \frac{x}{y}$$

where x is the number of pixels within the selected area (leaf) and
y is the average number of pixels per cm^2.

To check the accuracy of this procedure, three of the four squares were used to estimate the average number of pixel per cm^2, then the average value was used to estimate the area of the fourth square, results were always 1±0.02 cm^2.

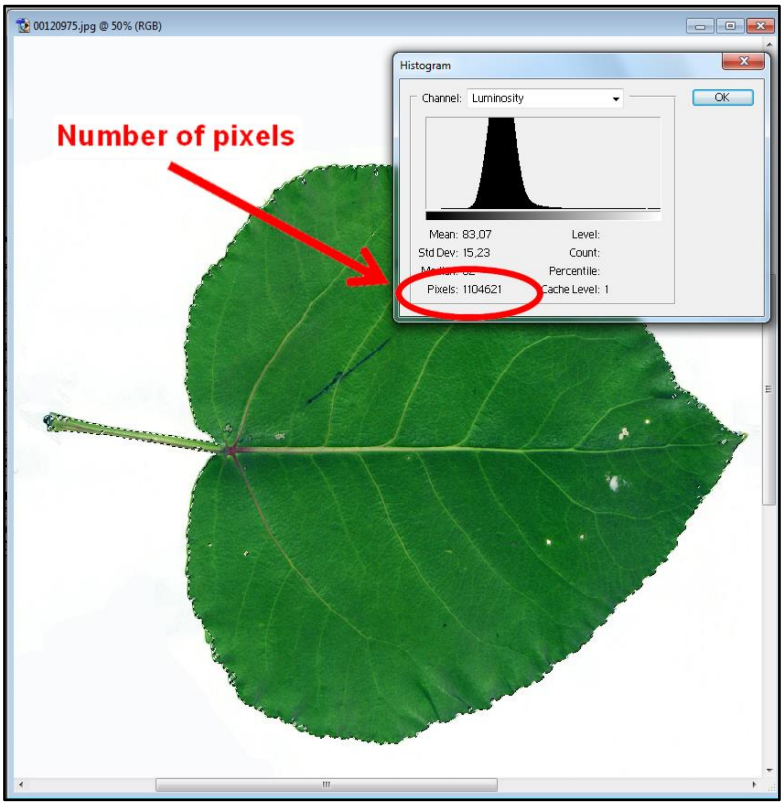


Figure 10. Measuring leaf area by counting number of pixels of a scanned fresh leaf using Adobe Photoshop software.

In addition to leaf area, Specific Leaf Area (SLA) is calculated as the ratio between the one-sided area of a fresh leaf and its oven-dry mass (leaf area per dry mass; m^2 kg^{-1}). Or leaf mass per area (LMA) which is the inversed value of SLA (1/SLA).

2.4.2. Leaf Area Index (LAI)

Photosynthesis is the most important process where atmospheric carbon is fixed by plants (Farooq et al. 2015). This process is strongly influenced by the leaf area of the tree canopy (King and Evans 1967) that may indirectly influence soil respiration and can be characterized by the leaf area index (LAI). For this reason, LAI for willow and poplar clones were estimated in order to investigate any correlation between LAI and soil respiration.

In general, the maximum leaf area index (LAI) is reached by willow trees in August under temperate climate (Iritz and Lindroth 1996) hence, hemispherical photographs were taken at the SRF site in August 2014 using a digital camera (Nikon Coolpix 4500) equipped with a hemispherical (fisheye) lens. Photos were taken using a self-leveling mount (type SLM2) with a tripod. The hemispherical images were analyzed later with HemiView Software® (Delta-T Devices Ltd) to measure LAI. For each plant species (clone), 12 images taken from four different points, with a minimum 10 m distance between each point (Figure 11).

Figure 11. Collecting Digital hemispherical photographs at SRF

2.4.3. Leaf sensitivity to high and low temperatures

The starting time leaf buds break in poplar trees in spring was observed 2–3 weeks later than willow. For that, a small test was carried out to check the sensitivity of their leaves to temperature. The procedure followed as described by Cornelissen et al. (2003). Two healthy, young and fully expanded leaves were collected from six randomly selected individuals of H275, Max 3 (poplar) Tora, Sven and Jorr (willow) trees with a minimum number of 12 leaves from each clone. Leaves were rinsed with deionized water and dried. From each leaf, four 5-mm-diameter leaf discs were cut and rinsed with deionized water for 2 h. For each replicate, two discs were submerged in 1 mL deionized water in Eppendorf 2 ml tubes. For each treatment, six replicates were made using 6 Eppendorf tubes (Figure 12).

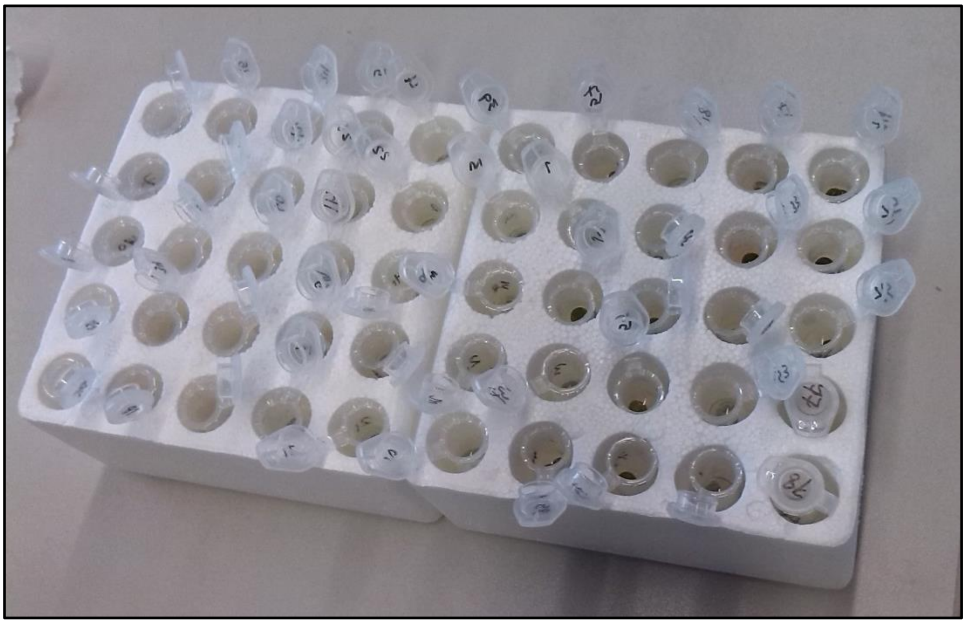


Figure 12. Leaf discs in Eppendorf tubes

To assess leaf sensitivity to cold and hot temperatures, six tubes for each clone were kept in darkness for 14 h under -20°C, 40°C and at room temperature 20°C as control (each clone has 18 tubes). Later, all samples were kept at room temperature until their temperatures reached the ambient, then electrical conductivity of solutions were measured using a calibrated compact conductivity meter (B-173 HORIBA®; Figure 13), with an accuracy value of ±2% when the conductivity is less than 10 mS/cm. Afterward, tubes were kept for 15 minutes in a boiling bath, left until the temperatures cooled down, then the electrical conductivity of the solutions were measured again.

Figure 13. Compact conductivity meter

The damage to leaves by low or high temperatures was calculated as the percentage of electrolyte leakage (PEL). For each sample, PEL is calculated by dividing its electrical conductivity measured directly after the treatment by the conductivity value after boiling it.

For each plant species, one average value of PEL for the control was calculated. Then, this value was used to calculate the corrected PEL as shown in the following equation:

$$\text{Corrected PEL} = \text{PEL}_{\text{treatment}} - \text{PEL}_{\text{control}}$$

where $\text{PEL}_{\text{treatment}}$ is the value of freezing or hot temperature treatment, and $\text{PEL}_{\text{control}}$ is the average value of PEL for each species kept under room temperature.

2.5. Soil characteristics

Investigating the physical and chemical properties of soil might help to explain the differences in soil emission of CO_2 among willow and poplar clones. For this purpose, 30 soil cores were taken to make six composite soil samples at the base of the willow and poplar clones, as well from the grassland surrounding the SRF site.

2.5.1. Soil sampling

Soil samples from the top 30 cm of the soil horizon were collected using a manual auger (semi-cylindrical stainless steel) at the SRF site in September 2014. From each clone, (5 clones), five sub-samples over an area of about 3,000 m^2 were mixed and homogenized to constitute a composite sample of ca. 1.5 kg each. Samples were oven dried at 40 °C, hammered and homogenized. For pH and cation exchange capacity (CEC) analysis, samples were passed through 2-mm sieves. For CNS and ICP analysis, samples were pulverized using an agate mill and then sieved to a particle size of less than 0.63 µm.
In December 2014, six undisturbed soil core samples were collected from depths between 10–20 cm from the immediately around the Tora clone using a soil sampling ring kit. The rings have an inner volume of 100 cm^3 (57 mm inner diameter, 40.5 mm height).

2.5.2. Soil Moisture Content % (SMC) by gravimetric method

Three soil samples of about 15 g each were oven dried at 110 °C to a constant weight. Soil moisture content (%) was calculated as a percentage of their dry weight based on the following formula:

$$SMC = \frac{W1 - W2}{W2} \times 100$$

where *W1* is the weight of wet soil (g) and
W2 is weight of dried soil (g).

2.5.3. Soil pH

A suspension of 1:5 (V/V) was prepared by mixing 10 g dry-soil sample sieved and has size less than 2 mm with 50 ml distilled water at room temperature. The suspension was shaken for 5 minutes, then allowed to settle for 15 minutes before immersing the electrode of the portable IDS pH- electrodes (SenTix® 91 WTW®), which was calibrated with standard solutions.

2.5.4. Soil Cation Exchange Capacity (CEC)

CEC was determined for two soil samples from Max (poplar) and Tora (willow) clones using UV VIS-Spectrophotometer as described by Blume et al. (2011).

2.5.5. Soil content of C, N, S and trace elements

Soil samples were prepared for analysis by adopting the common procedure used at the clean laboratories of the Institute for Mineralogy, TU Bergakademie Freiberg, where the analyses were done. Zinc, Ni, As, Cr, Cu and Pb were determined by inductively-coupled plasma atomic emission spectrometry (ICP-AES; Optima 3300DV), while Cd was determined by graphite furnace atomic absorption spectroscopy (GFAAS, Zeeman 4100). Detection limits were 0.4 (Zn), 0.8 (Ni), 6.3 (As), 0.8 (Cr), 0.1 (Cd), 0.46 (Cu) and 3.3 (Pb) mg kg^{-1}.

2.5.6. Soil porosity

Soil porosity is needed to calculate both the pore volume of the soil column, as well the soil in the field. It is estimated based on the following formula:

$$Soil\ porosity = 1 - (\frac{Bulk\ density}{Particle\ density})$$

2.5.7. Soil pore water

Samples of soil pore water were collected from three locations at the SRF site using suction cups. The sampling system consists of a porous ceramic cup placed underground (diameter 63 mm, length 35 cm), from which an empty PVC tube leads to a 1-L collection bottle on the ground surface. A second PVC tube connects the bottle to a hand-vacuum pump, which created a low pressure to about -0.8 bar, thereby creating a suction to withdraw pore water near the soil surface. The sampling system was left in field for about one week to retrieve pore water (Figure 14).

Figure 14. Pressure vacuum soil water sampler at the SRF site with a hand-vacuum pump

2.5.8. Soil hydraulic conductivity (Kf)

For the soil column experiment, the soil hydraulic conductivity, Kf value, is needed to estimate the speed at which water moves within a soil column. A soil saturated hydraulic conductivity test was done to determine the coefficient (k) in Darcy's equation by direct method in the laboratory, based on Schlichting et al. (1995). Six undisturbed samples were collected from the SRF field (Tora clone site) using steel cylinders with a volume of 100 cm^3. In the laboratory, the outside of the cylinders were cleaned before weighing them and prepared for the test. After cylinders were sealed at the bottom with a fine-nylon mesh and fixed with a rubber ring, the samples were immersed in water for one week until soil samples were saturated (Figure 15 and Figure 16). Care was taken to avoid trapping air when samples were immersed. Before conditioning the samples in the laboratory, tissues (nylon mesh), rubber rings, cylinders and soil samples were weighed.

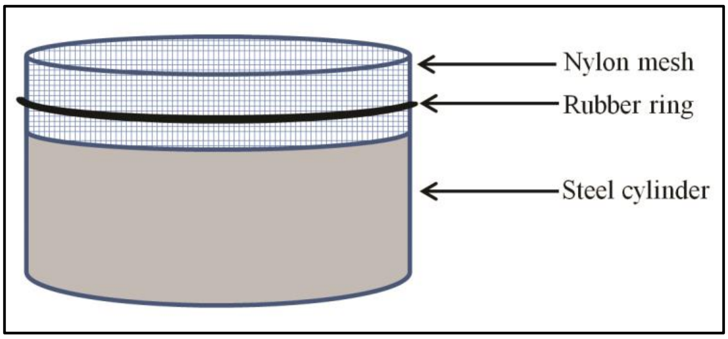


Figure 15. Mesh covered cylinder

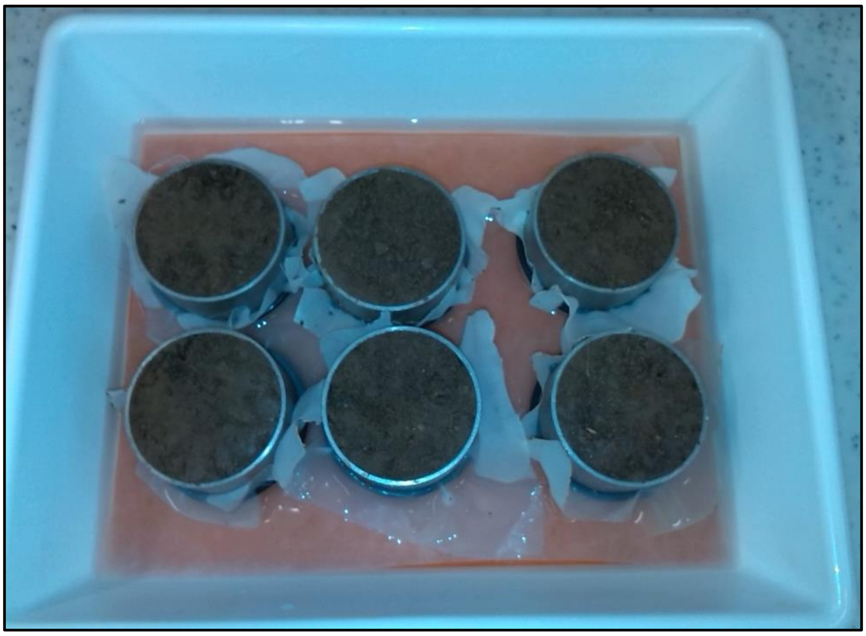


Figure 16. Conditioning samples

After one week, soil samples were ready for the test and moved to the sample holder ‘Hauben permeameter’. The samples were covered completely with water (Figure 17). For each sample, flow rate over certain time was estimated three times, then kf values were estimated based on Darcy's law using the following formula:

$$K = \frac{V \cdot l}{F \cdot t \cdot h}$$

where K is the hydraulic conductivity (cm s^{-1}),

V is the water volume (cm^3) flowed in a specific time t (s),

l is the soil height (cm),

F is the cross-section (cm^2), and

h is the hydraulic gradient (cm).

Figure 17. Soil samples are in the Hauben permeameter

2.6. Soil-column experiment

The soil-column experiment is important in investigating the fate of trace elements in soil, where the distribution coefficient K_d for trace elements (e.g., As, Cd, Pb and Zn) can be estimated. This experiment is also essential in estimating the remediation time of contaminated soils with trace elements that is needed to reach the legal limits set by the government. For example, the concentration of As in soil should not exceed 50 mg kg^{-1} in grasslands, as set by German Federal Soil Protection and Contaminated Site Ordinance (BBodSchV 1999).

2.6.1. Experiment set-up

Three polytetrafluoroethylene PTFE columns (inner diameter of 2 cm, 30 cm inner height) were filled with the soil composite sample collected from a willow clone (Tora) at the SRF site. During the experiment, columns were fed with rainwater (collected one day before running the experiment from the university campus) to simulate the field situation, and pumped from the bottom with a flow rate of 80 µL min^{-1} using a high precision peristaltic pump (Ismatec® IPC, Switzerland). Effluent were collected daily (125 ml every 24 h) in 250-ml tubes over a time period of 120 h (Figure 18). Effluent samples were immediately filtered with 0.2 µm cellulose acetate filters (Membrex, Germany) and acidified by adding few drops of HNO_3 30% and refrigerated for ICP-MS analysis, in addition, Rainwater samples were prepared in exactly the same way for ICP-MS analysis.

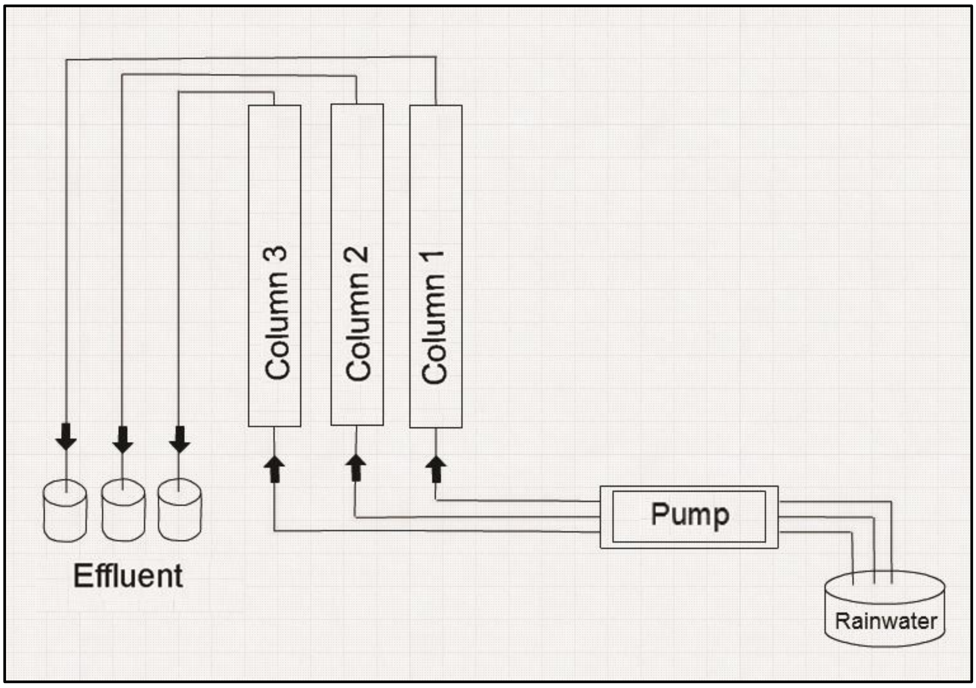


Figure 18. Schematic drawing of the experimental setup of soil-column experiment

2.6.2. Distribution coefficients (K_d)

Also known as solid–liquid partition coefficients, K_d is the ratio between the concentration of the element on the soil solid phase to its concentration in the soil solution phase. The lowest K_d values, is the highest leaching or moving element, for example, if an element has value of 0, this means the element has the same velocity of the water in soil, and there is no adsorption (Sheppard et al. 2009).

The K_d is calculated based on the following equation:

$$K_d = \frac{\text{Sorbed metal}}{\text{dissolved metal}}$$

where the sorbed metal expressed by the concentration of the metal in the solid phase (mg kg^{-1}) and the dissolved metal expressed by the concentration in the liquid phase (mg L^{-1}).

2.7. MICMAC approach

Providing the energy sector with woody-biomass from SRF goes through different stages; from establishing the field, via crop management, harvesting and transportation, to drying and biomass storage. Yet, the success of such a system is affected by various parameters. Thus to ensure the sustainability of such projects, we need to study and understand these parameters and their direct and indirect interdependencies. Humans are unable to explore indirect relationships in complex systems, or to process multifactor-interdependencies without the help of specialized software. The MICMAC® software (Cross-impact matrix multiplication applied to classification) has been developed by a French Computer Innovation Institute 3IE (Institut d'Innovation Informatique pour l'Entreprise). It can be used to analyse highly complex systems. It studies relationships between selected and potentially influential variables.

In order to apply the MICMAC approach, the recommended steps described in the manual of the software MICMAC® (version 6.1.3) were followed (see below).

2.7.1. Selection of variables

A comprehensive literature review, meetings and discussions with experts were carried out to identify the variables that characterize the system.

2.7.2. Description of direct relationships

Relationships between variables were described and scored using a dual-entry table. Values were recorded that represented the strength of the direct relationship (influence) between each pair of variables *i and j*, where *i* is the variable in raw position and *j* is in column position. A scale of 1, 2 and 3 was used to indicate a weak, average and strong relationship, 0 was used when relationships did not exist, and P indicated a potential relationship. A matrix of direct influences (MDI) resulted. All elements in the system are connected through this matrix, describing the system better. The highest sums of scores for each row "I" represents the most directly influencing factors and for each column "j" the most dependency factors.

2.7.3. Classification of variables

It is important to study the indirect relations between variables (V) in the system, e.g., if variable V1 influences V2, and V2 influences V3, then V1 will influence V3. Thus, indirect relationships were indicated to the fifth level. Based on the MDI, a Matrix of Indirect Influences (MII) was generated using MICMAC by multiplication through a number of loop iterations. In order to classify variables according to their direct and indirect relationships, maps of direct and indirect relations were produced by plotting parameters on two axes: X represents dependence power and Y represents driving power. In this way, variables are distributed according to their relation power and make it easier to visually understand the existing relationships between variables.

From the generated maps, variables were classified into four groups (clusters; Figure 19): Autonomous variables, dependence variables, linkage variables and driving or independent variables.

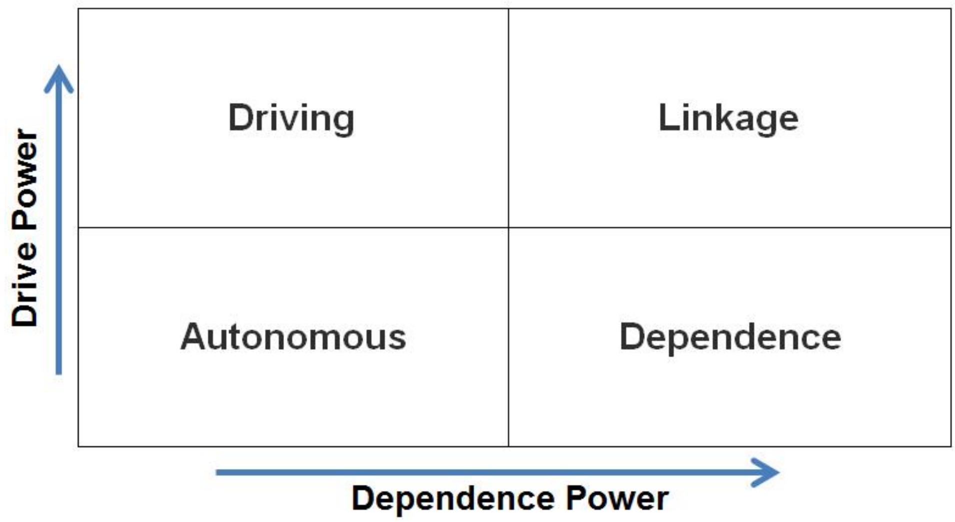


Figure 19. Influence/dependence map

2.8. Impacts of land-use change on the ecosystem quality

This part of the study aims to assess the impacts of land-use change and occupation on ecosystem quality, when land-use is changed from degraded land (grassland) to willow and poplar SRF. To conduct this assessment, the procedure described by Achten et al. (2008, 2010) was followed, which is based on the cause-effect chain, by selecting and quantifying many mid-points and end-points. The selected mid-points are parameters in the impact chain and link causes with the end-points (Bare 2010). For example, changing the soil physically can be considered a mid-point for the biodiversity end-point because this change may alter species composition and negatively affect the biodiversity (Brandão et al. 2011; European Union 2011). In this study, two end-points were selected and their impacts were quantified: the Ecosystem Structural Quality (ESQ) and the Ecosystem Functional Quality (EFQ). To quantify each of the end-points, three relevant mid-points were identified. The score of each end-point impact is the aggregation of its mid-point impacts. Accordingly, the impacts of soil fertility (Sf), biodiversity (Bd) and biomass production (Bp) were used to estimate the ESQ, while soil structure (Ss), vegetation structure (Vs) and on-site water balance (Wb) were used for EFQ. In this case, the basic and important impacts were covered: soil, biodiversity, vegetation and water (Achten et al. 2008). The mid-points are greatly interconnected and interdependent, e.g., biomass production is influenced by soil erosion, salinity, fertility and compaction (Brandão and Canals 2012).

Furthermore, the mid-points were assessed non-directly and quantified through indicators. It is recommended to select one or two relevant indicators for each mid-point according to data availability. In this work, one indicator was selected for each mid-point – in particular, soil cation exchange capacity (CEC), species richness (S), total aboveground biomass (TAB), soil organic matter (SOM), leaf area index (LAI) and evapotranspiration rate (ET) were used as indicators of soil fertility (I_{sf}), biodiversity (I_{Bd}), biomass production (I_{Bp}), soil structure (I_{Ss}), vegetation structure (I_{Vs}) and on-site water balance (I_{Wb}) mid-points, respectively (Figure 20).

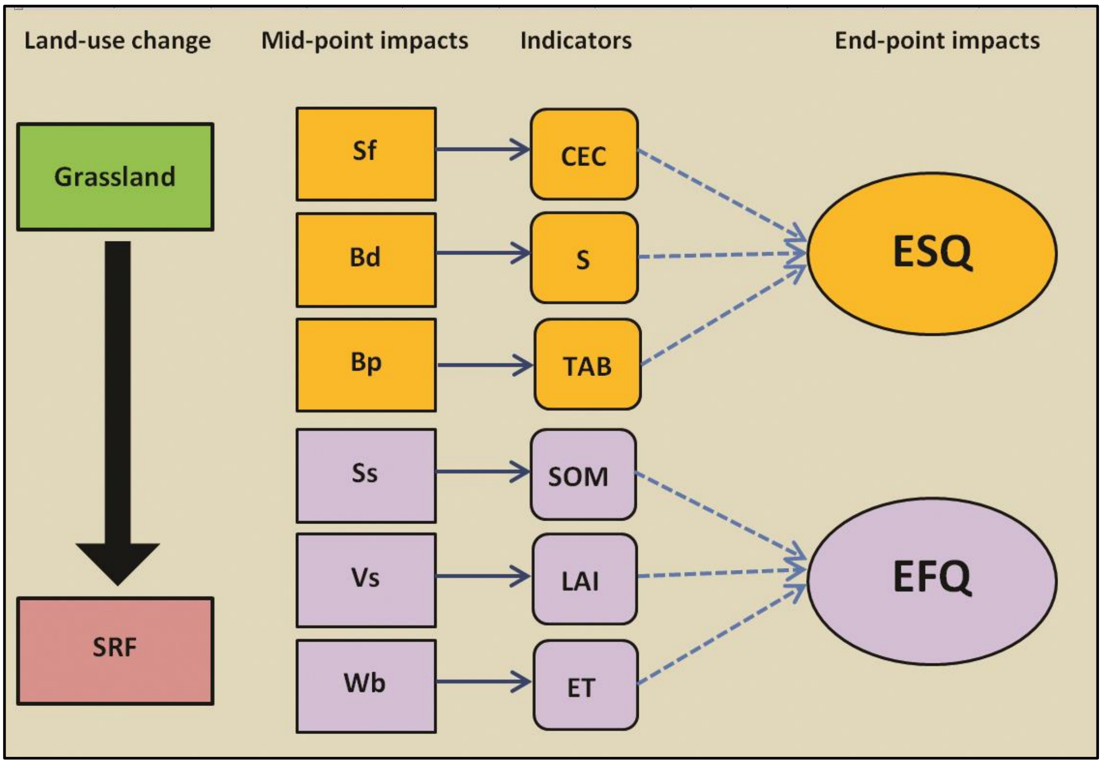


Figure 20. An outline of the assessment of land-use change and occupation impacts on the ecosystem quality, in which the linkage between the mid-points (solid arrows) and end-points (dashed arrows) through the indicators is shown (after Achten et al. 2008).

In order to assess the impacts of land-use change and land-use occupation on the ecosystem quality, reference sites are required. For land-use change impact, the former land-use is needed as a reference site, which is grassland, and was used against the new plantation which is the willow and poplar SRF. For land-use occupation impact, local potential natural vegetation (PNV) is used as the reference site. With the help of PNV maps, biome type can be determined. PNV is the expected natural vegetation of the land if is it left undisturbed by humans. For the state of Saxony, these maps are available online at the website of the Saxon State Ministry of the Environment and Agriculture (SMUL 2016).

Impacts on ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ) were calculated based on the equations reported by Achten et al. (2010).

For land-use change impacts, the following equations were used:

$$I_{ESQ} = \left(\frac{(TAB_{ref} - TAB_{SRF})}{TAB_{PNV}} + \frac{(Bd_{ref} - Bd_{SRF})}{Bd_{PNV}} + \frac{(CEC_{ref} - ECE_{SRF})}{CEC_{PNV}}\right) \div 3$$

$$I_{EFQ} = \left(\frac{(SOM_{ref} - SOM_{SRF})}{SOM_{PNV}} + \frac{(LAI_{ref} - LAI_{SRF})}{LAI_{PNV}} + \frac{(ET_{ref} - ET_{SRF})}{ET_{PNV}}\right) \div 3$$

While for land-use occupation impacts, the following equations were used:

$$I_{ESQ} = \left(\frac{(TAB_{PNV} - TAB_{SRF})}{TAB_{PNV}} + \frac{(Bd_{PNV} - Bd_{SRF})}{Bd_{PNV}} + \frac{(CEC_{PNV} - ECE_{SRF})}{CEC_{PNV}}\right) \div 3$$

$$I_{EFQ} = \left(\frac{(SOM_{PNV} - SOM_{SRF})}{SOM_{PNV}} + \frac{(LAI_{PNV} - LAI_{SRF})}{LAI_{PNV}} + \frac{(ET_{PNV} - ET_{SRF})}{ET_{PNV}}\right) \div 3$$

where I_{ESQ} is the impact score of the end-point ecosystem structural quality [%],
I_{EFQ} is the impact score of the end-point ecosystem functional quality [%],
$_{ref}$ indicates the reference site (grassland),
$_{proj}$ indicates the project or newly established land use (willow/ poplar SRF), and
$_{PNV}$ indicates the local potential natural vegetation.

2.9. Computer software

Graphs, statistical and regression analyses were made using STATGRAPHICS Centurion XVI version 16.1.11, OriginPro 9.1.0 and Microsoft Excel 2010.

3. Results and Discussion

This study provides answers to five research questions (listed in Section 1.9) that examine various aspects as to whether short rotation forestry biomass is sustainable. First, the driving forces of soil CO_2 emission from SRF site are examined and reveal that there is a significant correlation between soil emission of CO_2 and a number of environmental factors: soil temperature (ST), moisture content (SMC) and air temperature (AT). Correlations with some leaf characteristics (Leaf area LA and specific leaf area SLA) were also established. These findings can be used to model soil emission of CO_2 (filling data gap) when part of the data is missing or unavailable.

This study provides a comparison of soil respiration in areas with short rotation forests and rapeseed crops, in terms of the extracted bioenergy and emitted amounts of CO_2 from soil. Results of soil-column experiment investigated how SRF can affect the fate of trace elements in soil. The MICMAC approach investigated the driving factors for a willow and poplar SRF production system. Finally, the impacts on the ecosystem quality when land is used for SRF is assessed based on the results of a cause–effect chain analysis. On the whole, a general evaluation can be made about the sustainability of short rotation forestry biomass.

3.1. Environmental conditions

3.1.1. Photosynthetically active radiation (PAR)

Short rotation forestry has dense cultivation system, well developed and dense canopy, as well tree height were about 6–8 meters, these factors reduce light penetration and affect soil temperature. Photosynthetically active radiation (PAR) was measured below the canopy at the willow and poplar sites at about 50 cm above the soil surface and, as well at the adjacent grass site. There was a significant difference in PAR between the grass and SRF sites, yet no significant difference between willow and poplar sites (Figure 21).

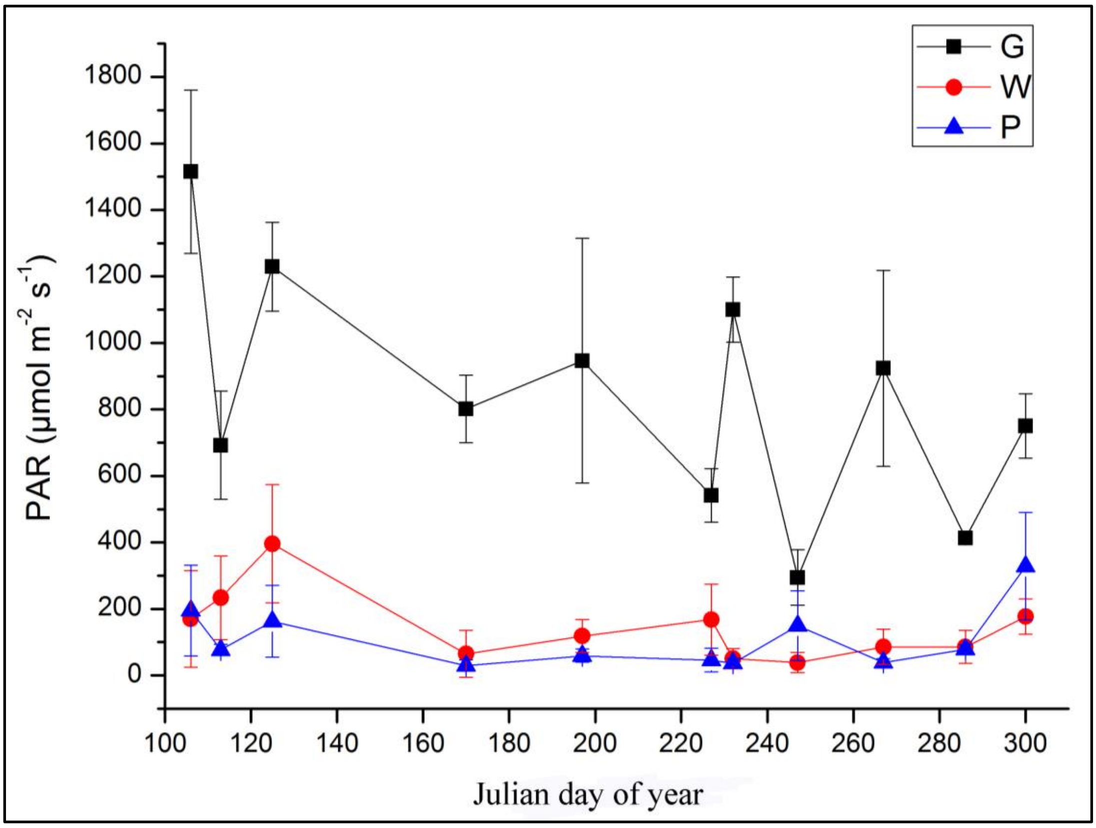


Figure 21. Photosynthetically Active Radiation (***PAR***) values measured at Grass (***G***), Willow (***W***) and Poplar (***P***) SRF sites in 2014.

3.1.2. Soil temperature

Leaf litter (mainly fallen leaves) at short rotation forestry sites normally mulch the soil and play a role in decreasing its temperature (Grigal and Berguson, 1998). The results showed that soil temperature in short rotation forests was lower than that at the neighbouring grass site (ca. 8–10 meters away from SRF site). Yet, the difference was smaller during October than that seen during the growing season from April to the end of September. The measured soil temperatures taken at a 10 cm depth at the willow/poplar SRF and grass sites can be seen in Figure 22. Soil temperatures at the poplar site were slightly cooler than at the willow during the period May–October. In April, however, the difference was either very small or the poplar site showed slightly higher soil temperatures because poplar broke dormancy about two weeks later than willow (mid April). Once the poplar leaves started to grow and reduce the direct sunlight reaching the soil, it had a cooling effect.

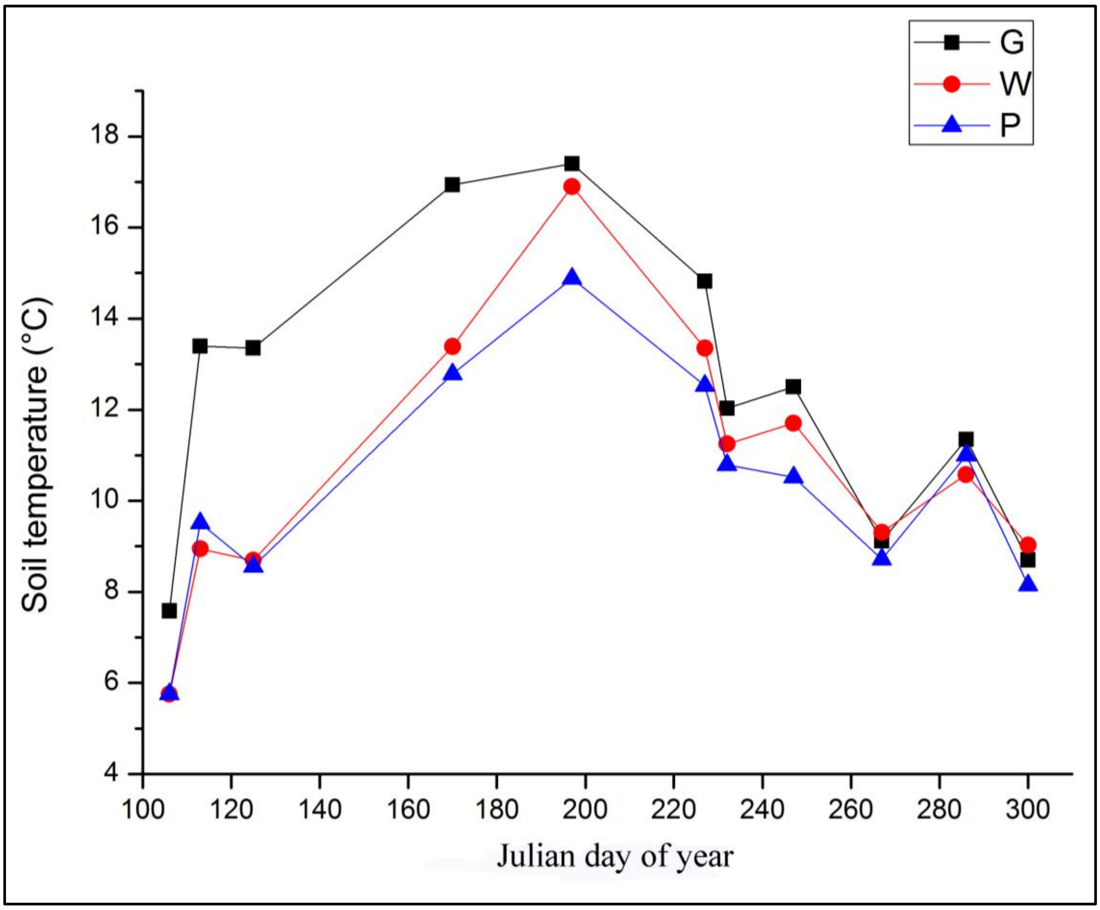


Figure 22. Soil temperature at 10-cm depth at Grass (***G***), willow (***W***) and Poplar (***P***) sites in 2014.

3.1.3. Soil moisture content

Average values for soil moisture content at SRF site ranged from 8 to 43.4%, the lowest value was measured in August 2014, and the highest in December 2014 (Figure 23).

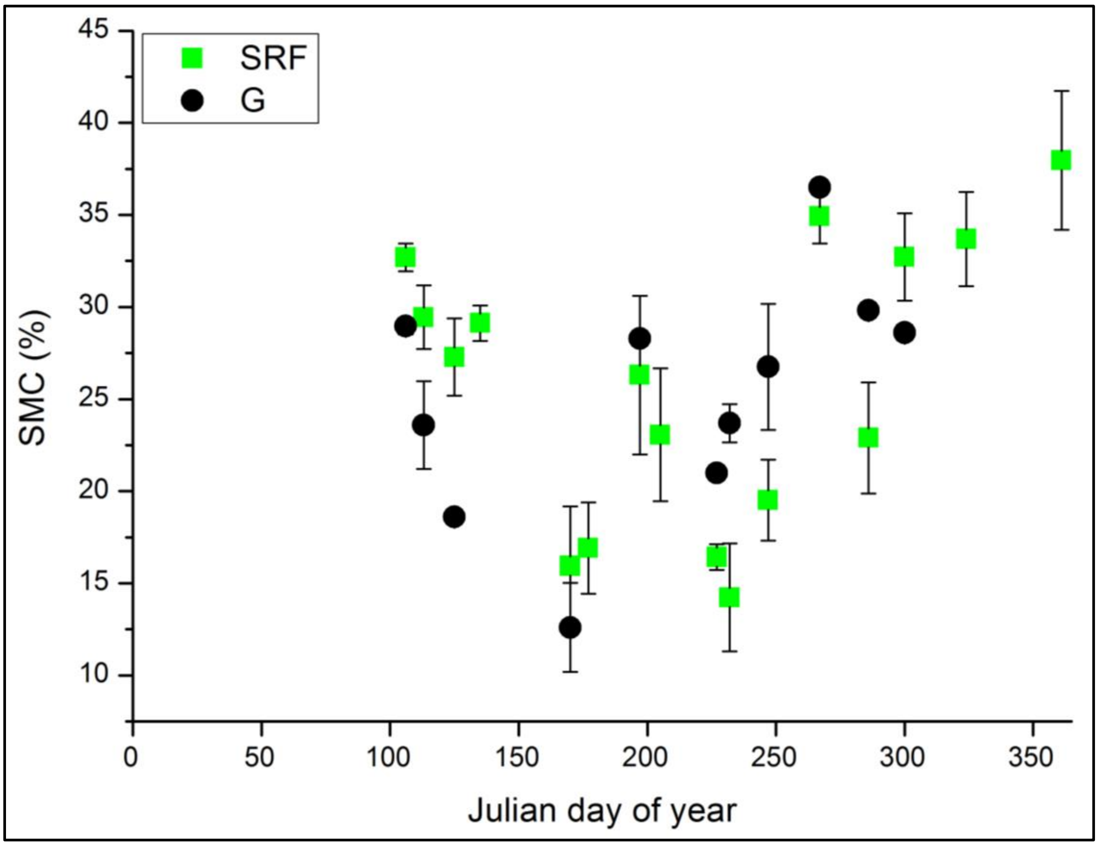


Figure 23. Average soil moisture content % (***SMC***) at willow and poplar short rotation foresty site (***SRF***) and grassland (***G***). Error bars represent two standard deviations.

As can be seen in Figure 23, at the beginning of the growing season, soil moisture content at the grassland site was higher than at SRF until the end of June. In contrast, from July until mid-October, grassland showed higher moisture content than SRF, and thereafter grasslands' moisture content started to decrease again. In this respect, it is expected that willow and poplar leaf area have an important role.

At the beginning of growing season, willow and poplar leaves were small, as seen by the leaf area (Figure 24). As leaf area increases, soil moisture content decreases and this is possibly a result of the increase in the evapotranspiration (Figure 25) for poplar SRF. The increase in leaf area is observed only until August, after that, leaf area starts to decline due to leaf rust disease (common fungal disease), in addition to the fact that leaves reach their maximum growth in July. The highest average leaf area was observed in poplar clones H 275 and Max 3, with values of 425±53 and 220±39 cm^2 $leaf^{-1}$ respectively. Barigah et al. (1994) observed wide differences in the individual leaf area of different hybrid poplar clones, which ranged from 66 to 254 cm^2 $leaf^{-1}$, with an average across all clones 148±69 cm^2 $leaf^{-1}$. Regarding willow clones, clone Tora had the highest leaf area, followed by Jorr and Sven, with values of 29.2±8.5, 27.7±2.7 and 26.7±2.9 cm^2 $leaf^{-1}$, respectively. However, the differences in leaf area between willow clones are not statistically significant.

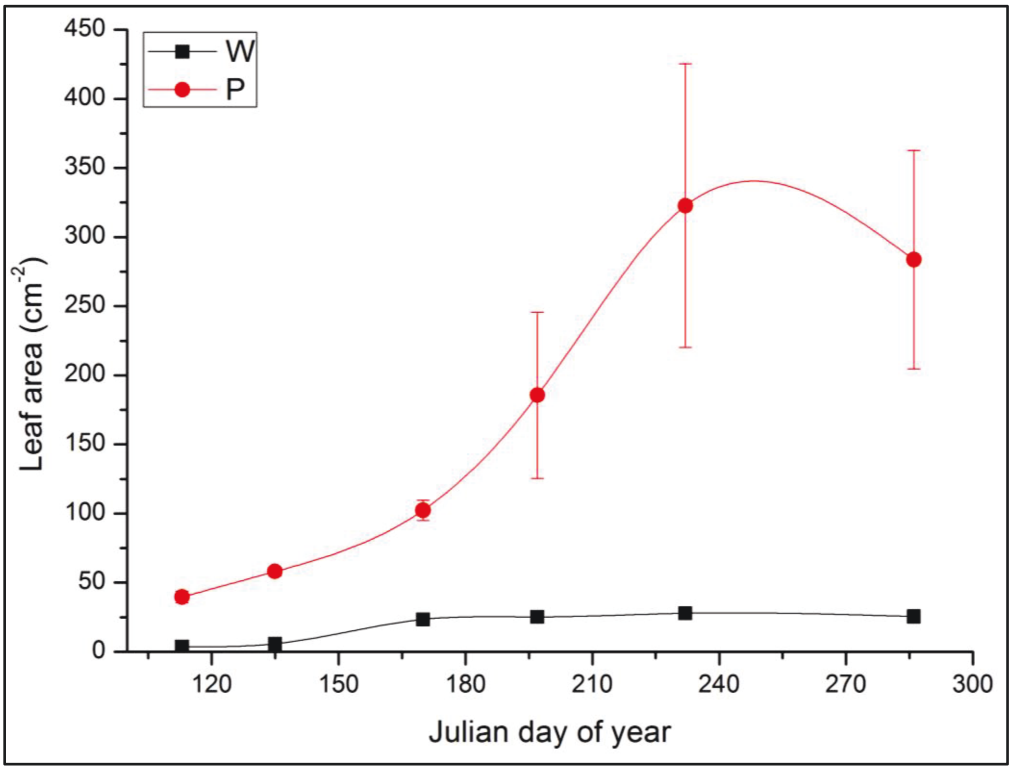


Figure 24 Average leaf area of willow (***W***) and poplar (***P***) at SRF site during the growing season in 2014

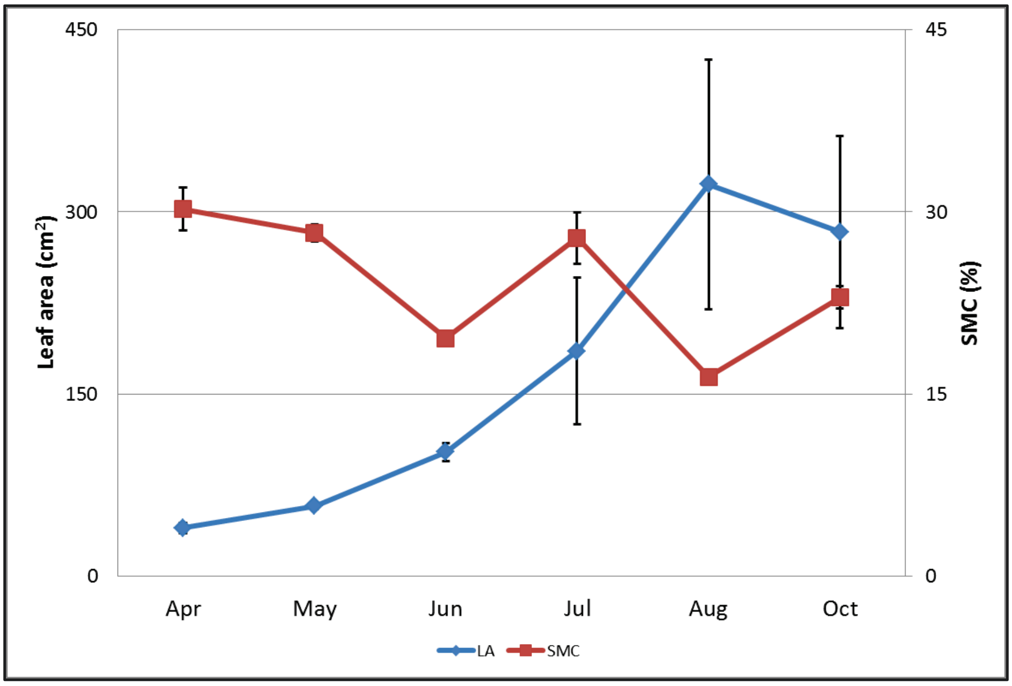


Figure 25 Poplar leaf area (***LA***) and soil moisture content (***SMC***) during the growing season in 2014

3.2. Soil emission of CO_2

3.2.1. CO_2 emission from soil at the short rotation forestry site

In general, emission rates ranged from 0.76 to 10.95 µmol CO_2 m^{-2} s^{-1} at the willow site and from 1.10 to 8.55 at the poplar site. For willow and poplar plantations, median values of soil emission were 5.62±1.81 and 5.08±1.37 µmol CO_2 m^{-2} s^{-1} during the growing season, and 2.54±0.81 and 2.07±0.56 µmol CO_2 m^{-2} s^{-1} during the dormant season, respectively, with an average emission of 3.83±2.16 µmol CO_2 m^{-2} s^{-1}. Emission of CO_2 from soils at the willow site was slightly higher than from the poplar site during the years 2013 and 2014 (Figure 26).

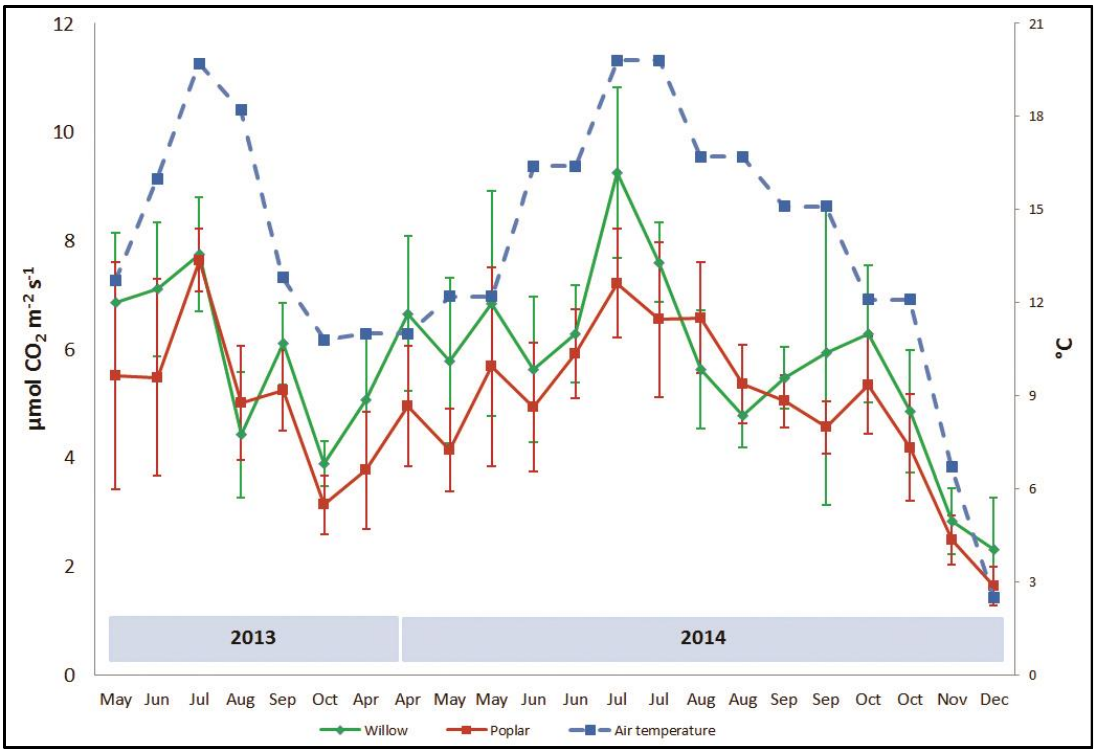


Figure 26. Monthly average air temperature and soil emission of CO_2 at willow and poplar SRF sites for the years 2013 and 2014. Bars represent two standard deviation of the mean.

As mentioned previously in Section 3.1.1 on photosynthetically active radiation, in April and early in the growing season, the difference between soil respiration at the willow and poplar plantations was statistically significant. Poplar starts its growing season about 2 weeks later than willow, which could influence the root activity. Hence, it can be deduced that the higher respiration rate from willow soil is a result of the higher autotrophic respiration R_a, namely willow's root respiration because environmental conditions (soil and air temperature and soil moisture content) at both sites were the same.

The results are consistent with earlier studies, e.g., Oertel et al. (2015) measured rate of about 3.5 µmol CO_2 m^{-2} s^{-1} of forestland in Saxony, Germany for summer. Dilustro et al. (2005) reported an emission rate of forestland in Georgia, USA. with values of 0.78 and 6.99 µmol CO_2 m^{-2} s^{-1} in winter and summer, respectively. Abou Jaoudé et al. (2011) also reported CO_2 emissions from a poplar SRF field in Central Italy: 0.9 and 5.8 µmol CO_2 m^{-2} s^{-1} for winter and summer, respectively. In addition to this, the dormant season findings of circa 0.76 µmol CO_2 m^{-2} s^{-1} from this study are in agreement with other research. Pacaldo et al. (2014) measured a rate of about 0.5 µmol CO_2 m^{-2} s^{-1} at a SRF site and Lagomarsino et al. (2013) provided value of 0.8±0.07 µmol CO_2 m^{-2} s^{-1} for a poplar SRF plantation.

Yet, values of soil emission from the SRF site in Krummenhennersdorf during the growing season are slightly higher than other researchers. For example, Yan et al. (2014) provided values for soil emission ranging between 2.92 to 4.74 µmol CO_2 m^{-2} s^{-1} from a hybrid poplar SRF site in China during the growing season. It is expected that dry conditions at such a site may play important role behind these low values, which may significantly influence soil respiration rate because average annual precipitation was about 200 mm where Yan et al. (2014) measured soil emission. Similarly, Lagomarsino et al. (2013) reported a low emission rate of 2.9±0.2 µmol CO_2 m^{-2} s^{-1} from a poplar SRF under Mediterranean conditions.

As mentioned previously, emission rates were measured once monthly during the year 2013 and biweekly during the year 2014. In Figure 27, soil emission rates of willow and poplar clones are shown using a color scale ranging from dark red indicating the highest emission rate to blue indicating the lowest. The color scale interval is 2 µmol m^{-2} s^{-1}, starting with less than 2 µmol CO_2 m^{-2} s^{-1} and ending with higher than 8 µmol CO_2 m^{-2} s^{-1}. This scale was used due to the fact that the highest emission rates (> 8 µmol CO_2 m^{-2} s^{-1}) were measured during the peak of the growing season in July, while the values dropped to below than 2 µmol CO_2 m^{-2} s^{-1} during the autumn and winter (dormant season).

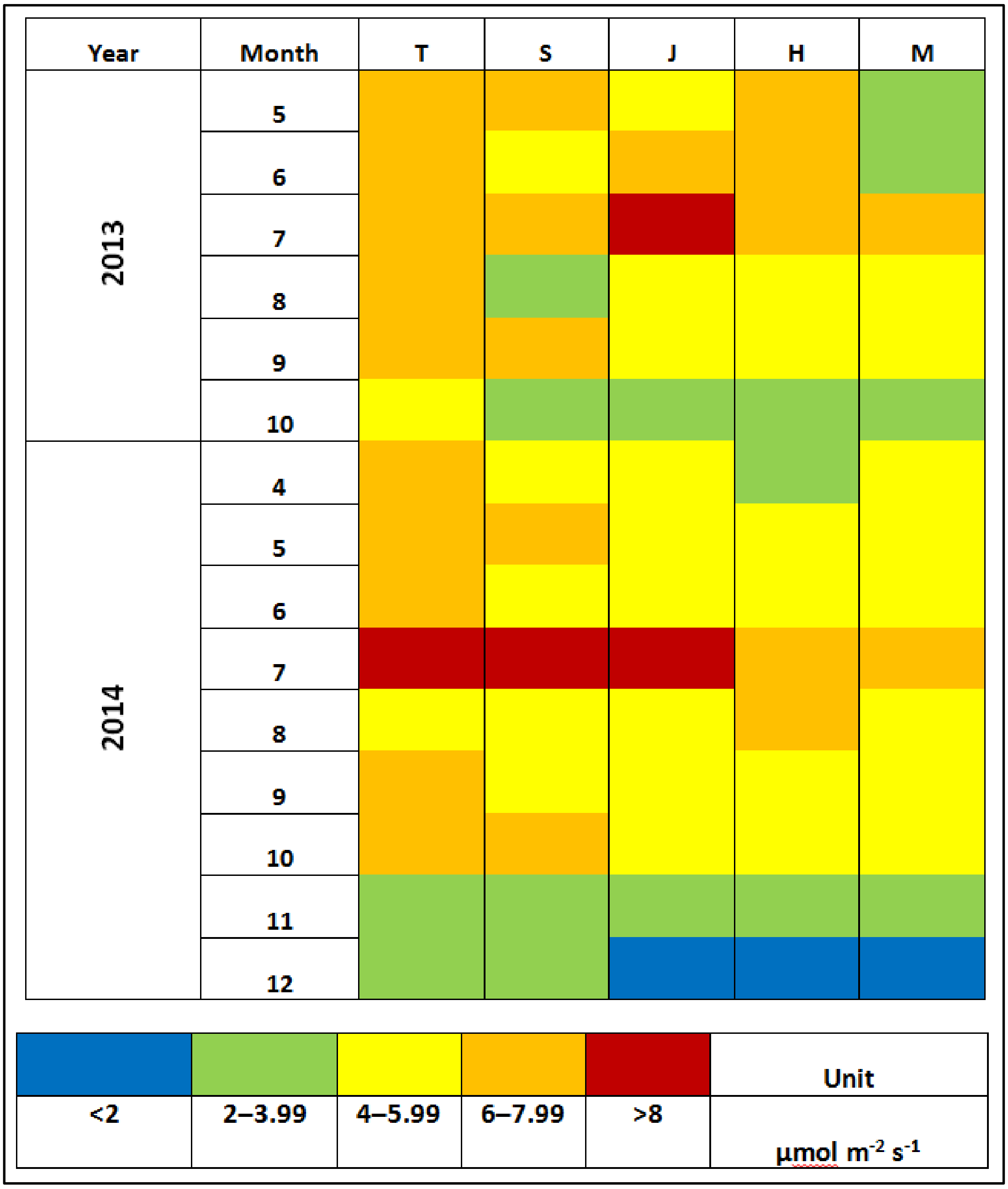


Figure 27. Soil emission rate of CO_2 from clones of willow; Tora (***T***), Sven (***S***), Jorr (***J***) and poplar; H275 (***H***) and Max 3 (***M***) in the years 2013 and 2014

3.2.2. Soil emission of CO_2 during the day and the night

A small laboratory experiment was carried out to compare soil respiration during the day and the night using 3 non-disturbed soil samples taken from the SRF site in Krummenhennersdorf. Samples were taken by inserting the same collars (diameter 25 cm, and soil depth ca. 30 cm) used to place the chamber to measure soil emission. A non-parametric test (W-test) was used to compare the median of emission rates. The results show that the difference between day and night emission rates was statistically not significant at the 95.0% confidence level, with values of 1.62±0.36

for daytime respiration and 1.16±0.25 μmol CO_2 m^{-2} s^{-1} for nighttime respiration (Figure 28).

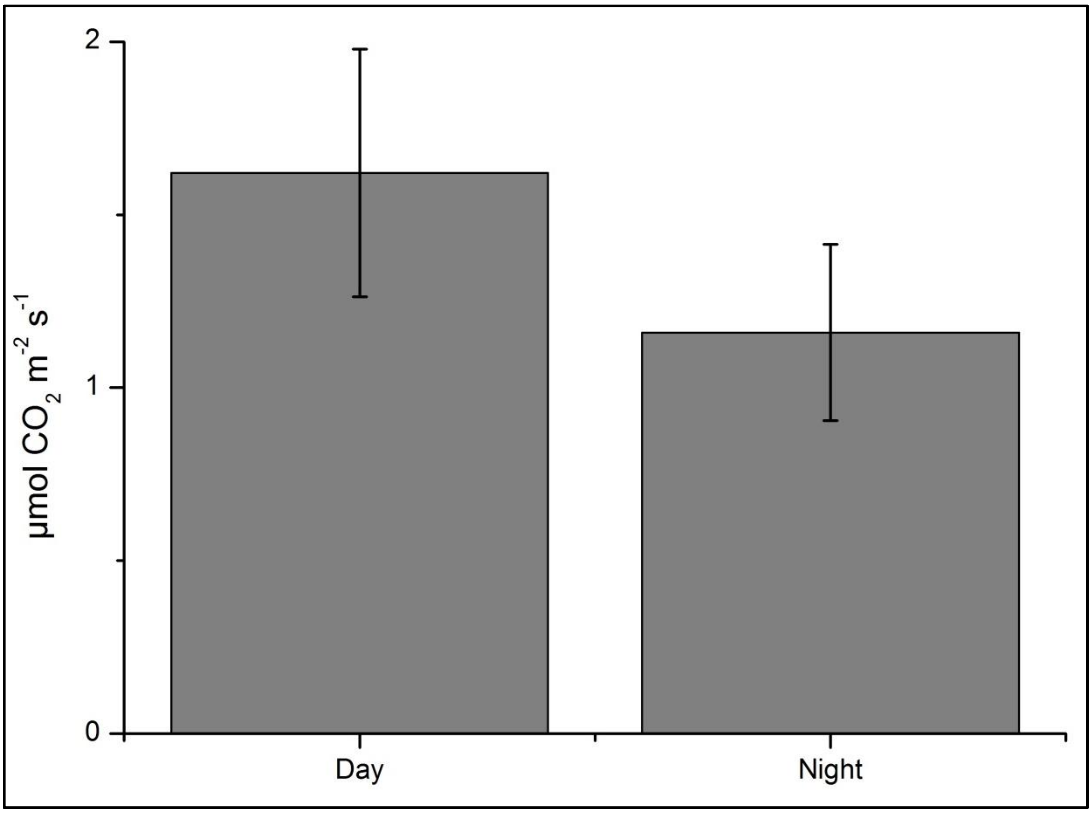


Figure 28. Soil respiration rate during the day and the night

It is important to mention that the measurements were conducted in November. Thus, and probably, most of the emission rate came from heterotrophic respiration (Rh).

3.2.3. Cumulative emission of CO_2

For each clone, the cumulative emission of CO_2 was calculated based on emission rates of year 2014. Due to the higher resolution, results show that emissions from poplar clone soil (H 275) were the lowest at 42.4±8.6 t CO_2 ha^{-1} $year^{-1}$, followed by Jorr, Max3, Sven and Tora with values of 45±3.4, 47.9±5.5, 51.3±6.3 and 53.8±6.4 t CO_2 ha^{-1} $year^{-1}$, respectively (Figure 29).

Thus, based on an estimate of the cumulative emissions of carbon dioxide from soils in this study, poplar shows less emissions 45.1±2.8 t CO_2 ha^{-1} $year^{-1}$ than willow 50±3.6 t CO_2 ha^{-1} $year^{-1}$.

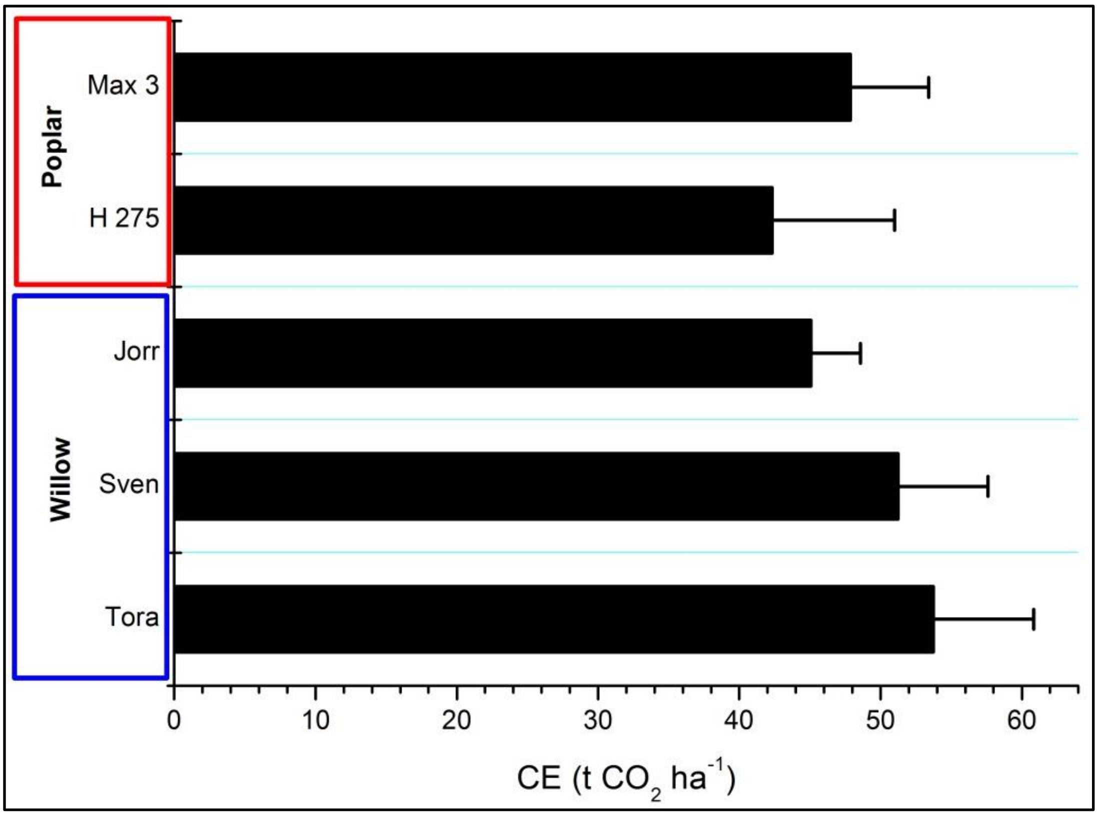


Figure 29. Annual cumulative emission of CO_2 (CE) from different willow and poplar clones under SRF plantation.

3.2.4. Comparison with other bioenergy crops

Since willow and poplar SRF are perennial bioenergy crops, soil CO_2 emissions from SRF are compared to those from other annual bioenergy crops (ABC) such as wheat, sugar cane and rapeseed, as well as emissions from forestlands (F). Therefore, a review of the published data on the emission rates was undertaken and a summary of this is shown in Table 2.

Table 2. Summary of published data on emission rates of CO_2 from soils under different vegetation covers used as energy sources

Vegetation cover	Emission rate $\mu mol\ CO_2\ m^{-2}\ s^{-1}$
Annual/Perennial Herbaceous Bioenergy Crops (ABC)	
Wheat	5.25[1], 3.95[2]
Barley	7.52[3], 3.18[4],
Sugar cane	4.86[5], 2.8[6]
Sugar beet	5[7]
Rapeseed	4.15[8]
Maize	7.05[9], 6[1], 6[10], 3.3[11]
Soybean	10.4[12]
Forests (F)	
Pine	4.1[13],3.9[14], 3.56[15], 2.79[16], 4.8[17]
Beech	3.42[18], 2.3[19] 3.7 [17]
Aspen	6.8[20]
Spruce	3.75[21], 3.1[17]
Dipterocarp	2.98[22]
Mixed	2.32[23] , 2.28[23], 1.96[23]
Fir	4.02[24]
Larch	5.7[25]
Various	3.86[26], 3.4[27], 2.06[28], 1.97[27], 1.85[28], 1.64[28], 1.38[29], 1[29], 1[30], 0.9[29], 0.83[31]
Short Rotation Forestry (SRF)	
Willow and poplar	4.86[32], 4.8[33], 4.15[34], 4.14[32], 3.71[35], 3.51[36], 2.9[37], 2.9[32], 2.17[38], 1.76[38]

[1]Zhang et al. (2013); [2]Liu et al. (2016); [3]Maljanen et al. (2004); [4]Lohila et al. (2003); [5]La Scala Jr et al. (2006); [6]Moitinho et al. (2015); [7]Fiener et al. (2012); [8]Zhang et al. (2007); [9]Zhang et al. (2014); [10]Astiani et al. (2015); [11]Gelfand et al. (2015); [12]Yang and Cai (2006); [13]Tyree et al. (2008); [14]Dilustro et al. (2005); [15]ArchMiller and Samuelson (2016); [16]wang et al. (2013); [17]Oertel et al. (2015) [18]Søe and Buchmann (2005); [19]Leitner et al. (2015); [20]Russell and Voroney (1998); [21]Laganière et al. (2012); [22]Hosea et al. (2014); [23]Shabaga et al. (2015); [24]Chen et al. (2010); [25]Liang, et al. (2004); [26]Wu et al. (2015);[27]Bond-Lamberty and Thomson (2010); [28]Mo et al. (2007); [29]Minkkinen et al. (2007); [30]Mäkiranta et al. (2007); [31]Borken and Brumme (1997); [32]Gong et al. (2012); [33]Vande Walle et al. (2007); [34]Pacaldo et al. (2014); [35]Yan et al. (2014); [36]Abou Jaoudé et al. (2011); [37]Lagomarsino et al. 2013); [38]Nikièma et al. (2012).

Since land management under SRF is less intensive than annual bioenergy crops and more intensive than forestlands, average CO_2 emission rates correlated with this order: the lowest emission rates were detected from forestlands, followed by willow and poplar SRF, and highest emissions were from annual bioenergy crops, with median values of 2.6, 3.6 and 5.0 $\mu mol\ CO_2\ m^{-2}\ s^{-1}$ respectively.

The Kruskal-Wallis test was used as a non-parametric test to check if there is a statistically significant difference amongst the medians at the 95% confidence level. As can be seen in Figure 30, there is a statistically significant difference between medians of annual bioenergy crops and both forestlands and willow/poplar SRF. Yet, the difference between medians of forestlands and willow/poplar SRF is not statistically significant.

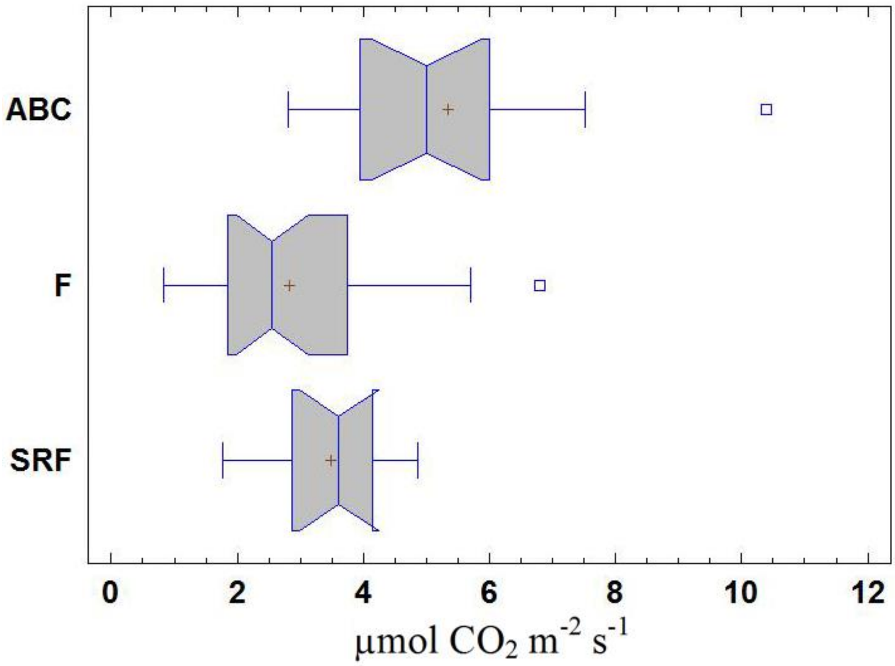


Figure 30. Box-and-Whisker Plot for soil respiration rates of Annual Bioenergy Crops ***ABC*** (n=13), Forests ***F*** (n=26) and Short Rotation Forestry ***SRF*** (n=10)

3.3. Q_{10}

Soil sensitivity to temperature Q_{10} for willow and poplar SRF for the year 2014 is found to be 2.17±1 and 2.58±0.8 respectively. These Q_{10} values for willow and poplar SRF seem similar to those measured at forestlands, e.g., Q_{10} values of 2.3±0.2 were measured at Hainich beech forest and 2.5±0.2 at Wetzstein spruce forest in Germany (Moyano et al. 2008). Average Q_{10} values for willow and poplar are listed in Table 3.

The value of Q_{10} is influenced by the measuring system, as well by measuring frequency, for example, using continuous measuring system such as automated chambers to measure soil CO_2 effluxes gives a better Q_{10} value than using the non-contiguous one because different soil temperatures and moisture contents may be missed between the successive measurements (Liang et al. 2004). Even soil emissions at the SRF site were measured with a non-continuous instrument, but the measurements were taken over a wide range of environmental conditions: high and low soil and air temperatures, different soil moisture contents, e.g., a minimum value of 8% soil moisture content and a maximum of 43.4% were measured at SRF site were in December and August, respectively.

Soil temperatures were taken at about 10-cm depth. Measuring soil temperature at different depths may, however, give different results for Q_{10}. Xu and Qi (2001) for example, estimated Q_{10} for soils at different depths (5, 10 and 20 cm) and observed a slight increase in Q_{10} with the increase in soil depth but not statistically significant.

Table 3. Q_{10} values for willow and poplar clones, based on soil temperature at 10-cm depth

Clone	Plant	Q_{10}	
		Growing season [1]	Dormant season [2]
Tora	Willow (*Salix* spp.)	1.14	2.11
Sven		1.21	2.70
Jorr		1.72	4.16
H 275	Poplar (*Populus* spp.)	1.87	3.25
Max 3		1.68	3.50

[1] 15. April–15. October
[2] 15. October–17. December

As can be seen in Figure 31, there is differences between summer and winter Q_{10} values. In summer where soil temperatures were higher than in winter, sensitivity of soil respiration to temperature was lower than in winter, these findings are in agreement with Xu and Qi (2001), who found a negative correlation between soil temperature and Q_{10} and a positive correlation with soil moisture content.

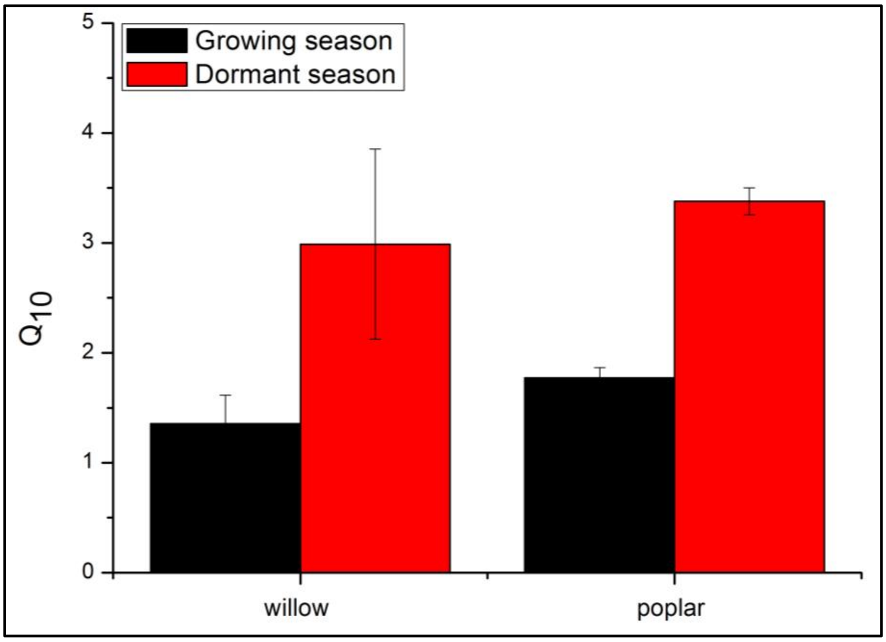


Figure 31. Average Q_{10} values for willow and poplar trees. Error bars represent two standard deviations.

3.4. Willow and poplar Leaf Characteristics

3.4.1. Leaf Area Index (LAI)

Leaf area index is an important factor controlling photosynthesis and plant productivity (Barigah et al. 1994). For this reason soil respiration will be indirectly influenced by a changing root respiration rate (autotrophic respiration), as well as by soil fauna and flora respiration, because these depend on the available substrate in the belowground. As photosynthesis increases, the translocated amounts of nutrients from the areal part to the belowground increases.

For this part of the work, normal distribution of data was tested by checking values of standardized skewness and standardized kurtosis; values were within the range (-2 and +2). Thus, the data is significantly normal distributed. To compare the means of LAI for the studied clones, Fisher's LSD intervals (Least Significant Difference) with 95.0% LSD intervals were calculated.

Leaf area indexes for willow and poplar clones ranged from 2.5 for clone Jorr to 3.4 m^2 m^{-2} for clone H275. Results show differences even between clones within the same plant type, e.g., the two poplar clones H275 and Max 3 have significantly different LAI values, as well as within willow clones: Sven significantly differs from Jorr and Tora. In general, willow clones have significantly lower LAI values than poplar ones (Figure 32).

Differences of LAI were found between different clones of hybrid poplars by other researchers. For example, Barigah et al. (1994) measured values ranges between 0.82 to 2.95 m^2 m^{-2}. Their average values were relatively lower than that of hybrid poplars at Krummenhennersdorf, which ranged between 1.94±0.8 to 2.85±0.3 m^2 m^{-2}. Rather than genetic differences, other factors may cause differences in LAI between clones, such as the age, size and density of plants (Al Afas et al. 2005). LAI at the Krummenhennersdorf site may be influenced by the foliage disease because the site was attacked with leaf rust in 2014 and this may have decreased its LA values, or it can be that the cultivated clones at the site have naturally low leaf area indexes. For example, Pellis et al. (2004) classified 18 different poplar clones based on their LAI into three groups: low, intermediate and high LAI with values of 2.1–2.7, 3.2–4.3 and 4.9–5.8 m^2 m^{-1}, respectively. Similar low values of LAI were measured by Al Afas et al. (2005) for hybrid poplar trees with values that ranged between 2.1 and 2.7 m^2 m^{-2}. However, higher LAI for hybrid poplar were measured with values ranging from 3.8 to 7.4 m^2 m^{-2} (e.g., Al Afas et al. 2005; Iritz and Lindroth 1996; Schmidt-Walter et al. 2014). Another reason behind the low values of LAI for willow and poplar clones at Krummenhennersdorf site is that the trees were coppiced in early 2013, thus, when LAI measurements were conducted, stools were in their second growing season, which is in agreement with other researchers such as Broeckx et al. (2015), they reported that LAI of poplar clones in their second growing season ranged between 0.87 to 4.63 m^2 m^{-2}, as well with Johansson (2012) who reported an average of 2.42±0.17 m^2 m^{-2} for hybrid poplar stands.

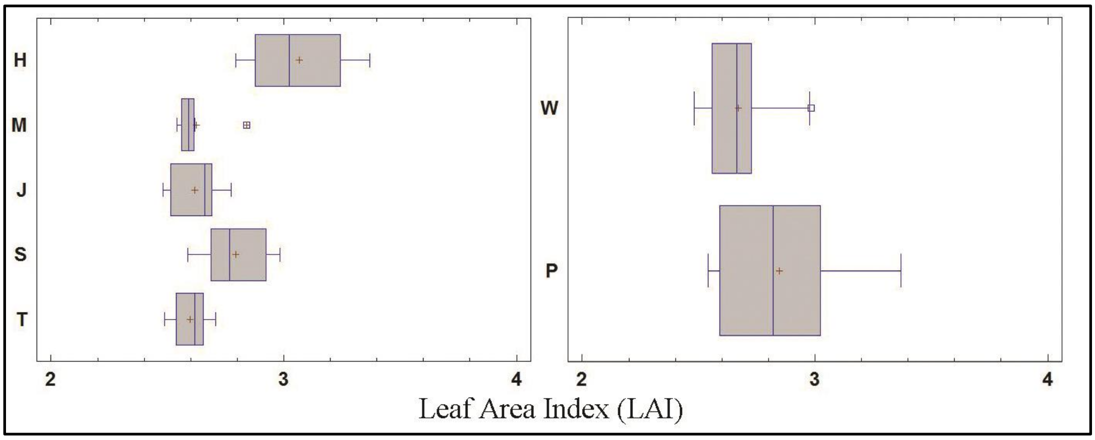


Figure 32. *Left*: Leaf area index (***LAI***) of H 275 (***H***), Max 3 (***M***), Jorr (***J***), Sven (***S***) and Tora (***T***). *Right*: In general, average values for LAI of willow (***W***) and poplar (***P***) with a confidence level of 95.0%.

3.4.2. Specific leaf area (SLA)

As mentioned previously, SLA is the ratio between the one-sided area of a fresh leaf and its oven-dry mass (leaf area per dry mass; $m^2\ kg^{-1}$ or $cm^2\ g^{-1}$). Results show that willow and poplar have high SLA values during the early growing season and then gradually decreased to a low level at the end of the growing season. Al Afas et al. (2005) found negative correlation between leaf area (LA) and SLA. Thus, as leaf area increases during the growing season, SLA decreases.

There is significant positive correlation between SLA and leaf nitrogen content (Al Afas et al. 2005; Pellis et al. 2004). Since SLA decreases during the growing season, this means that leaf content of total nitrogen decreases too, which agrees with the work of MacKerron and Haverkort (1999).

Willow leaves show slightly higher SLA values than poplar's, with average values of 13.5±2.2 for willow clones and 12.8±2.6 $m^2\ kg^{-1}$ for poplar clones (Figure 33). The SLA for willow clones ranged from 16.9±1.4 in the early growing season to 11±0.8 $m^2\ kg^{-1}$ at the end of the growing season. For poplar clones, SLA ranged from 16.3±0.8 to 9.1±1 $m^2\ kg^{-1}$ in the early and at the end of the growing season, respectively.

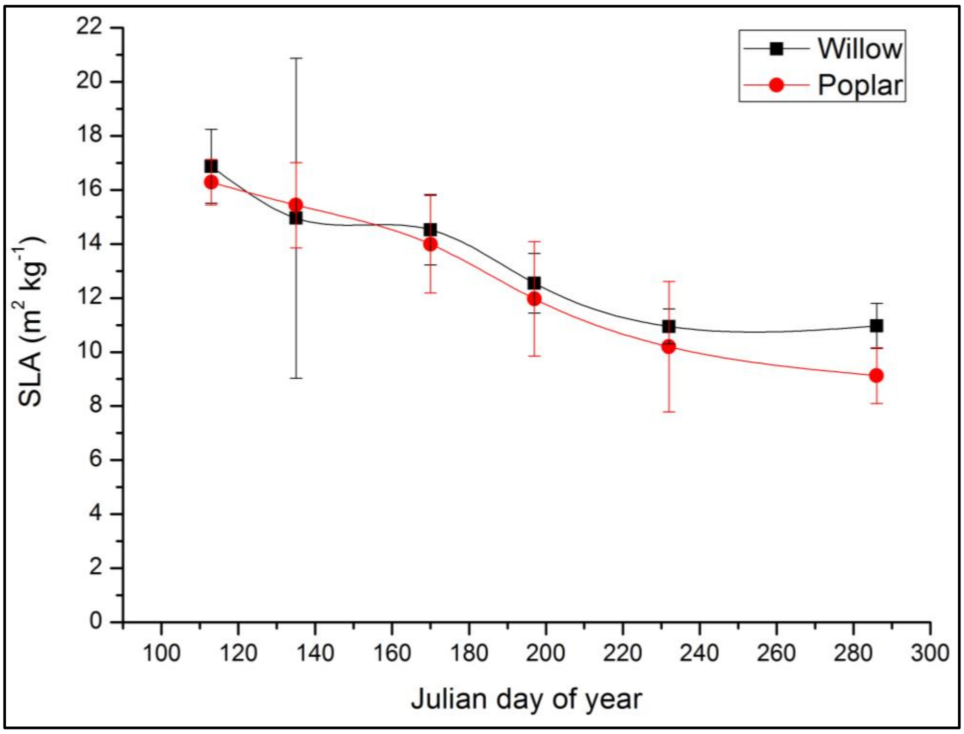


Figure 33. Average specific leaf area for willow and poplar leaves in 2014. Error bars represent two standard deviations.

Results of this study are in agreement with Tripathi et al. (2016), who reported an average SLA value of 13.05±0.2 for hybrid poplar under SRF plantation, which ranged from 12.6±0.3 to 13.9±0.1 cm^2 m^2 kg^{-1}.

Yet, higher values were reported in many studies, for example, a range of 16–21 m^2 kg^{-1} was reported by Pellis et al. (2004) and an average value of 17.8±0.4 m^2 kg^{-1} for hybrid poplar cultivated in Belgium (Al Afas et al. 2005). An extremely higher value of 32.5±0.2 was reported by Taylor and Ferris (2001).

It should be noted that the willow and poplar clones of this study are not the same studied by other researchers. Comparing SLA of different clones could be a reason behind the differences in SLA values. Moreover, the way that tree leaves are collected from the field can influence the SLA values. For example, shaded leaves show higher SLA values than those exposed to sun (Pellis et al. 2004), and leaves in the upper canopy had lower SLA than those in the lower part of the canopy (Al Afas et al. 2005). In addition, SLA is influenced by the availability of nitrogen in soil (Pellis et al. 2004).

3.4.3. Leaf sensitivity to temperature

Climate parameters at sites are important to the success of agricultural projects such as poplar SRF because they can limit plant growth (Cocozza et al. 2009). Therefore, choosing proper clones that are suitable for a region reduces the risk of frost damage mainly during bud development, which is an important factor for the sustainability. For this purpose, a comparison of leaf sensitivity to temperature between different willow and poplar clones was conducted.

In general, values of the percentage of electrolyte leakage (PEL) for willow and poplar leaves were normally distributed and are within the expected range for standardized skewness (-2 to +2). The results show a statistically significant difference between leaf samples of willow and poplar clones kept under low temperature at the 95.0% confidence level, as can be seen in Figure 34. Yet, the difference under high temperature conditions is not significant.

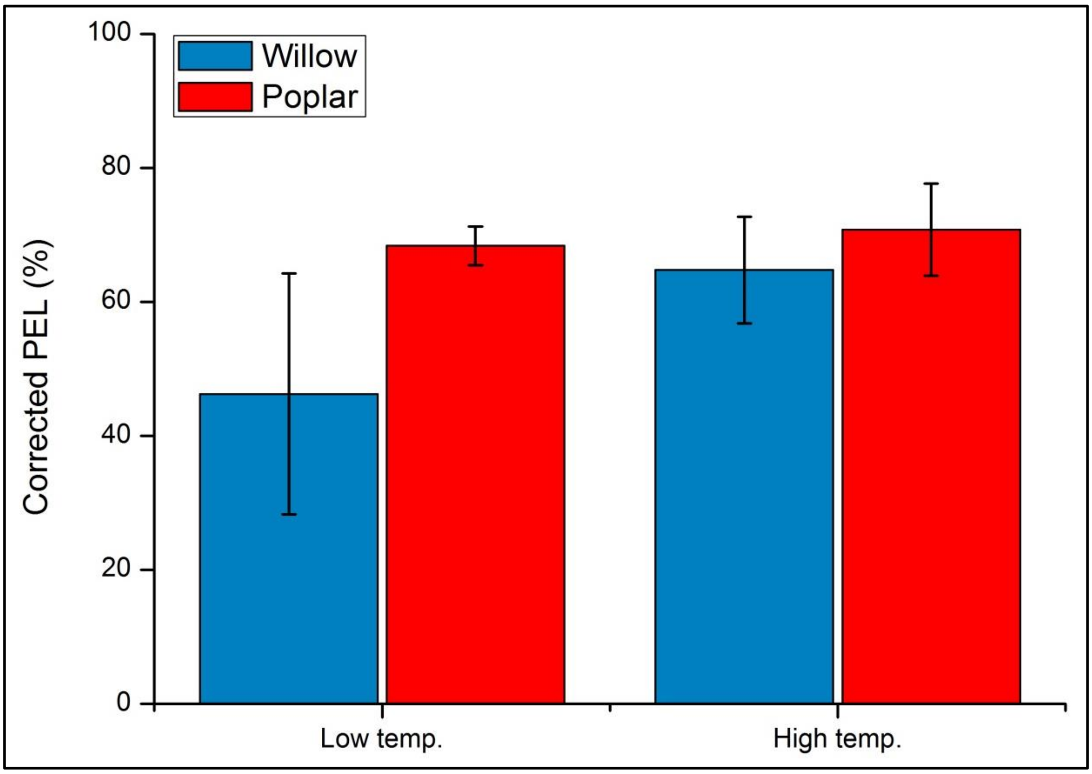


Figure 34. Mean corrected percentage of electrolyte leakage ***PEL*** from willow and poplar leaf samples kept at low and high temperatures. Error bars represent SD.

Leaf sensitivity to low temperature did not differ significantly among willow clones. As was also the case among poplar clones. In addition, all willow clones do differ significantly from poplar clones. Therefore, the clones of willow are better suited than poplar at sites where early frost is expected and foliage damage due to low temperatures needs to be avoided. Willow clones show higher resistance by having low PEL values, for instance, the Jorr clone shows the highest resistance, followed by Tora and Sven (willow clones) with values of 41.1±23, 47±16 and 49.9±14%, respectively. Furthermore, poplar clones H275 and Max 3 show a high percentage with values of 69.3±2.7 and 67.3±3%, respectively (Figure 35).

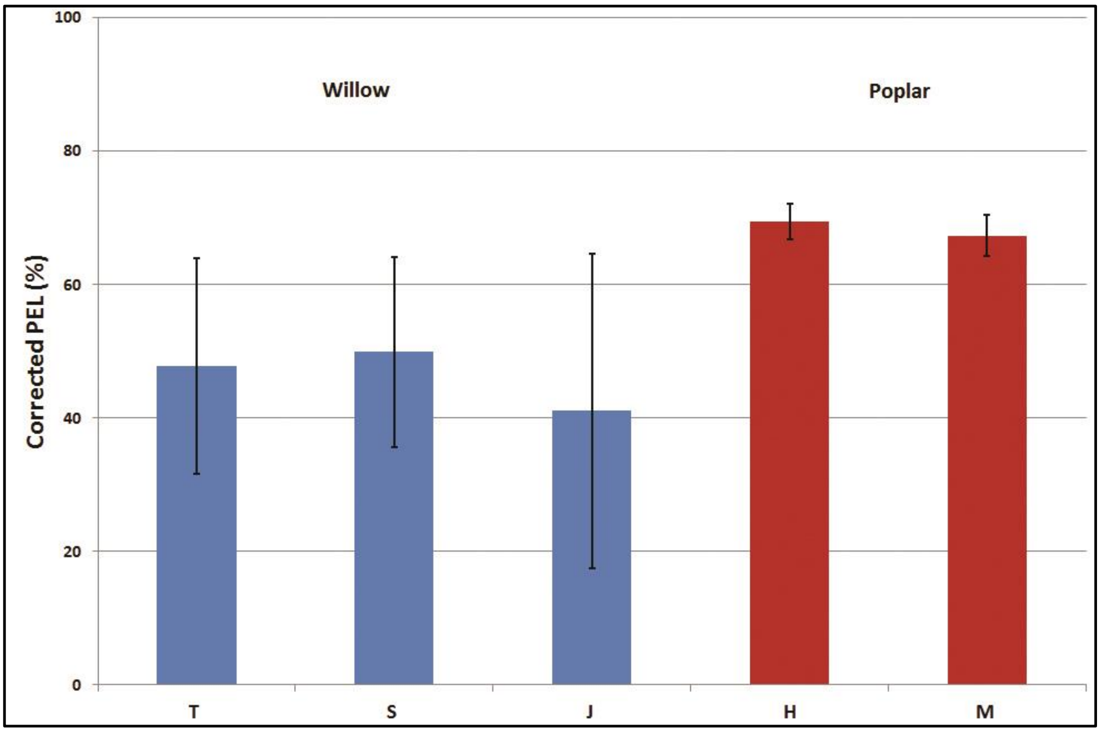


Figure 35. Corrected percentage of electrolyte leakage ***PEL*** values of willow clones; Tora (***T***), Sven (***S***) and Jorr (***J***), and poplar clones; H275 (***H***) and Max 3 (***M***) for the samples kept under low temperature. Error bars represent two standard deviations.

There is no statistical significant difference among willow and poplar clones when leaf samples were under high temperature conditions (40 ºC) at the 95.0% confidence level. This means both willow and poplar clones are very sensitive to high temperatures since all clones show high PEL values.

3.5. Correlations of soil CO_2 emission with soil temperature and moisture content

Gap-filling methods using fitted models are important when field data is missing or unavailable. In order to generate fitted models, correlations between soil emission of CO_2 and other environmental parameters need to be investigated, such as the parameters of soil temperature and moisture content at depth of 10 cm and air temperature. The quantitative estimation of soil respiration was assessed with the help of three statistical indicators: the root mean square error (RMSE), the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE). RMSE is widely used to evaluate the performance of models (Krähenmann and Ahrens 2013), where a lower RMSE value is the better indicator. In order to compare the estimated values over all the plant types in this study, Normalised root mean square error (NRMSE) was calculated, which is based on RMSE values. Yet, the unit of RMSE is the same of soil respiration rate (µmol CO_2 m^{-2} s^{-1}), while NRMSE is expressed as a percentage. RMSE and NRMSE and NSE were calculated according to the following equations:

$$RMSE = \frac{\sum(O_i - S_i)^2}{n}$$

$$NRMSE = \frac{RMSE}{O_{i,max} - O_{i,min}}$$

$$NSE = 1 - \frac{\sum(S_i - O_i)^2}{\sum(\bar{O}_i - O_i)^2}$$

where O_i is the observed value,

S_i is the simulated value,

n is the number of the measured samples,

$O_{i,max}$ and $O_{i,min}$ are the maximum and minimum observed values, respectively, and

$\bar{O}_i$ is the mean of the observations.

Equations of the fitted models for soil respiration and RMSE values are given in Table 4 and Table 5. Nash–Sutcliffe efficiency (NSE) was also computed because it provides more information about the model. When NSE is larger than 0, this means accuracy of the model is higher than the mean of the observed data. Value of 1 is the perfect fit between the model and the observed values (Gayler et al. 2013).

Table 4. Statistical summary of estimating soil respiration models.

Plant	Model	P-value	R^2 (%)	SE of Estimation	Equation	RMSE	NRMSE	NSE
Tora	1	0.0000	49.10	1.700	= -4.41578 + 0.195213 * SM + 0.645369 * ST	1.462	20.51	0.4401
Tora	2	0.0000	51.46	1.674	= -2.66716 − 0.134522 * AT + 0.192272 * SM + 0.71874 * ST	1.412	19.80	0.4779
Sven	1	0.0000	29.16	1.778	= -1.96581 + 0.128262 * SM + 0.471761* ST	1.333	19.78	0.0221
Sven	2	0.0000	29.48	1.794	= -1.53372 − 0.0332945 * AT + 0.127292 * SM + 0.490675 * ST	1.329	19.73	0.0276
Jorr	1	0.0000	76.96	0.821	= -1.37372 + 0.0533389 * SM + 0.478123 * ST	0.796	12.06	0.7058
Jorr	2	0.0000	77.05	0.826	= -1.5097 + 0.0155315 * AT + 0.0527776 * SM + 0.465814 * ST	0.798	12.09	0.7042
H 275	1	0.0000	53.59	1.159	= 3.13708 − 0.0446526 * SM + 0.281556 * ST	1.504	23.60	-0.0095
H 275	2	0.0000	53.76	1.166	= 3.14616 + 0.0187854 * AT − 0.0489086 * SM + 0.256563 * ST	1.533	24.05	-0.0485
Max 3	1	0.0000	75.26	0.824	= 0.974946 + 0.00883146 * SM + 0.403195 * ST	1.573	27.44	-0.1080
Max 3	2	0.0000	75.36	0.829	= 0.90755 + 0.0154521* AT + 0.00770017 * SM + 0.385407 * ST	1.429	24.93	0.0856
Willow	1	0.0000	33.97	1.702	= -0.691344 + 0.0778452 * SM + 0.444124 * ST	1.732	19.51	0.2931
Willow	2	0.0000	33.98	1.707	= -0.763635 + 0.00683962 * AT + 0.0779065 * SM + 0.439113 * ST	1.738	19.58	0.2882
Poplar	1	0.0000	50.40	1.175	= 1.76124 − 0.00544659 * SM + 0.343128 * ST	0.911	13.36	0.6831
Poplar	2	0.0000	50.55	1.177	= 1. 81996 − 0.0199452 * AT − 0.00300709 * SM + 0. 367024 * ST	0.907	13.29	0.6862

R^2 Coefficient of determination
SE Standard error
SM Soil moisture content
ST Soil temperature
AT Air temperature.

Model 1 includes SM and ST as predictors
Model 2 includes SM, ST and AT
RMSE Root mean square error units in µmol CO_2 m^{-2} s^{-1}
NRMSE Normalised root mean square error is expressed as percentage
NSE Nash-Sutcliffe efficiency

Table 5. Equations for best fitted model between soil respiration (***SR***), soil temperature (***ST***), soil moisture (***SM***) and air temperature (***AT***)

Plant	Parameters	Best fitted model	Correlation Coefficient	R^2 (%)	SE of estimation	P-value	Equation
Willow	SR-ST	Exponential	0.633	40.02	0.322	0.0000	SR = exp(0.951942 + 0.0720324 * ST)
Willow	SR-SM	Reciprocal-Y squared-X	0.502	25.20	0.115	0.0000	SR = 1/(0.0986405 + 0.000158389 * SM^2)
Willow	SR-AT	Squared-X	0.398	15.85	1.916	0.0000	SR = 3.75175 + 0.00567837 * AT^2
Willow	AT-ST	Linear	0.663	44.01	2.731	0.0000	ST = -0.671034 + 0.588404 * AT
Willow	AT-SM	Linear	-0.502	25.24	7.184	0.0000	SM = 43.4366 – 1.01466 * AT
Willow	SM-ST	Linear	-0.645	41.66	2.573	0.0000	ST = 17.8453 – 0.320157 * SM
Poplar	SR-AT	S-curve model	-0.557	31.01	0.348	0.0000	SR = exp(2.21522 - 11.4298 / AT)
Poplar	SR-ST	Exponential	0.758	57.49	0.273	0.0000	SR = exp(0.619978 + 0.0941872 * ST)
Poplar	SR-SM	Logarithmic-Y squared-X	-0.515	26.56	0.359	0.0000	SR = exp(1.95672 - 0.000608102 * SM^2)
Poplar	AT-ST	Linear	0.731	53.42	2.299	0.0000	ST = 0.382322 + 0.51421 * AT
Poplar	AT-SM	Square root-Y logarithmic-X	-0.412	16.95	0.622	0.0000	SM = (7.76977 – 0.942223* ln(AT))^2
Poplar	SM-ST	Linear	-0.745	55.53	2.433	0.0000	ST = 17.9805 – 0.327255 * SM

SE Standard error

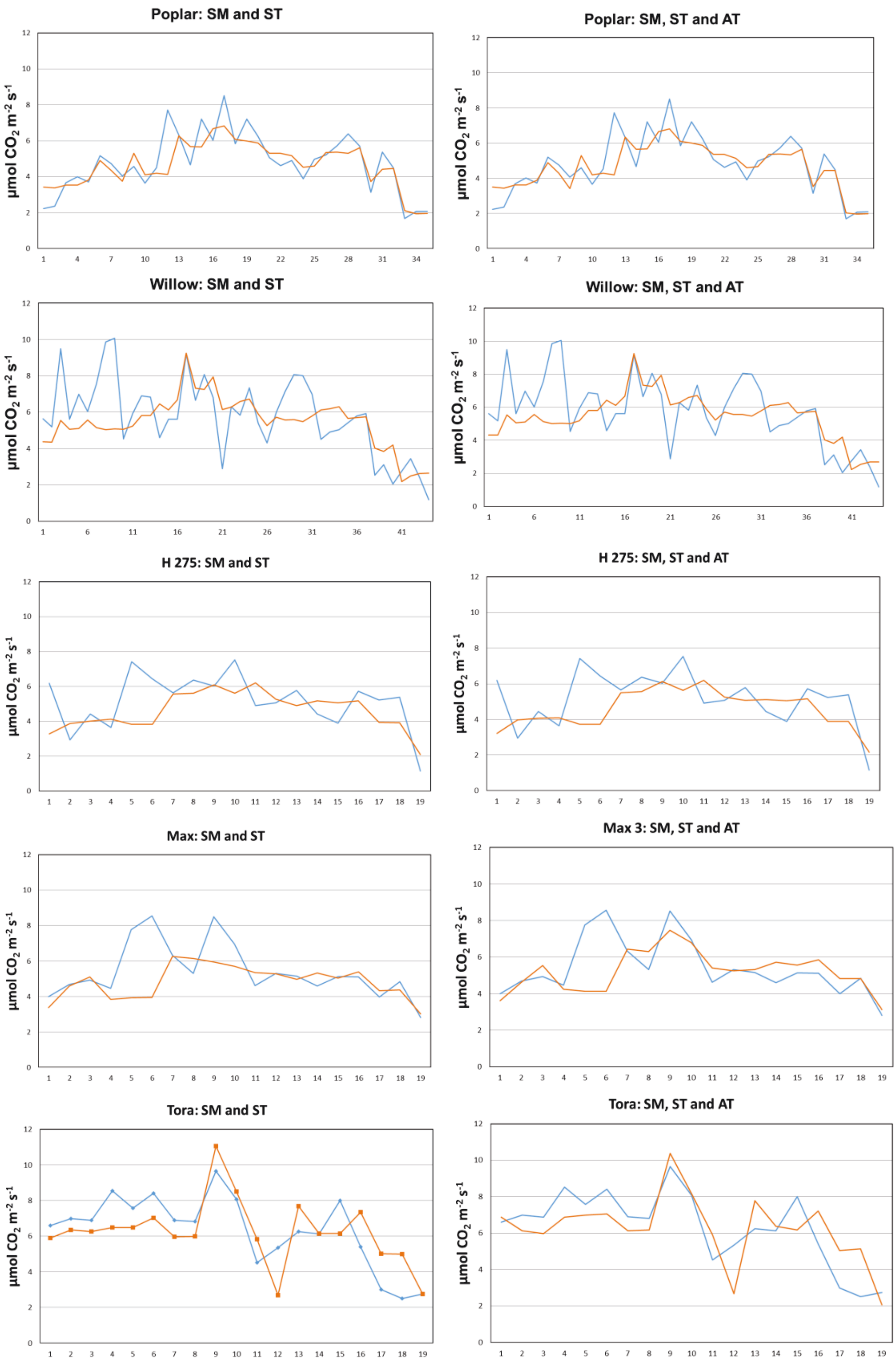
Willow clone (Jorr) and poplar clone (Max 3) have the highest R^2 values, the models can explain about 77 and 75 % of the variables, respectively. Yet, the highest score for NRMSE was about 25–27 and the lowest score for NSE was about -0.11 for clone Max 3, which indicates a weak performance of the model, even it has high R-squared value (about 75%) as shown in Figure 36. Hence, results show that it is not enough to depend on R^2 alone to evaluate how well the model used performs in simulating the soil emission rate of CO_2 and does the model fully recognize the importance of using further statistical indicators such as NRMSE and NSE.

While the lowest value of R^2 was associated with willow clone (Sven), this value agrees with the low value of NSE and the relatively high value of NRMSE, which reflect a weak performance of the model. In general, models for poplar show a better performance than willow in terms of R^2, NRMSE and NSE. In particular, poplar have lower NRMSE and higher NSE values than willow – this is may be due to the fact that the correlation existing between soil respiration and soil temperature of poplar is stronger than willows, with R^2 values of about 57% (poplar) and 40% (willow).

In addition, by including the predictor air temperature (AT) in models, model performances were neither enhanced nor weakened. It caused only slight increases or reductions, i.e. increases in R^2 and NSE and reduction in NRMSE.

The study's results show strong and statistically significant relationships between soil temperature and soil respiration, and between air temperature and soil temperature, with R^2 values of 40% and 44% for willow and 57% and 53% for poplar.

Comparing our correlation results of CO_2 emissions with other work on NO and N_2O, soil moisture is playing a more important role with N_2O emission than CO_2 (Schindlbacher et al. 2004).


Poplar: SM and ST
Poplar: SM, ST and AT
Willow: SM and ST
Willow: SM, ST and AT
H 275: SM and ST
H 275: SM, ST and AT
Max: SM and ST
Max 3: SM, ST and AT
Tora: SM and ST
Tora: SM, ST and AT
µmol CO_2 m^{-2} s^{-1}

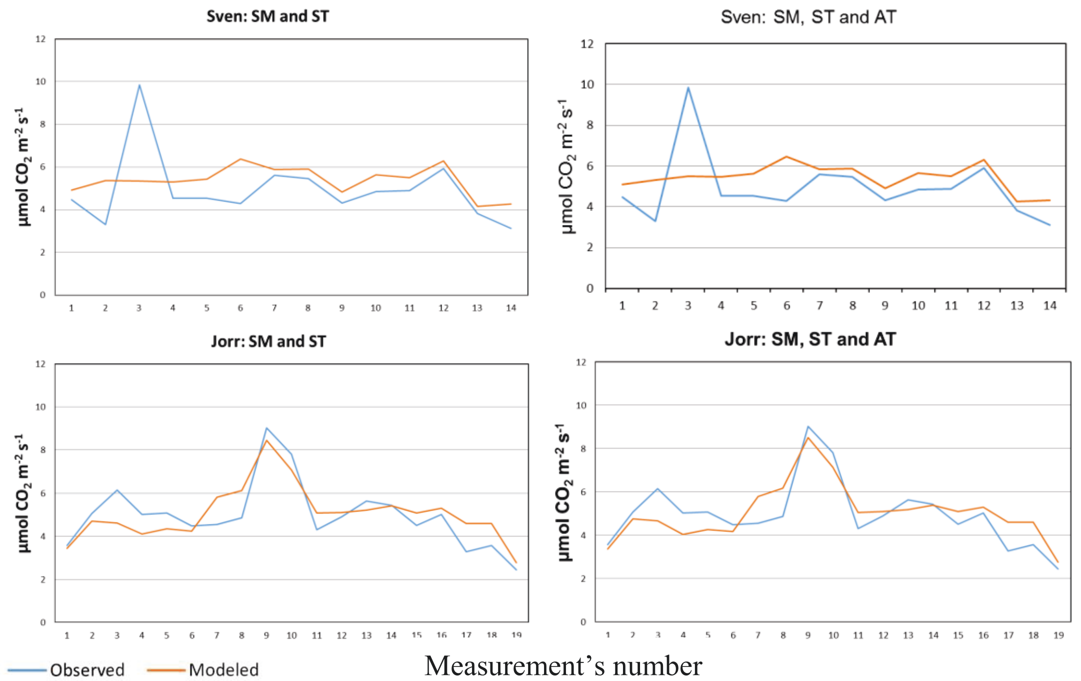


Figure 36. Observed versus modeled values for soil respiration rate for poplar clones H275 and Max3, and for willow clones Tora, Sven and Jorr. Soil moisture (***SM***), soil temperature (***ST***) and air temperature (***AT***) are predictors. *Blue line* is the observed data, and the *orange line* is the modelled.

3.6. Correlations of soil CO_2 emission with plant parameters

Significant correlations were found between soil emission of CO_2 and leaf area LA, and between specific leaf area SLA and 1/SLA for poplar clone H275. Other clones did not show significant correlations. Clone H275 had highest leaf area index LAI value among willow and poplar clones at the Krummenhennersdorf SRF site, such a correlation may exist only when LAI exceeds a threshold, which is about 3 m^2 m^{-2} in this case – this might be the reason behind these findings. It is known that significant correlations may appear when parameters reach specific values (thresholds). For example, Iritz and Lindroth (1996) observed a strong correlation between evaporation and net radiation beneath the canopy only when the leaf area index (LAI) of willow was higher than 2, and when LAI was in the range 0 to 1.5, a positive correlation was found with evapotranspiration.

Leaf area (LA) and specific leaf area (SLA) were used for conducting the multiple regression analysis as independent variables, and CO_2 emission from soil applied as dependent variable. The results show statistically significant relationships between the variables (Table 6).

Regarding the fitted model equations, linear regression can explain about 53.9% (R^2 value) of the data at the 95.0% confidence level when the parameters LA and SLA are used together:

$$Soil\ CO_2\ emission = 6.29123 + 0.00297191 \times LA\ - 0.118455\ \times SLA$$

Yet, relations between soil emission of CO_2 with LA and SLA separately show different results: the highest R^2 for the relationship was between soil CO_2 emission and LA (68.78%) and lower with SLA (51.15%). Thus, using the model of leaf area alone explains better CO_2 emission results than other models. When the Spearman rank correlation was used to test the correlation between LA, SLA and CO_2 emission, a correlation value of 0.8352 was obtained for LA and CO_2 with statistically significant correlation (P-value=0.0038) at 95.0% confidence level (Table 7).

Table 6. Statistical significance of relationships between soil emission and some leaf parameters

	Soil CO_2 emission	**LA**	**SLA**	**1/SLA**
Soil CO_2 emission	–	* *	*	*
LA	* *	–	* *	* *
SLA	*	* *	–	–
1/SLA	*	* *	–	–

* Statistically significant with p-value <0.05

** Statistically significant with p-value <0.01

Comparisons of alternative models that fit better with CO_2 were tested, the best fitted models that have the highest R^2 values are listed in Table 7.

Table 7. Best fitted models for soil respiration

Variable A	Variable B	Correlation Coefficient	R^2 %	Equation	Best fitted Model
CO_2	LA	–0.83	68.8	CO_2=(2.51624–20.6896/ LA)^2	Square root-Y reciprocal-X
CO_2	SLA	–0.72	51.2	CO_2=sqrt (45.8342–0.0945026*SLA^2)	Double squared
CO_2	1/SLA	–0.67	44.7		Squared-Y reciprocal-X
LA	SLA	0.90	80.8	SLA=1/(0.0587376 + 0.00011079*LA)	Reciprocal-Y
LA	1/SLA	0.91	83.2	1/SLA= sqrt (0.00306229 + 0.0000195656*LA)	Squared-Y

LA Leaf area **SLA** Specific leaf area **sqrt** square root

3.7. Insights into soil respiration and combustion heat per area

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 as average harvested biomass (oven dry tons ha^{-1} y^{-1}) from two rotations (two harvests in 2008 and 2010) were calculated for each clone based on data by Dietzsch (2011). Average productivity and combustion heat values for rapeseed were obtained from Wcislo (2005). 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}] using the following equation:

$$= \frac{\text{Cumulative emission}}{\text{productivity} \times \text{combustion heat value}}$$

During cold months (October to April), soil CO_2 emissions are generally rather low because of low temperatures and the 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 37). The main reason behind this decrease in respiration rate was the low precipitation in June, even if temperature was relatively high (Figure 38).

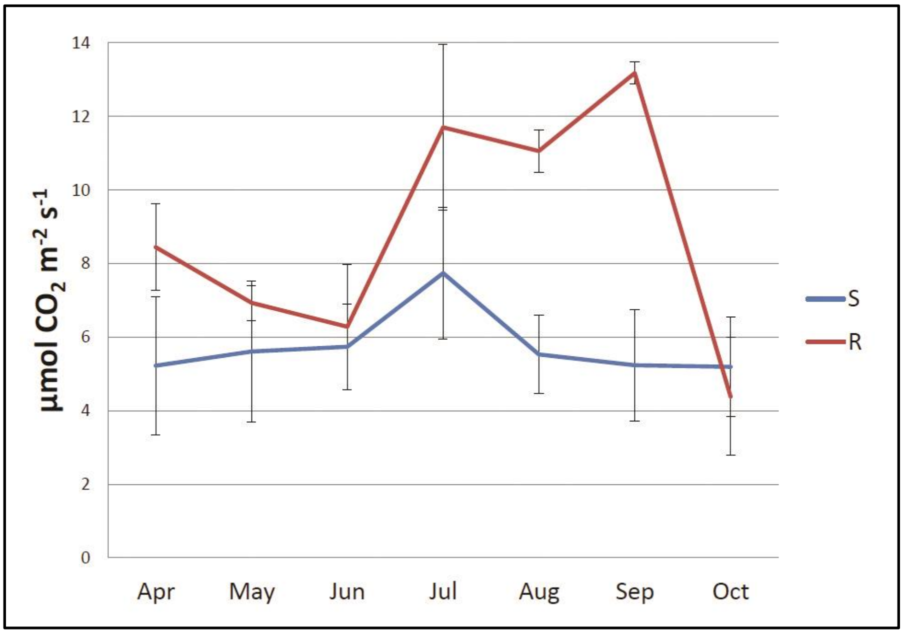


Figure 37. CO_2 emission rates from soils under willow and poplar SRF (***S***) and rapeseed (***R***) plantations during the growing season 2014. Error bars represent two standard deviations.

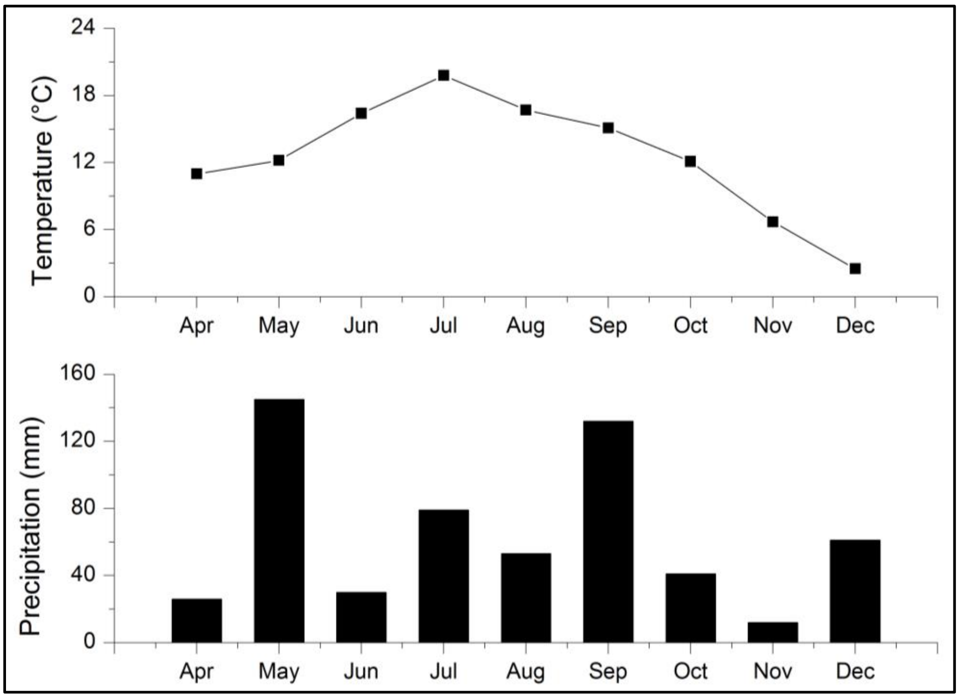


Figure 38. Mean monthly precipitation and air temperatures at the SRF and rapeseed sites in the year 2014.

3.7.1. 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 the following equation, which is after Li et al. (2013):

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

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 on 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.

Figure 39 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 there 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 those from 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 tonne of CO_2 ha^{-1} can be saved during this period.

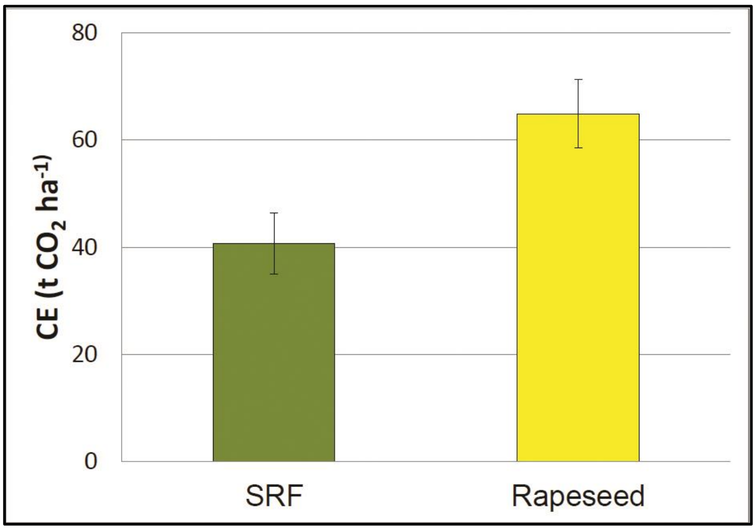


Figure 39. Average cumulative CO_2 emission (CE) from the SRF and rapeseed sites (April–October 2014).

3.7.2. 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 (Dietzsch 2011). Values for average productivity (1478.5±118.17 kg oil mass ha^{-1}) and combustion heat (38.9±0.54 MJ kg^{-1}) were calculated from 14 different rapeseed cultivars (Wcisło 2005). Thus, metabolizable energy (ME) was used to estimate the contribution of rapeseed cake (used to feed animals) to the output energy at a value of 13.71 MJ kg^{-1} (Esteban et al. 2011; Lindermayer and Propstmeier 2007). The amount of rapeseed is made up of its co-products: 40% rapeseed oil and 60% rapeseed cake.

3.7.3. $CO_{2(soil\ respiration)}$ / 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, the energy ratio was estimated between the cumulative seasonal CO_2 emission as a by-product of soil respiration (kg CO_2) to produce a specific energy-crop and its combustion heat obtained from different forms of the extracted biomass (wood pellets and oil) per hectare (MJ ha^{-1}).

This calculation for the extracted energy includes the harvested woody biomass of SRF plantation, while rapeseed oil and rapeseed cake used for feeding animals were considered from the rapeseed plantation. Leaf litter from SRF plantation and straw from rapeseed plantation are usually left in the field, thus they were not included in the energy balance (Figure 40).

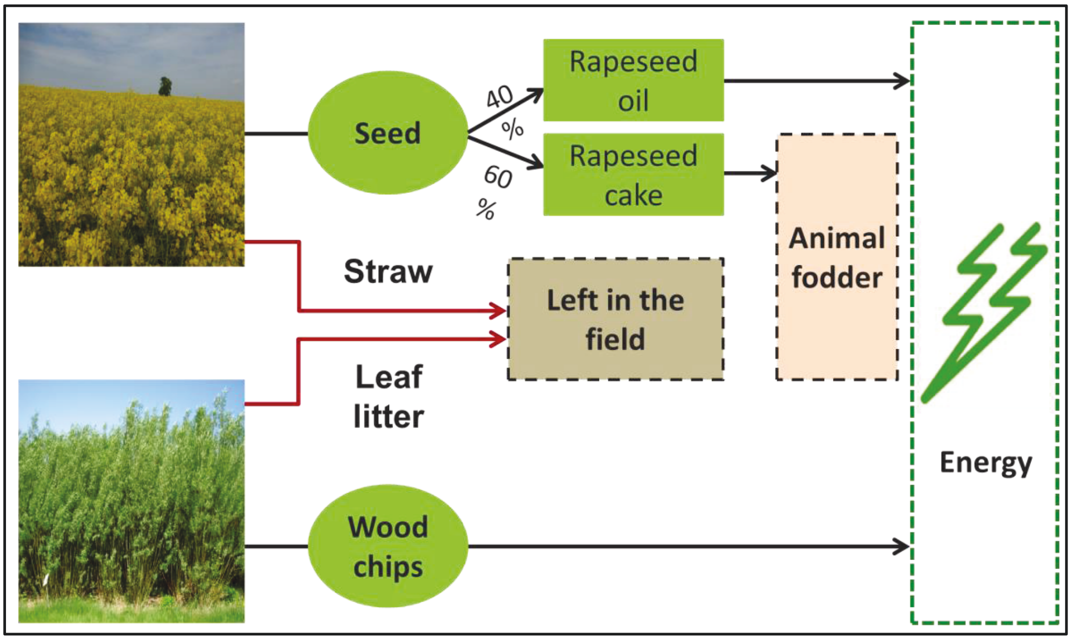


Figure 40. An overview of calculating energy balance for rapeseed crop and short rotation forestry

The average ratios between the emitted quantities of carbon dioxide from soil and the combustion heat obtained from the extracted products per hectare are shown in Table 8. 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.

Table 8. $CO_{2\ (soil\ respiration)}$ emission/energy ratio from the extracted products per hectare

	Tora (Willow)	Sven (Willow)	Jorr (Willow)	H 275 (Poplar)	Max 3 (Poplar)	Rapeseed
Soil CO_2 emission (kg CO_2 ha^{-1})	51,847	38,296	38,569	35,341	39,611	64,872
Production (kg ha^{-1}, L ha^{-1})	11,750	12,700	10,800	13,150	12,650	1,478 (oil) 2,218 (cake)
Combustion heat values (MJ kg^{-1})	18.34	18.34	18.34	18.44	18.44	38.9 (oil) 13.7 (ME-cake)
Combustion heat (GJ ha^{-1})	215	233	198	243	233	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
Relative to rapeseed (%)	32.6	22.3	26.4	19.8	23	100

The key message is that SRF has a lower average ratio of 183.1±38.7 than rapeseed, 738.0. Short rotation forestry is about 400% more efficient than rapeseed (Figure 41).

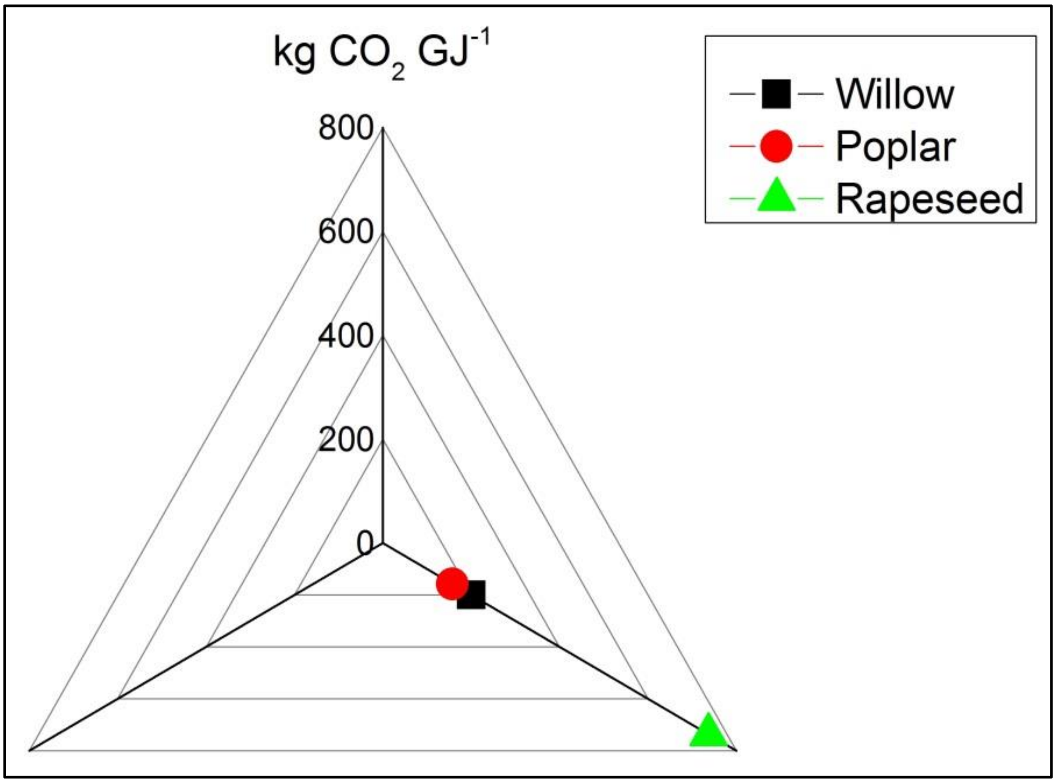


Figure 41. $CO_{2\ (soil\ respiration)}$ / Energy ratio for willow, poplar SRF and rapeseed

3.7.4. Global-warming potential (GWP)

It is possible to include other major GHGs in 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 (IPCC 2007). Drewer et al. (2012) reported that CH_4 emissions were very low and insignificant from SRF and rapeseed fields. Other authors like Hellebrand and Scholz (2000) reported that the annual CH_4 emissions 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 N-fertilization 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 (Don et al. 2012; Walter et al. 2015).

In order to calculate 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. (2015) from 43 sites. That value is equal to 1,058.3 kg CO_2-eq. For SRF, Zona et al. (2013) measured N_2O emission during the second year after establishing a short rotation forest on formerly fertilized agricultural land. They reported 0.42±0.17 Mg CO_2-eq ha^{-1}, which was used in this study's calculation and is equal to 429 kg CO_2-eq ha^{-1}. For the newly calculated CO_2-eq using the GWP see Table 9.

Table 9. Greenhouse gas emissions and net global warming potential of soils under SRF and rapeseed cultivations

	Tora (Willow)	**Sven (Willow)**	**Jorr (Willow)**	**H 275 (Poplar)**	**Max 3 (Poplar)**	**Rapeseed**
Soil GHG emissions (kg CO_2-eq ha^{-1})	51,847	38,296	38,569	35,341	39,611	64,872
Ratio (kg CO_2-eq GJ^{-1})	243	166	197	147	172	750
Relative to rapeseed (%)	32.4	22.2	26.2	19.7	22.9	100.0

3.8. Trace elements in soil

Trace elements in ecosystems are existing in different forms: in aerosol or gaseous form in the atmosphere, in organic form within the living and dead parts of plants and animals, in free ionic or complexed forms in soil solution or sorbed on soil (exchangeable and bioavailable for plants), and in solid form in primary and secondary minerals (Adriano 2001). The bioavailable part of trace elements is very important because it can increase risks of groundwater contamination. Thus, studying the distribution coefficients or solid–liquid partition coefficients (K_d) is very important to estimate the leachability and to predict the mobility of heavy metals, trace elements and other contaminates such as pesticides in contaminated soils.

3.8.1. Solid-liquid partition coefficients (K_d)

As mentioned previously, the willow and poplar short rotation forestry site in Krummenhennersdorf is contaminated with trace elements, some of which have already exceeded the legal limit such as arsenic (As), while other contaminates are within the legal limit but their concentrations in soil were elevated, such as Pb, Cd, Zn and Cr. There are fluxes of trace elements between ecosystem compartments, e.g., As is not only present in the lithosphere (soil), there are natural fluxes of As between the lithosphere, atmosphere, hydrosphere and biosphere (Matschullat 2000). Figure 42 presents an overview of how trace elements move through the SRF ecosystem parts and highlights the major points of cycling the trace elements.

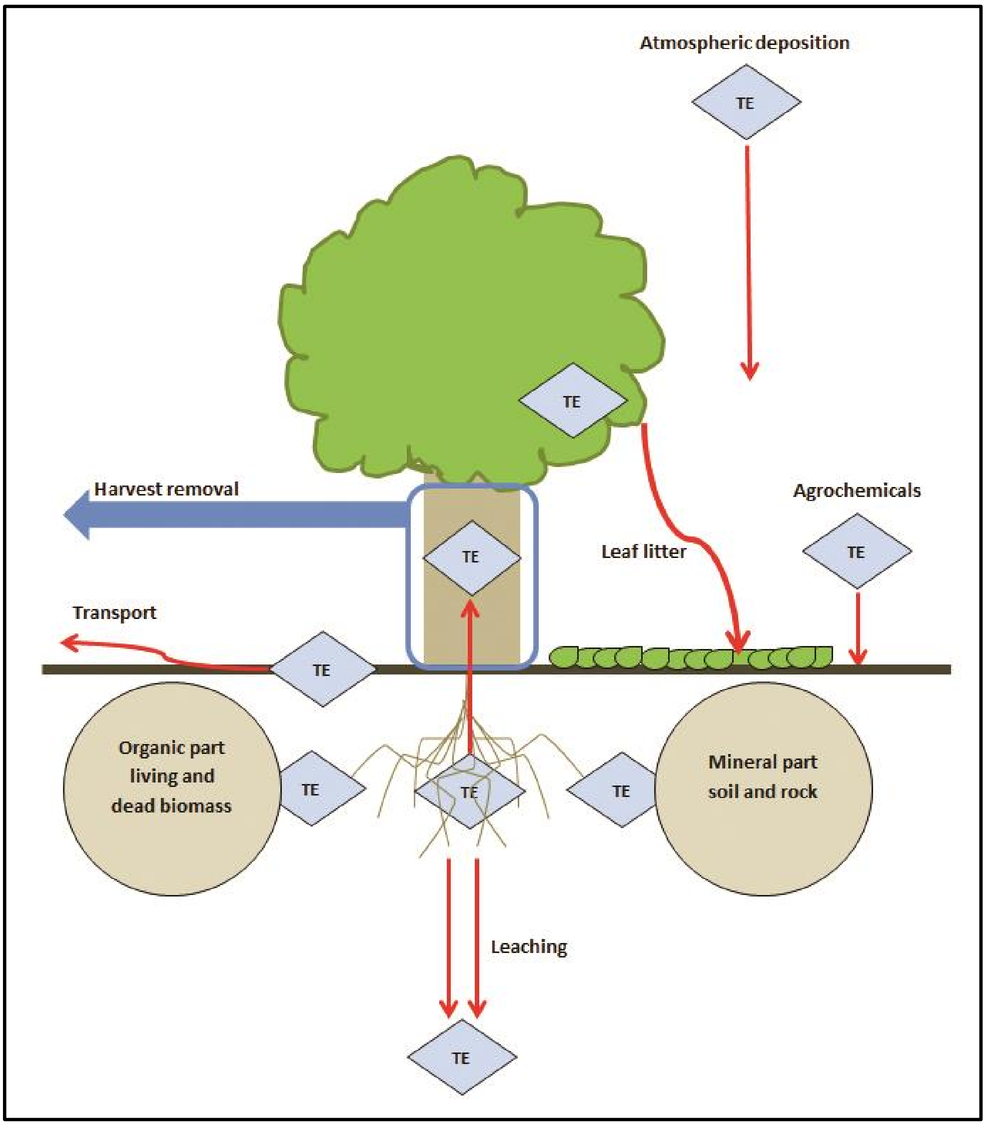


Figure 42. An overview of the distribution and pathways of trace elements (***TE***) in a short rotation forestry (SRF) ecosystem.

Regarding the inputs of trace elements to a SRF ecosystem, there are two main inputs, as can be seen in Figure 42: the first one is the use of agrochemicals at the site. An example of that are phosphate fertilizers and pesticides, which are sources of Cd and As, respectively (Adriano 2001). The second input is from wet and dry atmospheric deposition, such as dusts and emissions of mining and smelting activities, for example, Cu-smelting and coal combustion are the main anthropogenic sources of As (Matschullat 2000). In addition, As can be transported as volatile metalloids in gaseous form (Adriano 2001).

It can be observed from Figure 42 that part of the trace elements can be translocated to the above ground parts of trees. There, the translocated elements are fundamental constituents first of all in the tree stems and twigs that will be eventually harvested and removed from the field – the main output of trace elements from an ecosystem – and secondly in the tree leaves that will return back to the soil when they fall in late autumn and winter forming leaf litter. Besides the harvest of plant/tree parts, another output from the ecosystem may occur when trace elements are transported from a field either through erosion by wind and water runoff, e.g., as Pb and Zn in particle forms (Alloway 2013) or physical transport by machines and trucks used at a site. An output of elements also occurs through leaching down the soil profile to groundwater.

It is important to predict the mobility of the dissolved trace elements in soil water (bonds to organic acids or as free ions) because they are chemically and biologically very active (Carrillo-González et al. 2006). In addition, studying the distribution coefficients (K_d) helps to estimate the potential fate of trace elements in soil. Distribution coefficient values depend on many factors, such as soil pH, soil content of organic matter, soil depth and temperature, and it is expressed by either L kg^{-1} or m^3 kg^{-1} (Dollinger et al. 2015; Jakomin et al. 2015; Sheppard et al. 2009).

By running a soil-column experiment (ex situ) and collecting soil water samples from the field (in situ), values of the distribution coefficient K_d for trace elements in SRF soil were determined. Thereafter trace elements were arranged based on their K_d values, from the highest to the lowest. From the results of the soil-column experiment, K_d ranked in descending order as follows: Pb>As>Zn>Cd and from the field experiment: Pb>As>Cd>Zn. So according to both experiments, Pb has the highest K_d value, followed by As, and the difference between the soil-column and field results regarding Zn and Cd is statistically not significant. Thus, both results show the same order (Figure 43). This study's results are in agreement with previous studies, e.g., Adriano (2001) and Carrillo-González et al. (2006) reported that Zn and Cd cations have almost the same value of K_d for the same soil. Although K_d values in the soil-column experiment differ from those of the field experiment, both experiments show the same order of K_d values. The reason behind these differences may be due to a disturbed soil texture and hence changed its physical-chemical properties during the soil sample collection and filling into experimental columns. Such changes can cause a change in K_d values for the same trace element (Rutkowska et al. 2015).

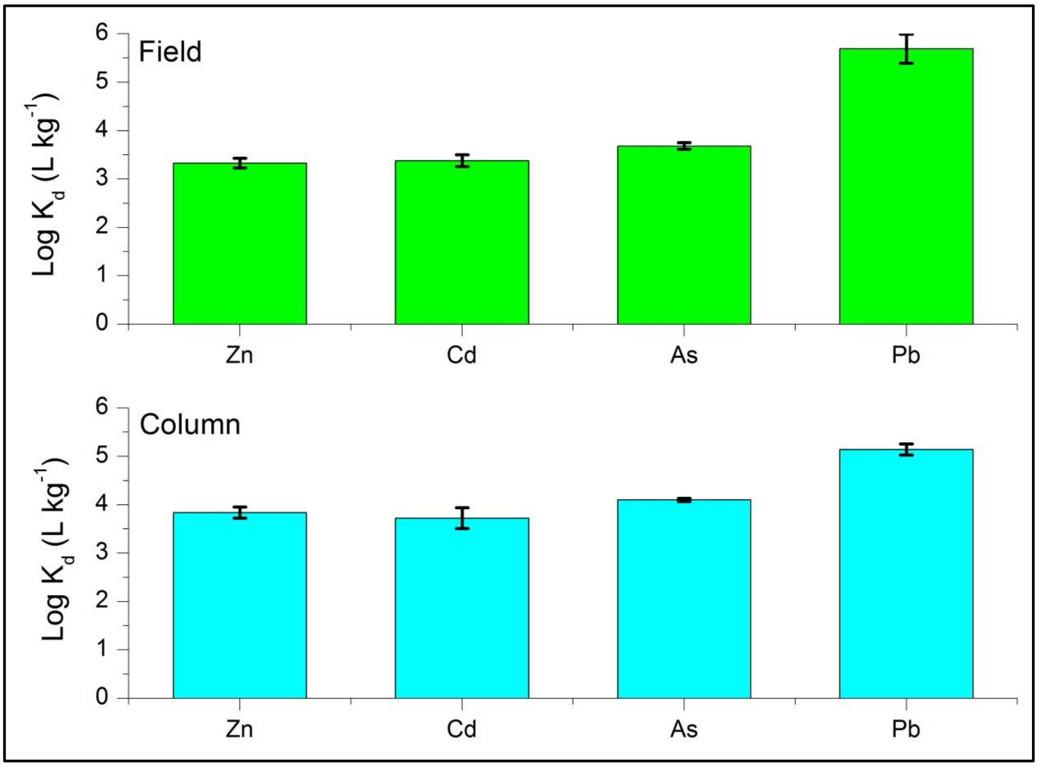


Figure 43. Solid-liquid partition coefficients (K_d) values for Zn, Cd, As and Pb from soil-column and field experiments.

From Figure 43, it can be seen that Pb has the highest K_d value; this means that Pb is stable in soil and sorbed to soil particles. In other words, a small part is bioavailable for a plant to uptake or to leach down. The findings of this study agree with the work of Shaheen et al. (2013) that reported that Pb is a strongly sorbed trace element, while Cd and Zn are more mobile, and that Cd more weakly sorbed to soil than Zn. Yet in this work, the difference between the K_d values of Cd and Zn was found to be slight and was not statistically significant. Likewise, these results correspond to Jakomin et al. (2015), in that K_d for Pb is higher than that of Zn and Cd. This means that the ability of Pb to be adsorbed on soil particles is stronger than Zn and Cd, and that Pb may exist in insoluble forms in soil, such as PbO_2 and $PbCO_3$.

Plant roots influence trace elements in the root zone via three main mechanisms that: change the soil environment (e.g., changing pH and organic content), transform chemical forms of trace elements (e.g., changing As^{III} to As^{V}) and use biosorption (Carrillo-González et al. 2006). The soil at the SRF site has higher concentrations of Pb (361.6±39 mg kg^{-1}) than Zn (195.6±22 mg kg^{-1}). In contrast, poplar and willow trees had higher concentrations of Zn than Pb in their stems, with values of 83.50 mg kg^{-1} Zn and 3.94 mg kg^{-1} Pb dry biomass of poplar trees, and 141.8 mg kg^{-1} Zn and 2.17 mg kg^{-1} Pb dry biomass of willow trees (Dietzsch 2011). Zinc is a trace element that is a vital micronutrient for plants and although Zn is non-toxic to plants and soil microorganisms (Adriano et al. 2004; Rutkowska et al. 2015), other non-essential elements for plants such as As, Cd and Pb are toxic and their biological functions in plants are not known. It is known that the uptake of trace elements by plants depends mainly on the genotype (Alloway 2013). Most plants avoid the uptake of As from soil because of the mechanisms they have to protect themselves (Reimann et al. 2009). Thus, these K_d results may contribute to the explanation behind the difference of Pb and Zn concentrations in soil and plant parts.

The uptake of trace elements by plants is influenced by many factors. For example, the existence of high concentrations of trace elements in soils, mainly the non-essential elements for plants, can reduce a plant's ability to uptake essential elements, i.e., Cd can reduce the uptake of Mn, and As(V) competes with phosphate for sorption places in soil (Adriano 2001).

The mobility of trace elements in soil is also influenced by many factors, and soil pH is the most important one. When soil is under acidic conditions (low pH), one expects to find more elements in the aqueous phase than under high pH conditions. For instance, changing soil pH from 5 to 7 will cause an approximately 100-fold in available Cd that are bounded on the solid phase (Carrillo-González et al. 2006). Furthermore, under acidic conditions, a small percentage of Pb will be in an exchangeable form in soil, and more Cd and Zn will be bioavailable as shown in Figure 44 (Chlopecka 1996). The SRF site has acidic soil, therefore, trace element percentages that are close to these can be expected to be found there in soil.

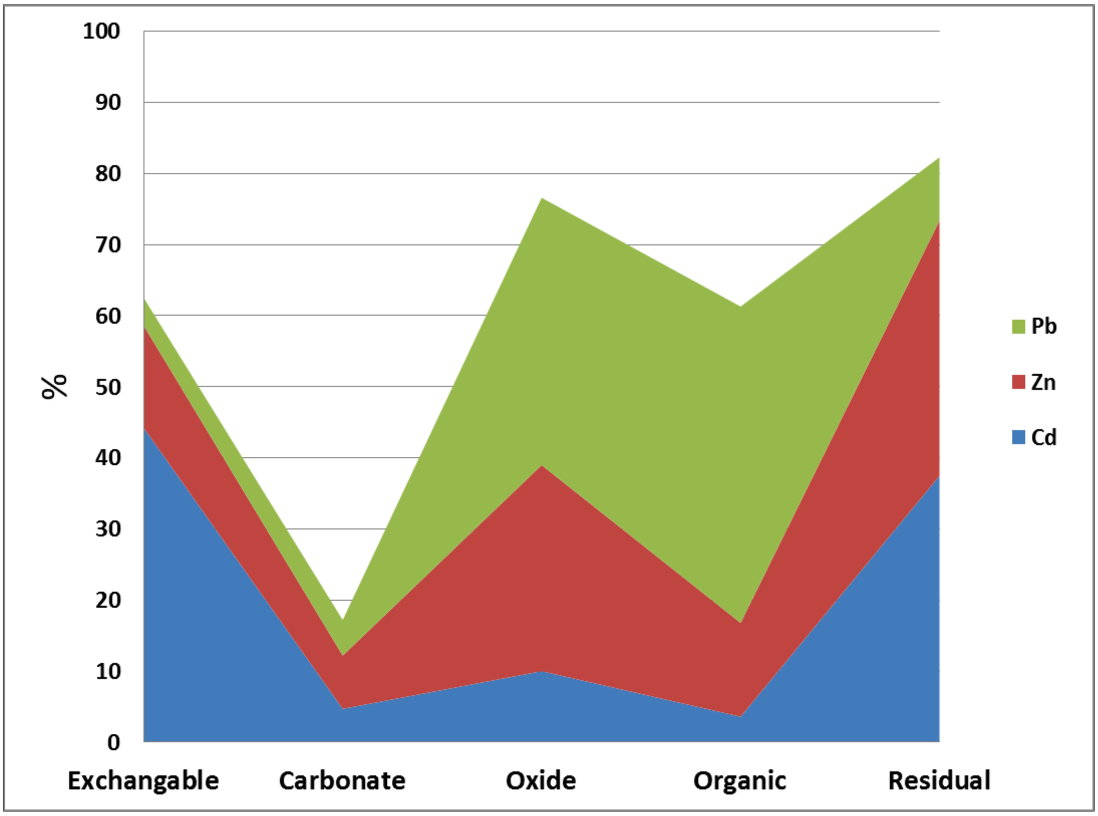


Figure 44. Forms of Pb, Zn and Cd in soil under acidic conditions, where soil pH ranged between 4.5 to 5.5 (after Chlopecka 1996).

So, negative effect of trace elements on the ecosystem can be minimized by increasing their K_d values. The uptake of trace elements by plants will be more difficult if phytoremediation was selected as a tool and implemented to remediate contaminated sites.

3.8.2. Estimating time of remediation

The concentration of As is about 89.6 mg kg^{-1} at Tora willow clone in Krummenhennersdorf, were soil columns were filled with this soil sample. This value exceeded the legal limit of 50 mg kg^{-1} in grasslands that is set by German Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV 1999).

Moreover, the soil at SRF site is acidic, and it is important to emphasize the positive correlation between soil acidity and As mobility. As soil acidity increases, the mobility of As increases, and human exposure to the As can cause diseases such as cancer of the skin, bladder and lungs (Matschullat 2000). Thus, it is important to compare the effect of the land use on As in soil.

The distribution coefficient result of As indicates that this trace element is easily leached out from soil profile under current conditions at the SRF site of soil properties. Furthermore, relative concentration (C/C_0) of As computed from soil-column experiment shows a relatively high value as can be seen in Figure 45.

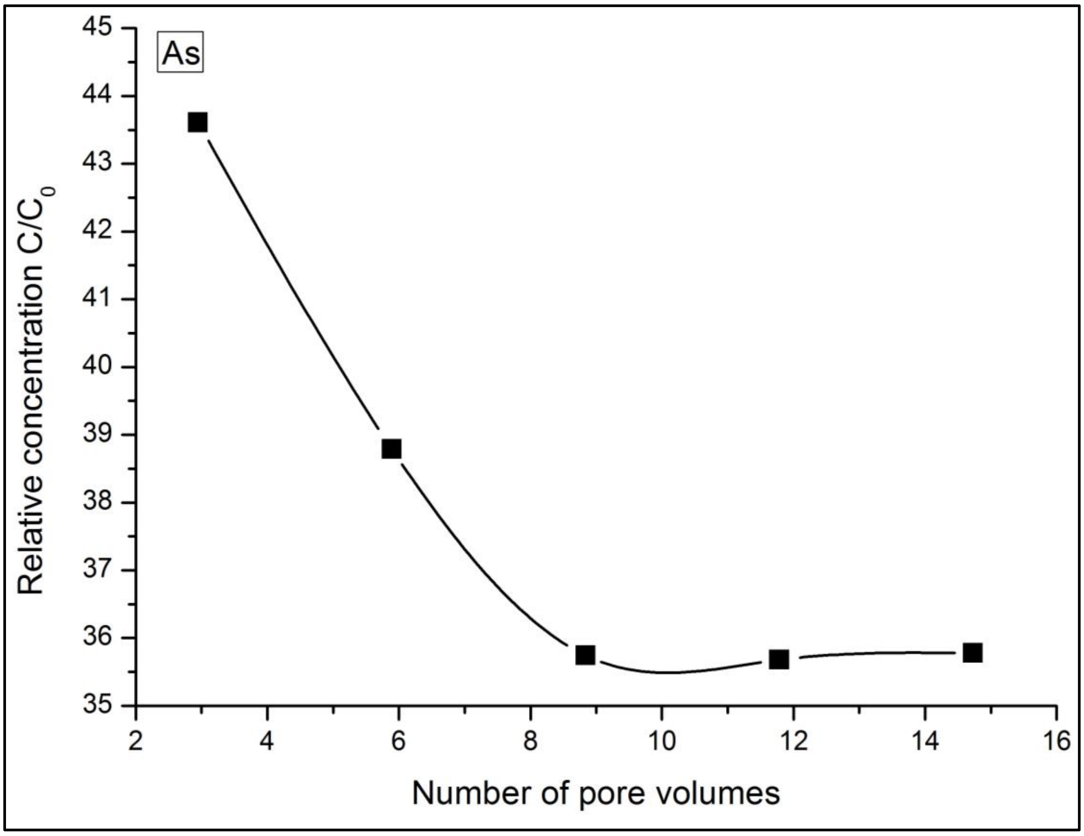


Figure 45. Relative concentration of As delivered by soil-column experiment, where ***C*** is the concentration of As in the effluent when it exits the soil-column, and ***C_0*** is the initial concentration of As when it enters the column which is equal to the concentration of As in the rain water collected from the region to feed the columns.

The remediation time of As to reach the legal concentration under two scenarios for land use was estimated. In scenario 1, the site is a rainfed willow and poplar SRF plantation, and in scenario 2, the site is a rainfed fallow field. The remediation time in scenario 1 was approximated by using the removal rate of the trace element (As) in poplar trees, namely, in stems and stools as harvested parts, whereas in scenario 2, the removal rate of the trace element by precipitation (leaching) was used and computed from soil-column experiment.

For both scenarios, a productivity of 10 t DM ha^{-1} $year^{-1}$ for poplar SRF was used and the topsoil layer (30 cm) is considered to be remediated as suggested by Dietzsch (2011).

In order to estimate the pore volume for soil, soil porosity is needed and it was estimated as follows:

$$Soil\ porosity = 1 - \left(\frac{Bulk\ density}{Particle\ density}\right)$$

Soil bulk density 1.45 g cm^{-3} was measured previously, soil volume is 0.3 m^3 for a depth of 0.3 m, and particle density is assumed to be 2.65 g cm^{-3}, which yields a soil porosity of 0.45 cm^3 g^{-1} (45%).

Hence, about 435 kg soil per square meter needs to be remediated at the site. This amount of soil has about 38,976 mg As (based on the current soil content of 89.6 mg kg^{-1} As). In the case of this study, remediation time is the time needed to reduce the current amount of As in the topsoil from 38,976 mg to 21,750 mg, which is equal to 50 mg kg^{-1}. In Dietzsch (2011) the remediation time was estimated based on removing all As in the topsoil and not on reaching the accepted standard level.

To determine an annual removal rate of As in the first scenario, it was postulated that a poplar stem had an As content of 0.12 mg As kg^{-1} (Dietzsch 2011). The annual productivity of poplar per hectare is 10 tonnes DM and this is equal to 1 kg DM m^{-2} $year^{-1}$. Accordingly, a removal of 0.12 mg of As per m^{-2} $year^{-1}$ is achieved when the site is a poplar SRF plantation.

In scenario 2 the removal rate by rain was estimated by dividing the average annual precipitation at the site by number of pore volumes needed to leach 1 µg of As from the soil profile (based on the soil-column experiment). The latter was calculated by plotting the cumulative amount of As removed from the soil profile against the pore volumes (Figure 46). Then, a linear equation $Y = 0.3359X + 0.2377$ was found to give the best fit between As removed from soil profile (leached) and pore volume, where Y is 1 µg of As, and X is the number of pore volume. In this case, it was found that 2.27 pore volumes are needed to allow 1 µg of As leave the soil profile. For a soil profile in the field and based on soil porosity, pore volume is estimated to be 0.135 m^3. Moreover, average annual precipitation at the SRF site is 820 mm, this is equal to 0.82 m^3 m^{-2}, this means that under a rainfed condition, precipitation causes about 6.074 pore volumes of leached water. Thus, the average removal rate of As from the soil profile by precipitation is about 2.676 µg As m^{-2} $year^{-1}$ or 26.76 mg As ha^{-1} $year^{-1}$.

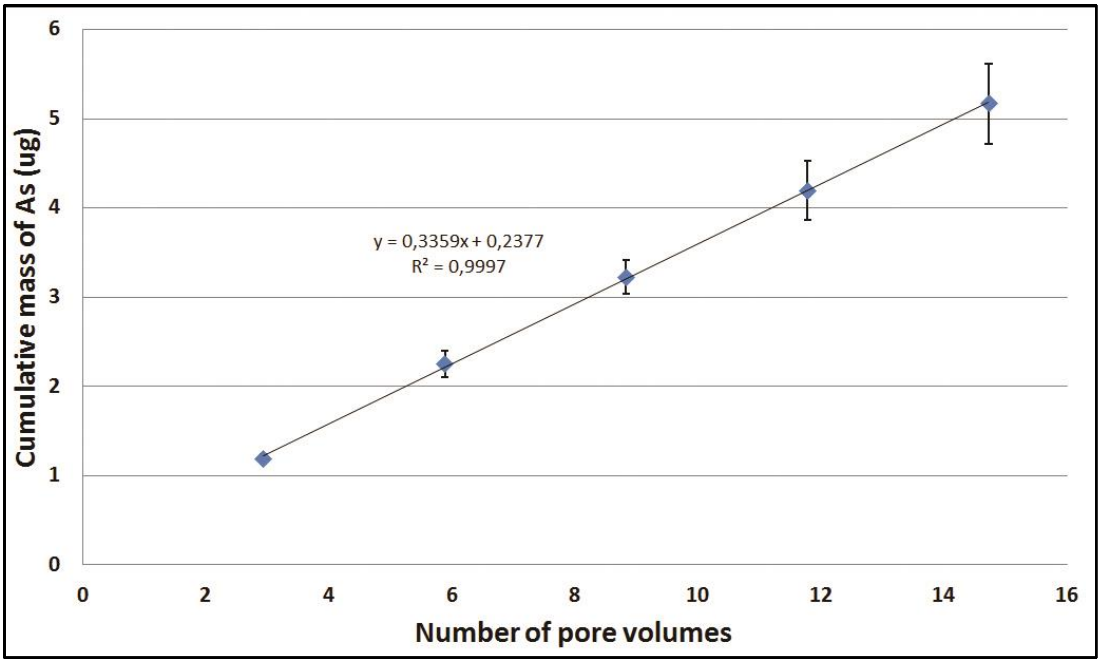


Figure 46. Cumulative leached As (µg) per pore volume in the soil-column experiment.

From results shown in Table 10, it can be can concluded that by continuing the SRF plantation on the contaminated site, remediation would need only about 3% of the time needed if the site was left as fallow field.

Table 10. Remediation time needed for scenarios 1 and 2

Amount of As in soil ($mg\ As\ m^{-2}$)		**Removal rate by ($mg\ As\ m^{-2}\ year^{-1}$)**		**Remediation time (thousand years)**		
Currently	Projected	SRF	Rain	Scenario 1 (this study)	Scenario 1 (Dietzsch 2011)	Scenario 2 (this study)
40,000	21,750	0.12	2.67×10^{-3}	181	360	6,500

Numbers are rounded

The concentration of Pb in soil at the SRF site did not exceed the legal standard limit. Pb concentrations were also estimated in the same way as As. On this basis, it was calculated that Pb needs about 21.1 pore volumes to let 1 µg of Pb leave the soil profile (30-cm depth), in other words, about 9.3 times slower than As. Thus, these results show that Pb has a longer residence time in soil than any other trace element (Figure 47). Therefore, a remediation mission of Pb will take longer than one of As.

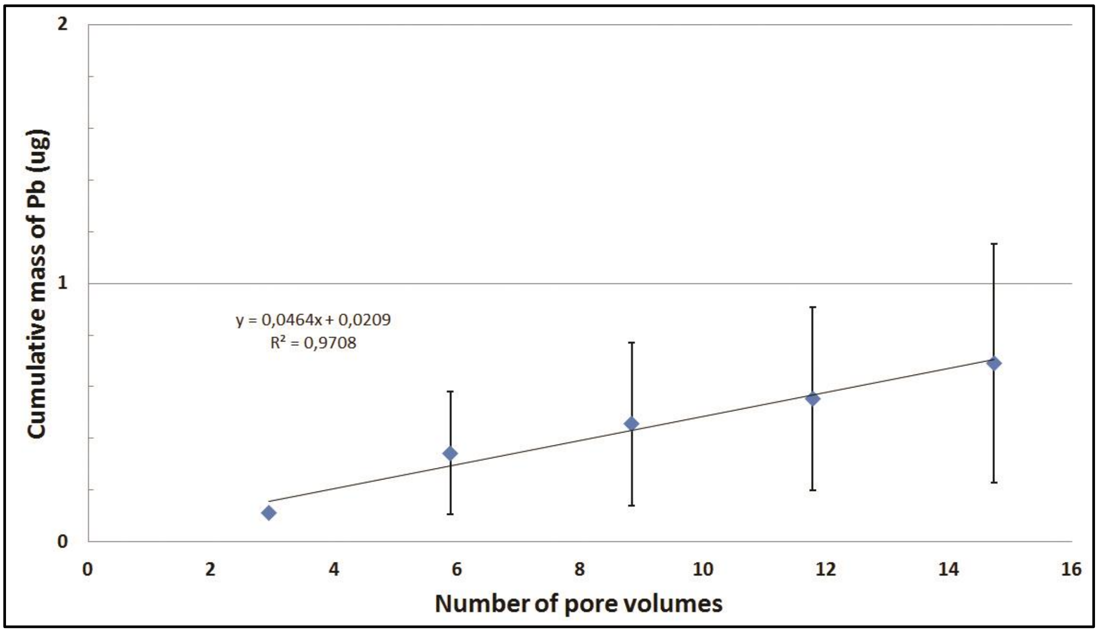


Figure 47. Leached amounts of Pb through soil profile in the soil-column experiment

The results of this work have sources of uncertainties like any experiment. For example, the removal rate by poplar trees is based on content of trace elements found in stems, here it cannot be established that all trace elements present in plant tissues were taken from the soil because plants can absorb some trace elements from atmosphere. Random errors may have incurred during the collection of soil and water samples in the field and soil-column experiments, as well as instrument errors in measuring different parameters over 120-h periods. For this reason, further experiments on a larger scale and for longer periods are recommended.

3.9. Identification and Prioritization of Key Parameters for Willow and Poplar Short Rotation Forestry (SRF) Production System

The recommended steps by the software MICMAC® (version 6.1.3) manual were followed as described in the methodology section (MICMAC approach). Fifty variables were selected that characterize the system and that potentially influence it. These variables are listed with a brief description in Table 11.

Table 11. Variables that characterize and potentially influence SRF system

No.	Variable	Short label	Description
1	Farmers' decisions	V1	To establish SRF
2	Insufficient farmer experience	V2	With SRF cultivations
3	Acceptance of land-use change	V3	From conventional crops to SRF
4	Changing subsidy regulations	V4	Encouraging farmers to establish new SRF plantations
5	Undeveloped wood-fuel market	V5	Includes facilities to dry and to store wood chips
6	Carbon taxation	V6	A decrease of carbon tax on fossil fuels
7	High initial cost	V7	To establish SRF fields, e.g., fencing and plant materials
8	Long-period projects	V8	Plantation life of 20–25 years
9	Long-term supply contracts	V9	Agreements with terms of at least 15 years
10	Decrease in wood price	V10	Payback period is dependant on wood price
11	Rise in grain prices	V11	May attract farmers to cultivate their lands with those grains rather than under SRF
12	Yield risk	V12	Harvested quantities is less than the expected or estimated
13	Carbon storage in soil	V13	SRF plantation may accumulate higher C amounts in soil, thus improving soil quality and trapping atmospheric CO_2 in soil
14	Groundwater quality	V14	SRF could lower the rate of nitrate reach to groundwater
15	Nutrient cycling	V15	Harvested wood has low nutrient contents compared to other bioenergy crops such as rapeseed
16	Animal production	V16	In regions of animal production (e.g., for dairy), land is needed for fodder rather than bioenergy production
17	No- or minimum tillage	V17	
18	Annual returns	V18	Depend on the harvesting year cycle, which varies from 2 to 5 years.
19	High harvesting costs	V19	
20	Worries about crop failure in the year of establishment	V20	SRF should extent for 20–25 years, failure in the first year due to different (biotic/abiotic) factors may affect its competitiveness top other crops.
21	Local employment	V21	SRF projects offer local job opportunities for employment
22	Low precipitation	V22	Less than 600 mm per year
23	Localized plantation	V23	Establishing SRF sites in areas located close to firewood and heating markets
24	Land-use conflict	V24	Conflicts may arise between bioenergy and food production
25	Terrain conditions	V25	When fields are not flat, it may negatively affect plant density and suitability of farming machines
26	Small field size	V26	Field with size of 2–3 hectares

Table 11. continued…Variables that characterize and potentially influence SRF system

No.	Variable	Short label	Description
27	Soil preparation and weed control	V27	Especially in the year of establishment
28	Low soil quality	V28	Nutrient-poor soils
29	Marginal and polluted sites	V29	Sites are not suitable for food production
30	Mixed pattern	V30	Cultivating field with mixture of varieties (willow and poplar)
31	Plant density	V31	Plant density at SRF sites ranges between 10,000 to 18,000 plants ha^{-1}
32	Row orientation	V32	For example: row length of more than 500 m may need additional passages
33	Plant diseases	V33	Mainly risk of fungi
34	Wild game	V34	Browsing of wild game, such as damages caused by roe deer
35	Fencing	V35	Construction of fences is expensive. It aims to prevent damages caused by wild game
36	Harvest cycle	V36	SRF are harvested in a 2–5 year cycle
37	Snow accumulation in the field	V37	Snow height in the field during harvesting will cause a loss of the harvested products because part of the biomass will be left at field.
38	Large stem diameters	V38	Stems with diameter more than 15 cm
39	Wood harvesting system	V39	Cut-and-chip or whole stem
40	Wood chip size	V40	Fine or course chips
41	Non-optimized warehouse	V41	May cause loss of product during storage time
42	Machine maintenance	V42	As plant age and density increases, machine maintenance will also increase, resulting in an increase of harvesting costs.
43	Biomass drying	V43	Drying the harvested biomass naturally or electrically.
44	Long distance transportation	V44	Normally, SRF biomass is a local fuel (harvest is transported <50 km) for local markets. Wood chips are expensive to transport due to their low density
45	High GHG emissions	V45	Due to activities in the field, e.g., applying fertilizers and chemicals, tillage and harvesting.
46	Unsuitable clones	V46	Selecting inappropriate clones for climate and soil conditions, resulting with a lower productivity or low quality products.
47	Not accurate biomass assessment	V47	Incorrect or inexact estimation of the stand biomass
48	Minimum initial costs for subsidy	V48	Variations between different governmental states subsidies normally encourage establishing large-size sites
49	Paperwork	V49	Farmers need to fill a lot of documents in order to apply for or receive a subsidy.
50	Rule restrictions	V50	Farmers who receive subsidies are restricted by rules, e.g., selection of specific clones.

3.9.1. Based on direct influence/dependence map:

In general, the most directly influencing variables are the farmers' decisions, the underdeveloped wood-fuel market, insufficient farmers' experience, changing subsidy regulations, and worries about crop failure in the year of site establishment (V1, V5; V2, V4 and V20 with values of 27, 26, 25, 23 and 22, respectively). The most powerful direct dependency factors are farmers' decision, yield risk, acceptance of land-use change, high GHG emissions and small field size (V1, V12, V3, V45 and V26 with values of 72, 42, 39, 38 and 35, respectively) Figure 48.

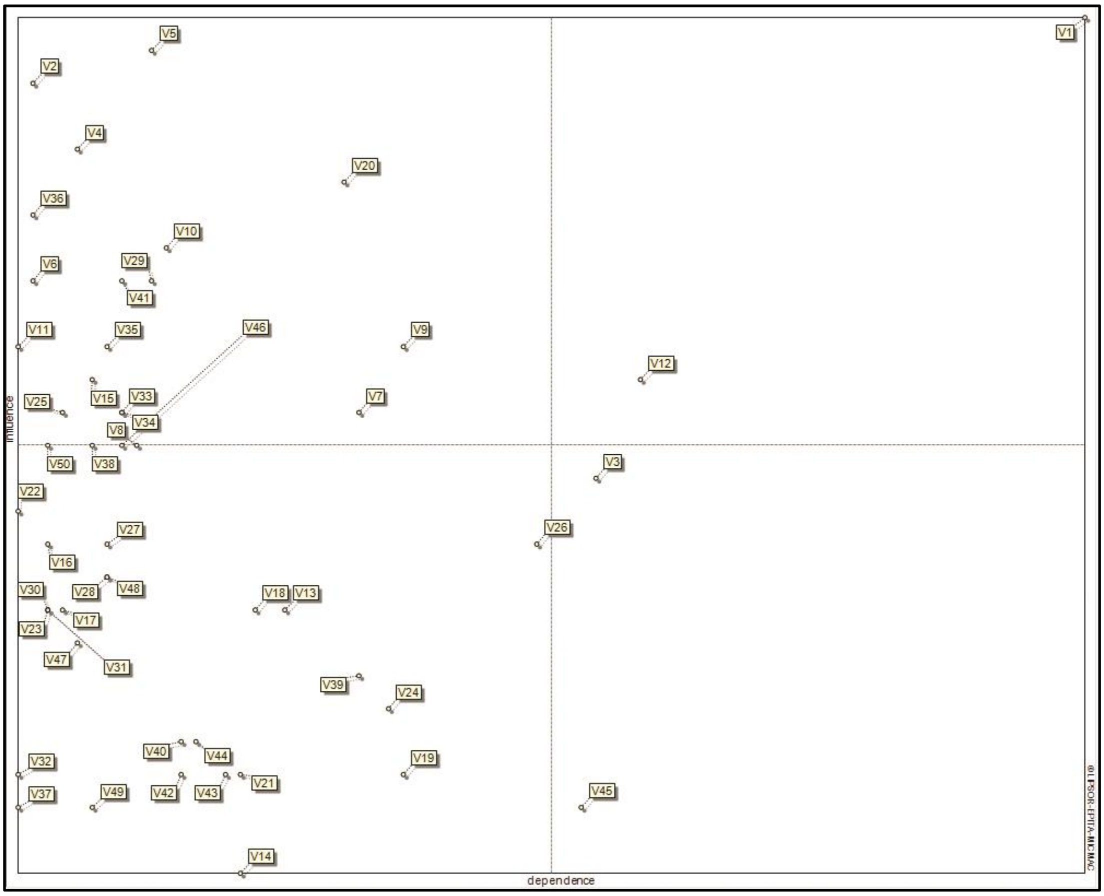


Figure 48. Direct influence/dependence map derived from MDI.

The grouping of the variables within clusters (Figure 19), is summarized in the following sections.

3.9.1.1. Autonomous variables

Variables within this group are normally described as being excluded from the system. These have limited links to the system and the linkage between them with others in the system is weak because they have a weak driving and dependency power (Dubey and Singh 2015; Srivastava and Dubey 2014). Thus, they do not play an important role in the system. In the case of this study, many variables fell into this group and were divided into two sub-groups: disconnected variables and secondary levers.

Disconnected variables: Variables within this sub-group are located near the origin of the graph (Elmsalmi and Hachicha 2014). Variables such as snow accumulation at field, paperwork and row orientation (e.g., length of planted rows) belong into this sub-group. These are not able to influence and to be influenced by other system variables.

Secondary levers: Generally, variables within this sub-group are located above the diagonal, their driving power (influence) is higher than their dependency. Elmsalmi and Hachicha (2014) recommended monitoring these variables in the system. In this study, a lot of variables fall within this sub-group and the most important of these are: machine maintenance, wood chip size, long distance transportation, biomass drying (technique), local employment and groundwater quality.

3.9.1.2. Dependency variables

Variables in this group are characterized by their strong power of dependency and their weak driving power. In general, variables falling into this group are unstable, and any change will influence themselves and other variables (Bag and Anand 2014). Only two dependency variables were identified: acceptance of land-use change and high GHG emissions.

3.9.1.3. Linkage variables

Variables within this group have a strong drive and dependency power. Variables fall under this category are generally unstable, and able to influence other variables when an action done on them (Bag and Anand 2014). We found only two variables under this category; farmers' decision and yield risk.

3.9.1.4. Driving variables

Variables in this group have strong driving power, yet their dependency power is weak. In general, Bag and Anand (2014) reported that variables within this group are important for successful Green Supply Chain Management. From this study's results, the most important driving variables are: the undeveloped wood-fuel market, insufficient farmer experience, changes in subsidy regulations, harvest cycle and worries about failure in the first year.

3.9.2. Based on indirect influence/dependence map:

As shown in Figure 49, the most indirectly influential variables in our case study are: insufficient farmers' experience, changing subsidy regulations, fencing, worries about crop failure in the year of establishment, wild game and an underdeveloped wood-fuel market (V2, V4, V35, V20, V34 and V5, respectively). The most indirect dependency parameters are: farmers' decision, acceptance of land-use change, small field size, high GHG emissions and land-use conflict (V1, V3, V26, V45 and V24, respectively).

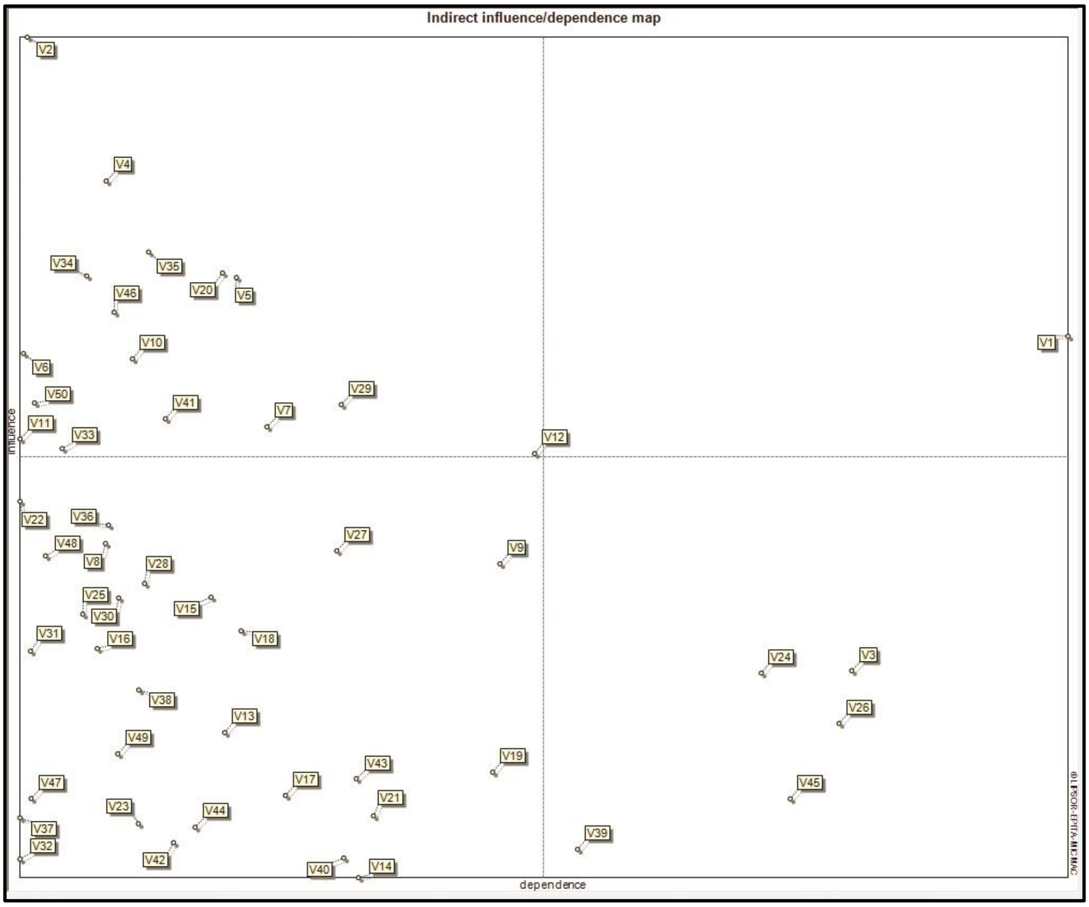


Figure 49. Indirect influence/dependence map derived from MII.

The difference between direct and indirect influence maps is shown in the displacement map (Figure 50). By looking at the direct influence/dependence map, it becomes obvious that some parameters are within autonomous cluster, this means they are not important for the system because they have poor relationships with others. Yet, when looking at the indirect influence/dependence map, some of variables were within the autonomous cluster (based on direct classification) became within the dependence cluster; these variables are wood harvesting system, land-use conflict and small field size (V39, V24 and V26). So based on the indirect classification, they are important and they may influence the system because they have (indirectly) strong power of dependency and weak driving power. This explains the importance of examining and understanding the indirect relationships within the system. When looking at the direct influence map, the graph shows that few parameters such as long-period projects, large stem diameters and subsidy-rule restrictions (V8, V38 and V50) are located at the boundary between the driving and autonomous clusters. This is because they have a moderate direct driving power, and for that it is difficult to distinguish to which cluster are the mentioned parameters belong. Yet, depending on the indirect classification, it clearly appears that rule restrictions (V50) belong to the dependence cluster, while long-period projects (V8) and large stem diameters (V38) belong to the autonomous one. In addition, long-term supply contracts (V9) and harvest cycle (V36) were within the driving cluster and became within the autonomous cluster depending on their direct and indirect influence classification.

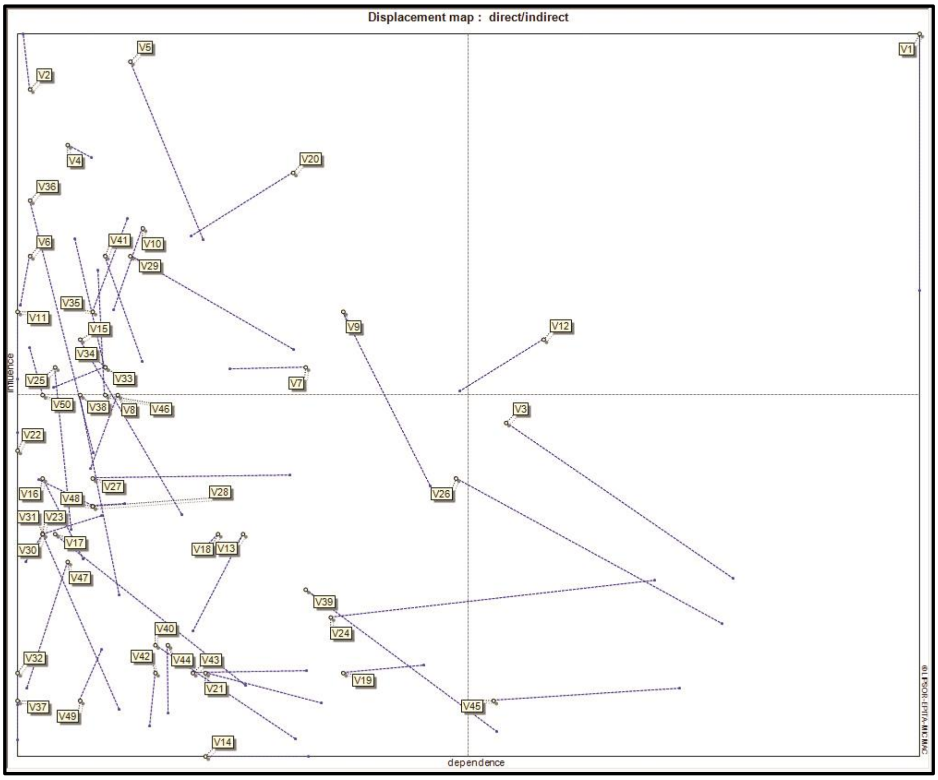


Figure 50. Displacement map shows differences between the direct and indirect influence/dependence maps.

As is evident from the direct influence graph (Figure 48), farmers' decisions (V1) has strong influence on other variables such as land-use conflict (V24), soil preparation and weed control (V27) and wood harvesting system (V39). In other words, it has stronger influence on personal and legal and operational factors rather than other categories.

As can be seen from the direct influence graph (Figure 51), a large number of strong relationships exist between variables. In this case, it can be suggested to classify variables that are strongly influenced by a minimum number of 5 variables (which comprise 10% of the studied factors) as *intensive, directly influenced variables* (IDI). These IDI variables consist of: farmers' decisions (V1), yield risk (V12), worries about crop failure in the year of establishment (V20), small field size (V26), acceptance of land-use change (V3) and long-term supply contracts (V9). Half of these IDI variables have financial influences. The Farmer's decisions variable has the highest number of direct relationships and is influenced by a lot of other variables, e.g., insufficient farmers' experience (V2), undeveloped wood-fuel market (V5), high initial cost (V7), long-period projects (V8), rise in grain prices (V11), annual returns (V18), worries about crop failure in the year of establishment (V20), marginal and polluted sites (V29), harvest cycle (V36), minimum initial costs for subsidy (V48), paperwork (V49) and rule restrictions (V50).

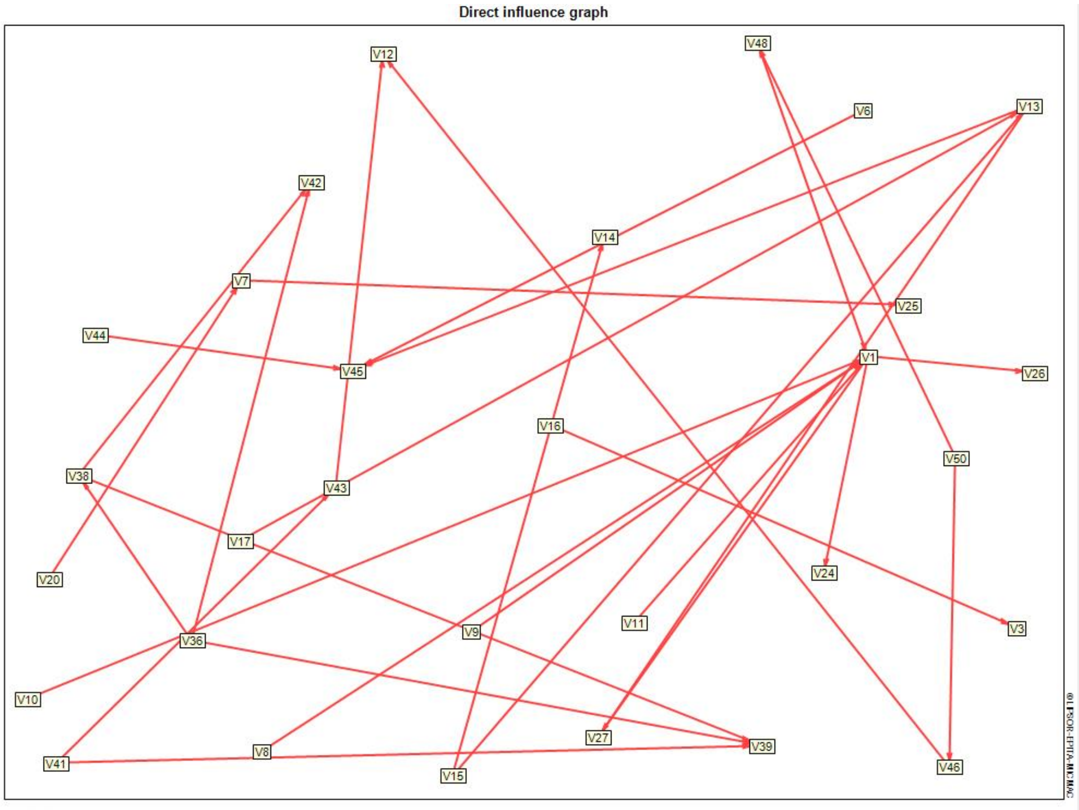


Figure 51. Graph showing 10% of the direct influence relationships between variables

Farmers' decisions (V1) is one of the important variables in the system that influence it. Based on the direct influence/dependence clustering, this variable belongs into the linkage cluster, which means that it has strong driving and dependency power. Variables within this cluster are unstable and for that reason, it is important to know which variables have relationships with VI and how strong are they. The indirect influence graph (Figure 52) shows that the variable, farmers' decisions, is influenced strongly by insufficient farmers' experience (V2), and relatively strongly by changing subsidy regulations (V4) and fencing (V35). It is moderately influenced by wild game (V34), unsuitable clones (V46), marginal lands and polluted sites (V29), high initial cost (V7) and yield risk (V12). A third of these influential variables are financial ones, which mean financial issues play important roles in making the decisions to establish SRF. To understand how these influential variables can change the system indirectly, the links between the strongest variable (insufficient farmers' experience) and the relatively strong variables (changing subsidy regulations and fencing) were examined with the other variables in the system. It was ascertained that insufficient farmers' experience (V2) has relatively strong power to indirectly influence: small field size (V26) and acceptance of land-use change (V3). Changing subsidy regulations (V4) has relatively strong power to influence farmers' decisions

(V1) and could moderately influence the acceptance of land-use change (V3), small field size (V26), high GHG emissions (V45) and land-use conflict (V24). Yet, fencing (V35) has no strong relationships with any of other variables. It has only one relatively strong power to influence farmers' decisions (V1). There are variables that are moderately influenced by fencing: acceptance of land-use change (V3), small field size (V26), high GHG emissions (V45) and land-use conflict (V24).

The small size of SRF sites (V26) is one of the most challenging issues in Germany. Approximately 50% of the sites are smaller than 1 ha, 20% are smaller than 1–2 ha and 17% are smaller than 2–5 ha (Wirkner 2015). This variable falls under driving cluster. This means its driving power is strong, while its dependency power is weak, which makes it important to influence the whole system. This analysis is trying to overcome this challenge and for this reason the existing indirect relationships that influence the small field size were examined. The results show that small field size is relatively strongly influenced by insufficient farmers' experience (V2) and moderately influenced by changing subsidy regulations (V4), fencing (V35), undeveloped wood-fuel market (V5), worries about crop failure in the year of establishment (V20), wild game (34) unsuitable clones (V46) and farmers' decisions (1). Generally, it appears that social and physical variables do not play a fundamental role in changing field size.

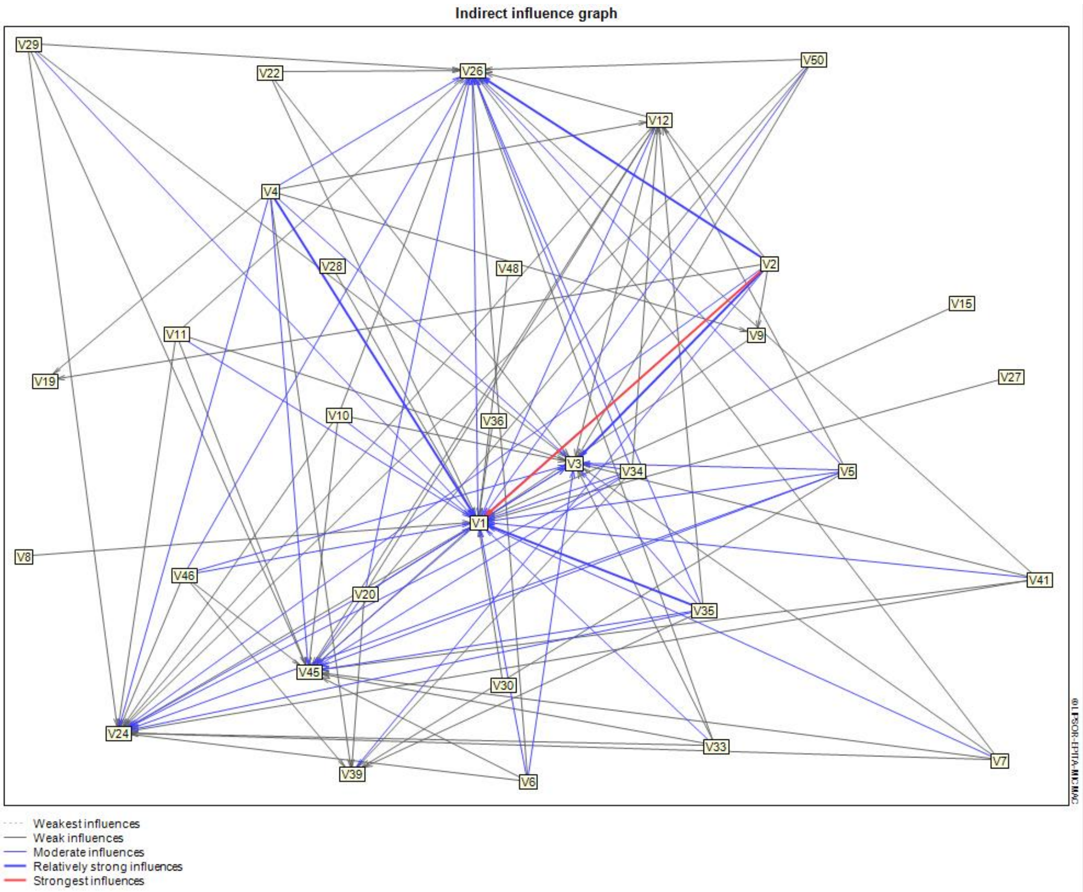


Figure 52. Graph showing 5% of the indirect influence relationships between variables

One of the main purposes of establishing SRF is to help reduce the amount of GHG released to the atmosphere. The variable GHG emission is classified as one of the most direct and indirect dependency parameters, it has a strong power of dependency, and it may influence other variables but weakly. It is easy to know which variables influence directly the emission rate, yet it is getting more difficult to define the indirect influences. For this reason, indirect influences on GHG emissions were examined. The variable GHG emissions (V45) is moderately influenced by insufficient farmers' experience (V2), changing subsidy regulations (V4), fencing (V35), worries about crop failure in the year of site establishment (V20), wild game (V34) and undeveloped wood-fuel markets (V5). Furthermore, it is weakly influenced by unsuitable clones (V46), farmers' decisions (V1), carbon taxation (V6), decrease in wood price (V10), marginal and polluted sites (V29), rule restrictions (V50), high initial cost (V7), non-optimized warehouse (V41), rise in grain prices (V11), plant diseases (V33), yield risk (V12), low precipitation (V22), harvest cycle (V36), minimum initial costs for subsidy (V48), low soil quality (V28), nutrient cycling (V15) and mixed pattern (V30).

Resolving conflicts over land use, namely between lands used for bioenergy and food production, is one of the desired benefits of establishing SRF. Based on the indirect influence/dependency classification, this variable V24 falls within the dependency cluster. This means that it is influenced much more by other variables in the system rather than influencing them itself due to its strong power of dependency. From the indirect influence map, it can be seen that land-use conflict is influenced moderately by insufficient farmers' experience (V2), changing subsidy rules (V4), fencing (V35), worries about crop failure in the year of site establishment (V20), wild game (V34) and undeveloped wood-fuel market (V5).

In brief, results show that farmers' decisions and the underdeveloped wood-fuel market exert the highest direct driving (influencing) force on the system, while farmers' decisions and yield risk have the highest direct dependency power. The insufficient experience of a farmer and changing subsidy regulations are variables that express a high indirect driving force, while farmers' decision making, acceptance of land-use change, and small field size are variables that generate the highest dependency power.

3.10. Impacts of Land-use Change on the Ecosystem Quality

An ecosystem is a complex interaction between living elements and their non-living components (abiotic environment) at a specific place to provide various benefits and services (Hoffmann et al. 2014). Humans benefit directly and indirectly from this range of ecosystem goods and services to fulfil their main needs for food, raw materials and energy. To support life on Earth, other important functions are needed and provided by the ecosystem, such as the regulation of atmospheric chemical compounds, global temperature and hydrological flows (Brandão and Canals 2012; Costanza et al. 1997).

Human land use causes wide impacts on the ecosystem, ranging from changes in species diversity to disturbances of ecosystem processes (Milà i Canals and Baan 2015). Unfortunately, ecosystem services lack attention from policy makers (Costanza et al. 1997). A clear example of that is the exclusion of land-use change and occupation impacts on the ecosystem when conducting life cycle assessments (LCA). Ecosystem services are for example involved in the provision of potable water and decomposition of wastes. This work examines anthropogenic influences and impacts, in the case where the land use/cover on degraded lands is converted from grassland to SRF.

Regarding the local potential natural vegetation (PNV) for the SRF site at Krummenhennersdorf and based on the PNV maps for Germany that are available on the website of the Saxon State Ministry of the Environment and Agriculture (SMUL 2016), the map shows a potential of beech-oak forest as shown in Figure 53. This biome type is used as a reference.

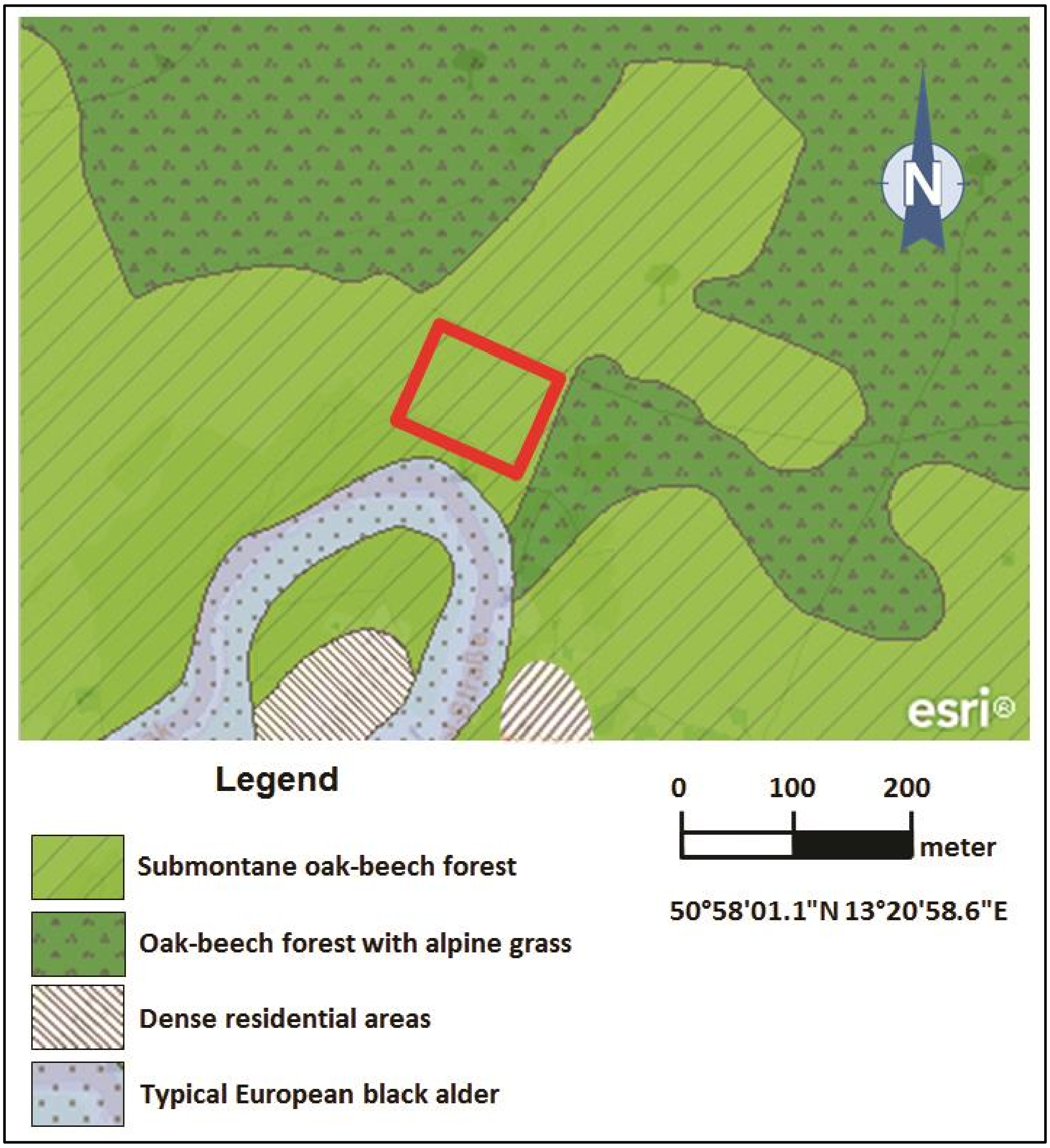


Figure 53. Potential natural vegetation (PNV) map shows the location *(red box)* of the short rotation forestry (SRF) study site at Krummenhennersdorf, Saxony, Germany. Map section modified after Saxon State Ministry of the Environment and Agriculture (SMUL 2016).

Most SRF values of the indicators used to estimate impacts on the ecosystem used in this section are own data that were obtained from measurements conducted at the SRF site in Krummenhennersdorf. Other values have been obtained from the work conducted by other researchers at the same site. For the grassland study, most of the data used are from published data derived from experiments done in grasslands in Germany. Regarding the local PNV, which is beech-oak forest, results of experiments were used that were done at Hainich forest in central Germany, which is composed of typical beech trees (*Fagus sylvatica*), in addition to other deciduous trees (Kutsch et al. 2010). Although Tharandt forest is just a few kilometers from the SRF site, data from Hainich forest were used for PNV parameters because it is more suitable in terms of soil and plant properties (Heilmeier H., personal communication, April 6, 2016).

In examining the biodiversity, specific data from the SRF and grassland sites were not gathered, and average values provided by Baan et al. (2013) of biodiversity damage potential (BDP) were used. These BDP values are based on species richness using 195 empirical studies and peer-reviewed papers from approximately 900 data points. The BDP are a world average for different land use type biomes, e.g., the BDP value for a non-used forest is zero and considered a semi-natural one. Finally, values of five different indicators – cation exchange capacity (CEC), total aboveground biomass (TAB), soil organic matter (SOM), leaf area index (LAI), and evapotranspiration (ET) – are used to estimate the mid-points impacts on the ecosystem (Table 12).

Table 12. Values of the indicators used to estimate impacts on ecosystem structural quality I_{ESQ} and ecosystem functional quality I_{EFQ}.

Indicator	Value			Units
	Project (SRF)	**Reference (Grassland)**	**PNV Beech-oak forest**	
Cation exchange capacity (CEC)	10.7±0.6 [1]	12.8±0.02 [1, 2]	11.2±3.9 [3]	cmol kg^{-1}
Total aboveground biomass (TAB)	14.8± 1.5 [4, 5, 6, 7]	6.7±1.5 [8, 9]	6.82±1.4 [10, 11, 12]	t dry mass ha^{-1} yr^{-1}
Soil organic matter (SOM)	2.46 [1]	2.58[4]	4.8±1.18 [13]	%
Leaf area index (LAI)	3.1±0.2 [1]	2.55±0.4 [14, 15, 16]	4.6±0.5 [17, 18, 19]	m^2 m^{-2}
Evapotranspiration (ET)	493.8±30.5 [20, 21, 22, 23]	343.6±84.6 [24, 25, 26]	525±59 [19]	mm yr^{-1}

[1]Own data; [2]Lutter et al. (2016); [3]Guckland (2009); [4]Dietzsch (2011); [5]Guidi Nissim et al. (2013); [6]Stolarski et al. (2008); [7]Verlinden et al. (2015); [8]Borchard et al. (2015); [9]IPCC (2003); [10]Brumme and Khanna 2009); [11]Tum et al. (2011); [12]FAO (2015); [13]Kutsch et al. (2010); [14]Falge et al. (2005); [15]Preusser et al. (1999); [16]Spank et al. (2013); [17]Bernhofer et al. (2011); [18]Korn (2004); [19]Herbst et al. (2015); [20]Bungart and Hüttl (2004); [21]Busch (2009); [22]Petzold et al. (2010); [23]Schmidt-Walter and Lamersdorf (2012); [24]Harsch et al. (2009); [25]Hussain et al. (2011); [26]Müller et al. (2010).

It is important to mention that a negative value of the impact reflects improvement in the ecosystem quality, while a positive value reflects deterioration. From land-use change impacts results (Figure 54), it can be observed that SRF causes a slight decrease in soil structure quality, where impact of soil structure I_{SS} has a value of 4.65%. This is a result of the slightly higher content of soil organic matter (SOM) at the grassland site than that at the SRF site in Krummenhennerdorf. It needs to be pointed out that SOM values are based on the results of the topsoil samples, however, normally at SRF plantations (in situ) soil stores more organic matter at depths deeper than 30 cm (Lutter et al. 2016). Thus, if SOM for the whole soil column is included (1-m depth), then this result may change. However, the result of I_{SS} is based on results from one site. If an average value for SRF influence on the SOM is used, as the percentage cited from the recent work of Lutter et al. (2016) that monitored 51 research sites shows, after 15 years of establishing a SRF plantation, soil organic carbon increases by 10.4% in the top and 17.2% in the bottom soil layers. When this percentage over 15 years is applied to this calculation, the new I_{SS} value rose to -5.4±0.65 for the land-use change. In other words, an improvement of about 5% of the soil structure is evident, whereas the previous results showed a slight reduction in the soil structure (about 2.5%).

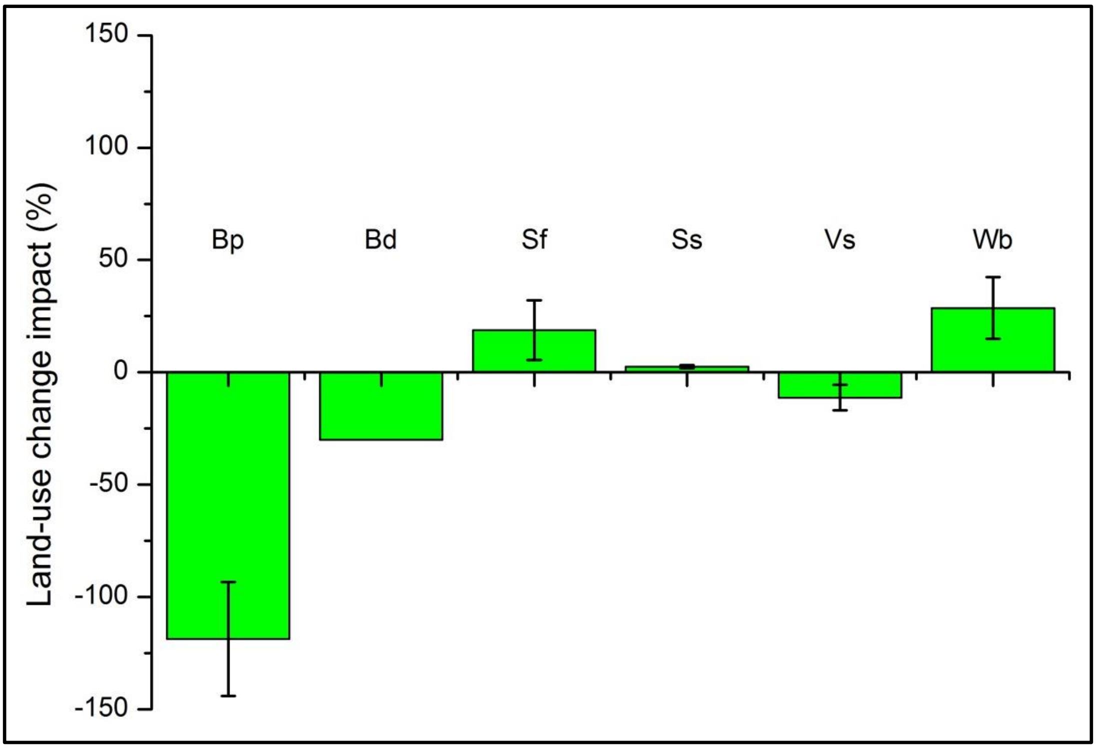


Figure 54. Impact of land-use change (LUC) on: biomass production (***Bp***), biodiversity (***Bd***), soil fertility (***Sf***), soil structure (***Ss***), vegetation structure (***Vs***) and on-site water balance (***Wb***).

The midpoint scores of the land-use change impacts were aggregated in order to estimate the ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ) as described previously in the methodology Section 2.8. Results of land-use change impacts on the ecosystem show that converting degraded land (grassland) to SRF generates an improvement of the ESQ with value of 43.1±4%. Yet, a slight reduction in its EFQ was noticed with value of 6.6±6%, as seen in Figure 55. Through this improvement in the ecosystem structural quality ESQ, it is readily understood that the storage capacity in terms of biomass, structure and biodiversity at the SRF site is higher than that of the grassland site on degraded land. On the other hand, the message behind the reduction of the ecosystem functional quality EFQ is that SRF land has less control over fluxes of water, material and nutrients than that of grassland. The evapotranspiration (ET) of SRF is much higher than that of grassland, and there is a lower content of organic matter in SRF soils compared to grassland – this plays a role in this reduction of ecosystem functional quality EFQ at the SRF site.

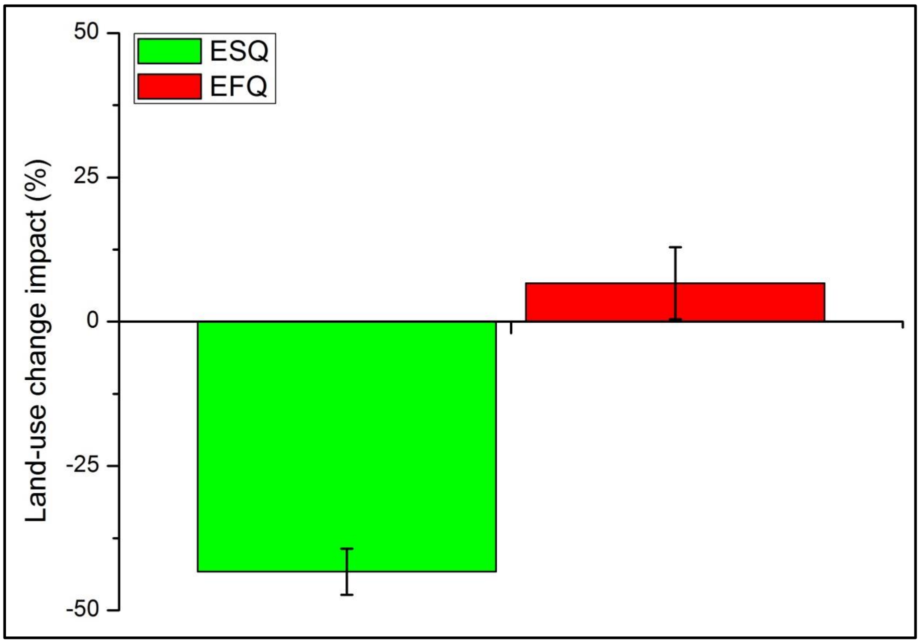


Figure 55. Land-use change impact (LUC) of short rotation forestry (SRF) on the ecosystem structural quality (***ESQ***) and on ecosystem functional quality (***EFQ***).

Regarding the land occupation impacts, normally this type of impact assessment is used to compare different land-use scenarios (Fehrenbach et al. 2015). As shown in Figure 56, the SRF land-use occupation can be compared to grassland. These mid-point impacts show that SRF plantations have much more power to improve the ecosystem quality than grassland and beech-oak forest in terms of the capacity to produce biomass. In addition, SRF plantations are less harmful to the biodiversity than grassland.

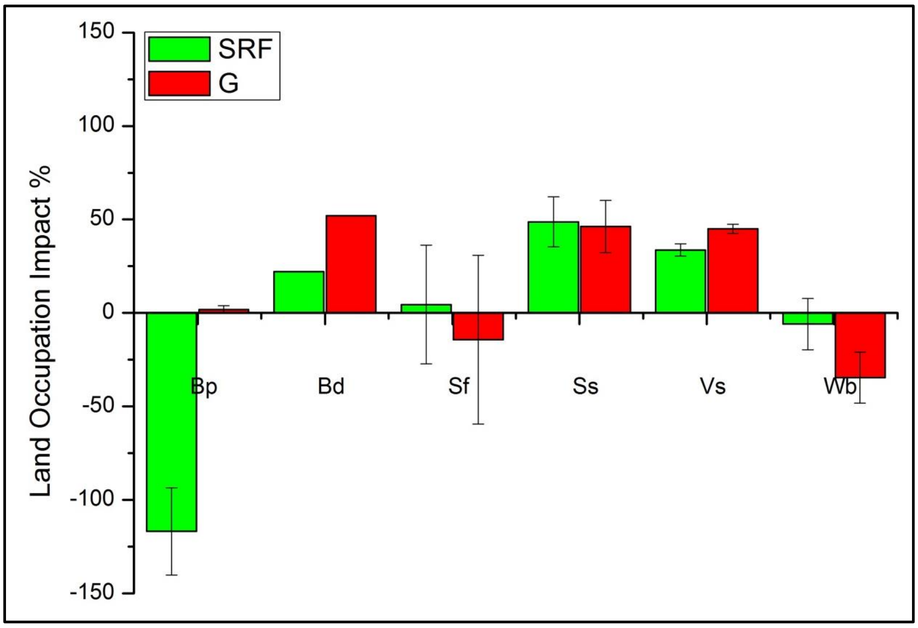


Figure 56. Mid-point impacts of land occupation for short rotation forestry (***SRF***) site and for grassland (***G***).

The impacts of land occupation by SRF on the ecosystem structural quality ESQ and ecosystem functional quality EFQ (Figure 57) show that both the potential ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ) would decrease if the land is used as grassland, with impact values of 13.2±14.4 and 18.9±0.9%, respectively. In contrast, the SRF plantation improved the ESQ (with a value of -30.1±2.8%), while it reduced the potential ecosystem functional quality (EFQ) of the land to about 25.5±1.0% compared to the PNV.

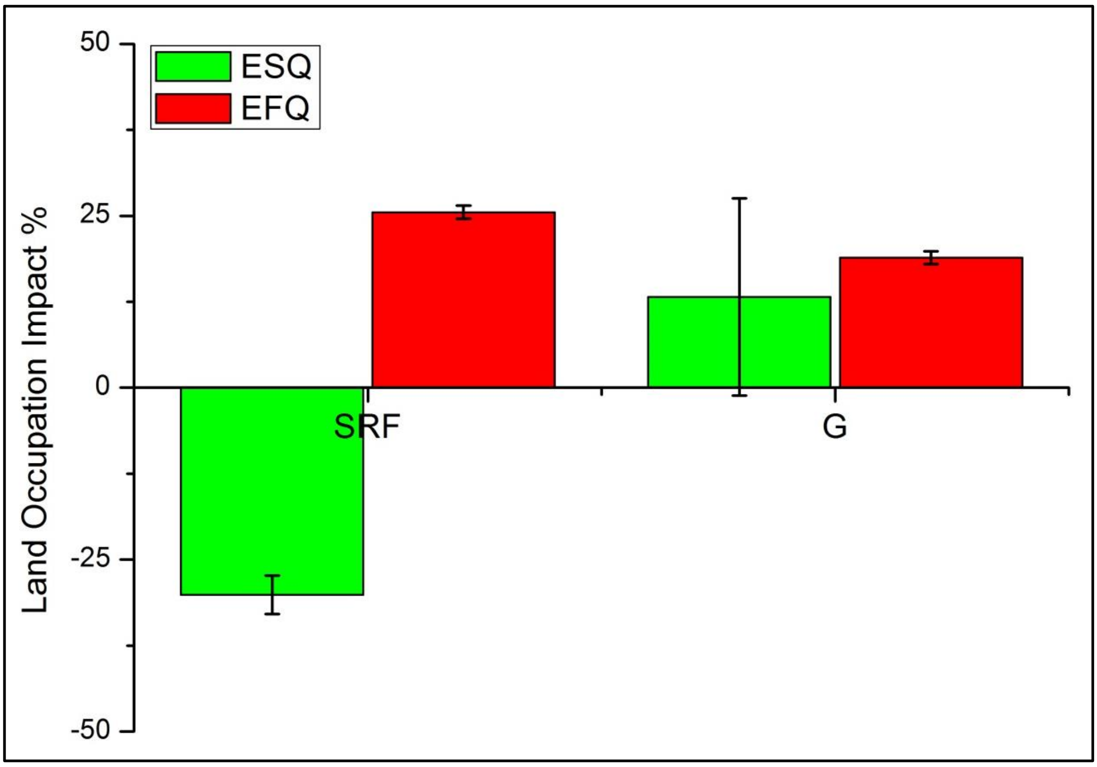


Figure 57. Land occupation impact on the ecosystem structural quality (***ESQ***) and ecosystem functional quality (***EFQ***) for short rotation forestry (***SRF***) and grassland (***G***).

From land-use change impact results, the aggregated impacts of mid-point to endpoints show that SRF land has higher storage capacity in terms of controlling the solar energy and nutrients flow. Furthermore, as seen from the negative value of its ecosystem functional quality EFQ impact, SRF land has the ability to maintain and store the ecosystem structural quality ESQ, whereas an increase of about 12% is observed for grassland. Furthermore, SRF land has the ability to provide better environmental services than grassland, as well as to improve its ecosystem quality over time. Thus, the conversion of grassland to SRF is found to be encouraging in this study.

Compared to a beech-oak forest (which is the expected local potential natural vegetation), SRF land shows about a 30% improvement on its ecosystem structural quality, while showing a deterioration of 25% on its functional quality. This means this SRF land may never regenerate back to its original state because it has less control on energy- and nutrient-flows. It also has less capacity to restore and maintain its ecosystem structural quality ESQ.

4. Conclusions and Recommendations

In conclusion, it is recommended to plant short rotation forests on marginal land and brownfields, parallel to other sustainable land management options. Such land usage will reduce the demand for fertile and non-contaminated arable land for energy crops. Consequently, more fertile land remains available for food and animal feed production. At the same time, SRF contributes on a longer term to continuous soil quality and biodiversity improvement, groundwater protection, and soil erosion prevention.

Greenhouse gas 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. The results of this study are in good agreement with those of other research (Firrisa et al. 2014; van Duren et al. 2015) that report 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. (2013) compared the ability of annual GHGs savings between different bioenergy crops, rapeseed, maize and Miscanthus. Results showed that rapeseed used for biodiesel production was the lowest.

Based on an analyses of the driving factors for a willow and poplar short rotation forestry (SRF) production system, the MICMAC method was used to describe the system with matrixes that linked all factors (elements) together. This study concludes that to enhance the success of this system, decision makers should focus on ensuring a developed wood-fuel market, on increasing farmer's experience (training), on improving subsidy regulations and on recommending a proper harvesting year cycle.

The assessment of impacts of land-use change on the ecosystem quality, which was discussed in Section 3.10, indicates that establishing SRF plantations on degraded lands improved the ecosystem structural quality (ESQ) and ecosystem functional quality (EFQ).

Finally, and based on all results, establishing poplar and willow SRF on degraded lands to extract biomass for energy is sustainable and highly recommended.

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Appendix

Table A1. Variables sorted by **a)** their driving (influence) power (based on MDI), **b)** their power of dependency (based on MDI), **c)** their driving (influence) power (based on MII), **d)** their power of dependency (based on MII)

Based on MDI				Based on MII			
a		b		c		d	
Rank	Variable No.	Rank	Variable No.	Rank	Variable No.	Rank	Variable No.
1	1	1	1	1	2	1	1
2	5	2	12	2	4	2	3
3	2	3	3	3	35	3	26
4	4	4	45	4	20	4	45
5	20	5	26	5	34	5	24
6	36	6	9	6	5	6	39
7	10	7	19	7	46	7	12
8	6	8	27	8	1	8	9
9	29	9	7	9	6	9	19
10	41	10	39	10	10	10	21
11	9	11	20	11	50	11	14
12	11	12	13	12	29	12	43
13	35	13	18	13	41	13	40
14	12	14	14	14	7	14	29
15	15	15	21	15	11	15	27
16	7	16	43	16	33	16	17
17	25	17	44	17	12	17	7
18	33	18	40	18	22	18	18
19	34	19	42	19	36	19	5
20	8	20	10	20	8	20	13
21	38	21	5	21	27	21	20
22	46	22	29	22	48	22	15
23	50	23	8	23	9	23	44
24	3	24	33	24	28	24	42
25	22	25	34	25	15	25	41
26	16	26	41	26	30	26	35
27	26	27	46	27	25	27	28
28	27	28	27	28	18	28	38
29	28	29	28	29	16	29	23
30	48	30	35	30	31	30	10
31	13	31	48	31	3	31	30
32	17	32	15	32	24	32	49
33	18	33	38	33	38	33	46
34	23	34	49	34	26	34	36
35	30	35	4	35	13	35	4
36	31	36	47	36	49	36	8
37	47	37	17	37	19	37	16
38	39	38	25	38	43	38	34
39	24	39	16	39	17	39	25
40	40	40	23	40	47	40	33
41	44	41	30	41	45	41	48
42	19	42	31	42	21	42	50
43	21	43	50	43	37	43	47
44	32	44	2	44	23	44	31
45	42	45	6	45	44	45	2
46	43	46	36	46	42	46	6
47	37	47	11	47	39	47	11
48	45	48	22	48	40	48	22
49	49	49	32	49	32	49	32
50	14	50	37	50	14	50	37

Table A2. Comparison of Alternative Models, correlation between 1/SLA and CO_2 for clone H275

Model	Correlation	R-Squared
Squared-Y reciprocal-X	-0.6683	44.67%
Reciprocal-X	-0.6637	44.04%
Square root-Y reciprocal-X	-0.6599	43.55%
S-curve model	-0.6552	42.93%
Squared-Y logarithmic-X	0.6494	42.18%
Double reciprocal	0.6432	41.37%
Logarithmic-X	0.6425	41.28%
Square root-Y logarithmic-X	0.6378	40.67%
Squared-Y square root-X	0.6374	40.63%
Multiplicative	0.6322	39.96%
Square root-X	0.6293	39.60%
Squared-Y	0.6241	38.95%
Double square root	0.6240	38.93%
Reciprocal-Y logarithmic-X	-0.6185	38.26%
Logarithmic-Y square root-X	0.6178	38.17%
Linear	0.6146	37.78%
Square root-Y	0.6087	37.05%
Reciprocal-Y square root-X	-0.6033	36.40%
Exponential	0.6021	36.25%
Double squared	0.5948	35.38%
Reciprocal-Y	-0.5867	34.42%
Squared-X	0.5827	33.95%
Square root-Y squared-X	0.5756	33.13%
Logarithmic-Y squared-X	0.5679	32.25%
Reciprocal-Y squared-X	-0.5506	30.32%
Logistic	<no fit>	
Log probit	<no fit>	

Table A3. Comparison of Alternative Models, correlation between SLA and CO_2 for clone H275

Model	Correlation	R-Squared
Double squared	-0.7154	51.18%
Squared-Y	-0.7113	50.60%
Squared-X	-0.7079	50.11%
Squared-Y square root-X	-0.7065	49.91%
Square root-Y squared-X	-0.7027	49.38%
Linear	-0.7022	49.30%
Squared-Y logarithmic-X	-0.6997	48.96%
Logarithmic-Y squared-X	-0.6966	48.53%
Square root-X	-0.6963	48.49%
Square root-Y	-0.6963	48.48%
Exponential	-0.6895	47.54%
Logarithmic-X	-0.6885	47.40%
Logarithmic-Y square root-X	-0.6829	46.63%
Reciprocal-Y squared-X	0.6819	46.49%
Square root-Y logarithmic-X	-0.6817	46.47%
Squared-Y reciprocal-X	0.6809	46.36%
Multiplicative	-0.6741	45.45%
Reciprocal-Y	0.6737	45.38%
Reciprocal-X	0.6673	44.53%
Reciprocal-Y square root-X	0.6664	44.40%
Square root-Y reciprocal-X	0.6595	43.49%
Reciprocal-Y logarithmic-X	0.6569	43.15%
S-curve model	0.6510	42.37%
Double reciprocal	-0.6321	39.96%
Double square root	<no fit>	
Logistic	<no fit>	
Log probit	<no fit>	

Table A4. Comparison of Alternative Models, correlation between LA and 1/SLA for clone H275

Model	Correlation	R-Squared
Squared-Y	0.9120	83.17%
Linear	0.9087	82.57%
Double square root	0.9055	81.99%
Square root-X	0.9050	81.89%
Logarithmic-Y square root-X	0.9030	81.55%
Square root-Y	0.9026	81.47%
Double squared	0.8995	80.92%
Log probit	0.8983	80.69%
Squared-Y square root-X	0.8956	80.21%
Logistic	0.8953	80.15%
Exponential	0.8935	79.83%
Reciprocal-Y logarithmic-X	-0.8851	78.33%
Multiplicative	0.8844	78.22%
Square root-Y logarithmic-X	0.8797	77.38%
Squared-X	0.8792	77.30%
Logarithmic-X	0.8721	76.05%
Reciprocal-Y	-0.8670	75.17%
Square root-Y squared-X	0.8643	74.70%
Squared-Y logarithmic-X	0.8495	72.16%
Logarithmic-Y squared-X	0.8463	71.63%
Reciprocal-Y squared-X	-0.8030	64.48%
Double reciprocal	0.7787	60.64%
S-curve model	-0.7582	57.48%
Square root-Y reciprocal-X	-0.7437	55.31%
Reciprocal-X	-0.7267	52.81%
Squared-Y reciprocal-X	-0.6873	47.24%
Reciprocal-Y square root-X	<no fit>	