Chapter 14
Perennial Energy Crops on Drained Peatlands in Finland

Narasinha J. Shurpali

Abstract Finland has a large area under peatlands (more than 10 M ha). Under pristine conditions, peatlands are a sink for atmospheric CO_2 and a source of methane to the atmosphere. Since the 1950s, peatlands in Finland have been drained for forestry, agriculture, and peat extraction for energy. Once drained, peatlands transform into large sources of CO_2 to the atmosphere and weak sinks for methane. Finding a suitable after-use option for drained peatlands is complicated by the specific nature of the drained peatland type. As an after-use option on a cutover peatland, the cultivation of a perennial bioenergy crop on a drained peatland in eastern Finland was explored during 2004–2011. The long-term measurements of greenhouse gas exchange from this study site showed that the benefits from bioenergy crop cultivation vary strongly depending on the climatic conditions during the crop cultivation phase.

Keywords Bioenergy · Greenhouse gas exchange · Climate change

1 Introduction

Peatlands occupy a small part of the Earth's land area (Turetsky et al. 2015). However, they are globally important because of their high carbon content. Pristine peatlands are currently a weak carbon sink and a moderate source of methane (Frolking et al. 2011; Nilsson et al. 2008). Peat is a decaying organic matter that has accumulated under-saturated conditions. Formation of peat occurs in areas with surplus soil moisture (Camill 2000). Peatlands are common in regions with high precipitation excess (e.g., the temperate and boreal zones). The northern peatlands account for about a third of the world soil carbon (Gorham 1991). They sequester

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N. J. Shurpali (✉)
Biogeochemistry Research Group, Department
of Environmental and Biological Sciences, University of Eastern Finland,
Yliopistoranta 1 DE, 70211 Kuopio, Finland
e-mail: narasinha.shurpali@uef.fi; nshurpali@gmail.com

S. J. Varjani et al. (eds.), *Biosynthetic Technology and Environmental Challenges*, Energy, Environment, and Sustainability,
https://doi.org/10.1007/978-981-10-7434-9_14

more carbon dioxide from the atmosphere than they emit. This biogeochemical C cycle is greatly perturbed when peatlands are subjected to drainage and land use. Since the 1950s, nearly 60% of the original peatland area has been drained for several purposes such as forestry, agriculture and peat extraction for energy (Minkkinen et al. 2002). About six million ha of peatlands have been drained in Finland (Laiho and Laine 1997). The drainage of peatlands affects the regional carbon cycle in a way that the originally carbon accumulating ecosystems are transformed into strong sources of CO_2 to the atmosphere.

Drainage of peatlands has an important role in regulating the regional and thus, the global climate (Limpens et al. 2008). A lowering of the water table triggers drying (Artz et al. 2008) so that the soil decomposition processes tend to be not limited by the lack of oxygen (Fenner and Freeman 2011). With more oxygen available, the soil organic matter (SOM) decomposes more rapidly leading to more carbon dioxide being released into the atmosphere. Simultaneously, methane emissions from drained peatlands decline due to a decrease in methane production and increased oxidation. Moreover, several studies hinted that the drained peatlands may even act as small-scale methane sinks (Hyvönen et al. 2009).

While the use of peatlands as an economic resource was deemed necessary, the fact that such land use (drainage) leads to environmental problems is increasingly being realized the world over since the 1990s. Hence, continued attempts are being made in Finland and elsewhere to find suitable land use options for drained peatlands after their intended land use (Vasander et al. 2003). Simply abandoning these lands is considered environmentally untenable. Therefore, several options have been suggested as after-use options: intensive forestry, rewetting, restoration to a functional peatland, creation of artificial wetlands, use of cutover peatlands for agriculture and cultivation of energy crops, etc. Decision on which option to use at a given drained peatland is complex. In view of the peatland formation processes and origin, every peatland is different in its physiography, hydrology, the physical and chemical characteristics of the remaining peat, etc. In addition, the physical layout of the drainage ditches varies from one location to the other. Thus, peatland restoration and reclamation criteria are specific to the peatland site under investigation (Vasander et al. 2003).

2 Ecosystem Greenhouse Gas (GHG) Exchange

Quantifying GHG (CO_2, CH_4, and N_2O) exchange from a given ecosystem and understanding the processes that describe the measured exchange rates are necessary for identifying sinks and sources of GHGs. Since the GHGs are radiatively important, their increasing levels in the atmosphere are a cause for concern. Increasing GHG concentrations in the atmosphere is directly linked to increasing global surface temperature and thus to climate change (Oreskes 2004). Currently, the two most widely used techniques for measuring GHG exchange are the eddy covariance (EC) and the closed chamber (manual or automated) methods (Riederer et al. 2014). The eddy covariance method measures turbulent GHG fluxes for monitoring trace gas flux dynamics at a landscape level (Baldocchi 2014). EC towers have become a common approach for monitoring direct and continuous (year-round) GHG fluxes from different ecosystems. Nowadays, the EC fluxes of CO_2 and water vapor are routinely made across all continents. A global network of EC stations called "FLUXNET" links across a range of regional networks in different parts of the world (http://fluxnet.fluxdata.org). This network has registered more than eight hundred active and historic flux measurement sites distributed in diverse climatic and vegetation zones.

EC fluxes are measured by estimating the covariance between the fluctuations in vertical velocity and target scalar mixing ratios (water vapor, all GHGs and biological volatile organic compounds, etc.) at a given measurement site (Baldocchi 2014). With the eddy covariance method, one can measure fluxes directly over a large area with no disturbance to the microenvironment under investigation. High-frequency EC measurements are collected for the purpose, capturing diurnal and seasonal dynamics. EC method is the first choice if the research objective is to characterize the site average GHG sink/source strength. However, as the EC method presents a large area integrated flux rate, chamber-based methods (either manual or automated) assume importance if the research interest is in understanding the inherent spatial heterogeneity of a site in terms of the distribution of cold and hot spots of GHG dynamics. EC method is resource-intensive, as this method requires expensive, fast response instruments for detecting small changes in the atmospheric GHG concentrations. Large datasets collected through EC techniques require personnel trained in instrumentation and micrometeorology. On the other hand, manual chamber methods are inexpensive, easy to use, and are suited for developing process-level understanding of soil, plant, and microbial interactions.

3 Annual Cropping Systems on Drained Peat Soils

Finland is the world's northernmost agricultural country. Finnish farmlands reach from the 60th latitude to north of the Arctic Circle. The major crops include cereals (wheat, rye, barley, and oats), turnip, rape, potato, sugar beet, and grasses (Natural Resources Institute Finland 2017). These soils have been reported to trigger increased annual emissions of CO_2 and N_2O (Statistics Finland 2015). The GHG emissions from agricultural peat soils in the Nordic countries (Finland, Sweden and Norway) have been compiled (Maljanen et al. 2010). This compilation of all available data on GHG emissions as of the time of this publication included 16 perennial grass sites, 6 sites cultivated with barley, and 1 site each with potato and carrot. Agriculture plays a minor role in the Nordic economy that is dominated primarily by the forestry sector. Nevertheless, considering the fact that the Nordic region is among global regions that are most vulnerable to climate change, the available data on GHG emissions from Nordic agriculture are far too limited for developing proper mitigation strategies. The GHG emissions from agricultural peatlands vary in magnitude owing to differences in cultivation methods, crops, and climatic conditions. Based on the available data, it can be inferred that the peat soils used for crop cultivation are significant sources of CO_2 and N_2O to the atmosphere (Maljanen et al. 2010).

Most of the measured GHG emissions from agricultural peat soils are based on chamber methods with a few studies employing the EC method to monitor the net ecosystem CO_2 exchange (NEE) (Maljanen et al. 2010). Depending on the water table level, croplands on peat soils are small sinks or sources of CH_4 (Hyvönen et al. 2010). Annual crops on peat soils (cereals) are larger sources of CO_2 and N_2O than perennial grasslands owing to increased pore space resulting from regular tillage. The cereal crop cultivated on a peat soil in Finland has been shown to be a minor sink for CH_4 and a source of CO_2 (17.7 t CO_2 ha^{-1}) and N_2O (17.1 kg N_2O ha^{-1}). Annual N_2O emission from a potato field has been estimated to be 15.7 kg ha^{-1} (Regina et al. 2004). Compared to mineral soils, annual crops on drained peat fields have been shown to be a net source of CO_2 owing to a high degree of decomposition of the soil organic matter. In addition, these soils have been known to emit high amount of N_2O to the atmosphere in comparison to mineral soils as they contain a large N-pool. While CO_2 accounts for 80% of the global warming potential of an agricultural peat soil, N_2O emitted from these soils accounts for the remaining potential. The methane sink strength of the drained peat soils is too low to have any cooling impact unless the water table level is artificially elevated to reintroduce methanogenic microbes in these peat soils.

4 Perennial Agriculture on Drained Peat Soils

It is apparent from the above discussion that converting agricultural drained peat soils into croplands or grasslands for forage has not succeeded as a sustainable after-use option for drained peatlands in Finland. To circumvent this problem, policy suggestions were made to employ perennial energy crop cultivation on such problematic soils, a potential sustainable solution in the Nordic region, Germany, and Estonia where peat extraction for energy is a common practice (Lewandowski et al. 2003). Indeed, the idea of growing reed canary grass (RCG—*Phalaris arundinaceae*, L.) as a perennial bioenergy crop on cutover peatlands in Finland gained momentum since the mid-1990s. This crop was the obvious choice at the time as several studies reported that RCG is well suited for cultivation under low temperatures and humus rich, waterlogged, nutrient-poor soils of the Nordic countries (Lewandowski et al. 2013). An additional reason for selecting this crop as a source of renewable energy was that the atmospheric carbon taken up by the crop during the process of photosynthesis would compensate the emissions resulting from the combustion of harvested RCG biomass. Thus, the RCG cultivation was considered to be a carbon-neutral energy source (Lind et al. 2016). However, the basis for such assumptions was a few studies wherein the aboveground biomass or productivity was viewed as an indicator of the ability of this crop to fix the atmospheric carbon. Most of the studies conducted on reed canary grass cultivation on organic soils in Finland focused on measurement of rates of biomass accumulation under different agronomic practices (Sahramaa and Jauhiainen 2003). The objective of these studies was to generate biomass data for peat energy industries to assess the role of RCG as a fuel supplement to peat-derived energy. Such studies addressing the agronomic traits of the RCG crop recommended the use of RCG as a perennial bioenergy crop on marginal soils of cutover peatlands in the Nordic countries (Sahramaa and Jauhiainen 2003). However, some studies suggested that the bioenergy crops should be banned from cultivation on organic soils owing to their high CO_2 and N_2O emissions (Beringer et al. 2011; Crutzen et al. 2008). In view of these conflicting reports, the Biogeochemistry Research Group at the University of Eastern Finland undertook a field experimental study with the broad aim of investigating the environmental impact of the cultivation of RCG on the carbon balance and N_2O emissions from a cutover peatland. The results of this study are summarized in the following.

The field experiment was conducted on a 15-ha cutover peatland site with reed canary grass cultivation in the Linnansuo peat harvesting area (62° 30′N latitude and 30° 30′E longitude) in the Tuupovaara village in eastern Finland. Based on the 1961–1990 climatic averages, the region experiences a mean temperature of −11.9 °C in January and 15.8 °C in July. The annual mean temperature of the region is 2.0 °C and annual precipitation amounts to 600 mm. The mean annual duration of snow cover in the region is 183 days with a mean annual snow depth 63 cm. An aerial view of the study site with the location of the EC instrument tower marked in red is shown in Fig. 1 (left panel).

The instruments were mounted on a tower (Fig. 1: Middle panel) at a height of 3.7 m above the ground and aligned at an angle of 225°, in the direction of the predominant winds in the region. The EC system consisted of a 3-D sonic anemometer (CSAT-3, Campbell Sci.) and an open-path infrared CO_2/H_2O

Fig. 1 Left panel: aerial view of the drained peatland site in Eastern Finland where the reed canary grass (RCG) was cultivated as a perennial bioenergy crop (the red mark shows the location of the Eddy Covarinace (EC) instrument tower at the site); middle panel: the EC instrument tower with various instruments mounted at 3.7 m above the soil surface; right panel: a close-up of the fast response infrared gas analyzer (IRGA) and three-dimensional sonic anemometer mounted on the EC tower (*Photo credits* Alpo Hassinen and Jari Huttunen)

analyzer (IRGA, Li-7500, LI-COR) for measuring high-frequency (10 Hz) vertical wind velocity and CO_2 and water vapor mixing ratios, respectively (Fig. 1: Right panel). Supporting measurements included air temperature, air relative humidity and pressure, net radiation and its components, photosynthetically active radiation wind speed and direction, soil temperature profile, precipitation, soil water potential, soil moisture, water table level, and snow depth. The measurements began in early 2004 and continued until the end of 2011. Flux calculations were performed employing the standard procedures (Papale et al. 2006) to obtain 30 min averaged flux estimates. Further details on the data processing procedures are available in our published work on the topic (Shurpali et al. 2009, 2010, 2013). In addition to the EC-based estimation of net ecosystem CO_2 exchange, chamber-based emissions of soil CO_2, CH_4, and N_2O emissions were carried out at the study site (Hyvönen et al. 2009; Shurpali et al. 2008).

The various crop-growing seasons during the study period exhibited contrasting climatic conditions. Based on several years of continuous CO_2 balance measurements, the RCG cultivation system was found to be a strong sink for atmospheric C on organic soils (Shurpali et al. 2009, 2010, 2013). In response to varying rainfall patterns, the net ecosystem CO_2 exchange (NEE) from the perennial bioenergy crop showed a wide interannual variation. Carbon cycling in this ecosystem was found to be sensitive to the amount and timing of precipitation. The crop fixed large amounts of atmospheric CO_2 during wet years (annual rainfall above the 30-year average), while the photosynthetic potential of the crop was drastically reduced during dry years owing to the climatic stress (Shurpali et al. 2009).

Some studies have reported that biofuels may not bring the intended atmospheric benefit owing to high emissions of N_2O during crop cultivation (Crutzen et al. 2008). For example, the amount of N_2O emitted from bioenergy crops such as rapeseed and corn have been found to be twice the amount of N_2O than previously thought (Crutzen et al. 2008). Such high N_2O emissions override any benefits of avoiding fossil fuels and potentially contributing to global warming (Crutzen et al. 2008). However, the bioenergy crop at our site emitted consistently low amounts of nitrous oxide and methane each year (Hyvönen et al. 2009). The low N_2O emissions resulted from the perennial nature of the crop cultivation system (requiring no tillage on an annual basis), low NPK fertilizer requirement of the crop, and poor nutrient status of the organic soil (C:N ratio of greater than 40). Methane emissions in this drained organic soil were low due to reduced methane production and high methane oxidation (Kettunen et al. 1999).

Having characterized the carbon balance and soil GHG emissions, a proper accounting of all energy inputs and outputs of the RCG crop was done to perform a life-cycle assessment (LCA) (Shurpali et al. 2010). For the purpose, the various crop management practices, costs associated with fertilizer manufacturing, and distances (about 70 km) involved in transporting the biomass from the field to nearby combustion plants were considered. Owing to low nutrient requirement of the crop and biomass yields, the estimated management-related emissions were a minor part of the bioenergy LCA in this ecosystem. Chemical inputs (fertilizers and lime) and transport of harvested biomass were the major components in the annual total CO_2 emissions related to the management of the RCG cultivation system at this study site (Shurpali et al. 2010). Net GHG emissions from the bioenergy crop were compared with those from coal. Except during exceptionally dry years, net GHG emissions from bioenergy were found to be consistently lower than emissions from coal (Shurpali et al. 2010). This study showed that bioenergy crops could be cultivated on such marginal organic soils as the one under investigation in this study. This study also refuted the gross generalization that bioenergy crops are carbon-neutral. Net GHG emissions from the bioenergy crop were compared with those of coal. The long-term field experiment described here showed that the bioenergy benefits are strictly dependent on climate. Favorable climatic conditions (well-distributed rainfall and moderate temperatures) favor atmospheric C fixation in crop biomass and in the soil (Shurpali et al. 2009, 2010). However, adverse climatic conditions leading to climate stress affect the photosynthetic potential of the bioenergy crops and thus reducing the bioenergy benefits. The RCG crop cultivation on this soil was found to be equivalent to using coal in terms of the net GHG emissions per unit of energy during dry growing seasons. The bioenergy crop performed better than coal during years when the climatic conditions favored high CO_2 sequestration by the plants and soil.

From an environmental friendliness point of view, bioenergy crops hold promise. The long-term field data from this experiment show that environmentally sustainable bioenergy production is possible even on some organic soil types. More long-term studies on different soil types and climatic conditions are needed for developing better bioenergy strategies. With this in view, RCG as a perennial crop on a mineral soil in Eastern Finland was cultivated (Lind et al 2016). The RCG crop had higher capacity to take up CO_2 from the atmosphere on a mineral soil than on the drained peatland site. However, while the N_2O emissions from the drained organic soil were negligible, they were high [2.8 kg N_2O ha^{-1} (Shurpali et al. 2016)] on the mineral soil. Therefore, for developing sound bioenergy policies, complete life-cycle analyses need to be performed. These analyses should take into account GHG dynamics during the crop cultivation phase and all other input and output costs in terms of CO_2 equivalents. In conclusion, whether a bioenergy crop is sustainable in all aspects depends not only on the environmental friendliness but also on the suitability of the biomass type for combustion in incineration plants. Burning certain biomass types may have detrimental effects on the furnaces used for combustion and the emanating flue gas may contain chemicals that are not conducive to human health (Sippula et al. 2017).

Acknowledgements This work is supported by the funding from the Academy of Finland (project no. 311970—Holistic processes and practices for clean energy in strengthening bioeconomic strategies (INDO-NORDEN).

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