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Life cycle assessment of poplar production: Environmental impact of different soil enrichment methods

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ABSTRACT

The bioeconomy is expected to play an important role in the low carbon economy and poplar could be one of the species providing lignocellulosic feedstock for bioindustries. Since mineral fertilizers are expensive, alternative methods of plant fertilisation are currently being sought. Therefore, the aim of this study was to determine the environmental impact of the production of poplar grown on poor mineral soil fertilized with mineral fertilizers (F), lignin (L) and mineral fertilizers plus lignin (LF) and unfertilized (C) using a life cycle assessment. The system boundaries embraced the production and use of fertilizers, agricultural operations and field emissions associated with poplar cultivation (from cradle to farm gate). Negative greenhouse gases (GHG) emission was observed in variants: L (-37.0 kg Mg^{-1} d.m. CO_2 eq.) and LF (-20.6 kg Mg^{-1} d.m. CO_2 eq.). The emission in variant C was 25.2 kg Mg^{-1} d.m. CO_2 eq. In all of the cultivation variants except C, a very high normalized score was determined for freshwater eutrophication, followed by variants L and LF in categories: freshwater and human ecotoxicity. A low impact of poplar cultivation was determined for fossil depletion and terrestrial ecotoxicity. A low normalized score was also calculated for climate change. The analyses indicated that lignin can be recommended as the optimum method of fertilisation. Using only mineral fertilizers is slightly less beneficial for the environment. Variant LF is not recommended due to the high impact on freshwater eutrophication, terrestrial acidification, human and freshwater ecotoxicity and depletion of fossil resources.

1. Introduction

According to the OECD, the bioeconomy will involve three elements: advanced knowledge of genes and complex cell processes, renewable biomass and the integration of biotechnology applications across sectors. It is assumed that the bioeconomy will be global, with large involvement from OECD and non-OECD countries, especially in agriculture and industry (OECD, 2009). The bioeconomy is expected to play an important role in the low carbon economy in European Union, as well. Europe has a number of well-established traditional bio-based industries, ranging from agriculture, food, feed, fibre and forest-based industries. Scarlat et al. (2015) estimated that the current bioeconomy market is worth €2.4 billion and includes agriculture, food, agro-industrial products, fisheries and aquaculture, forestry, wood-based industry, biochemical, enzymes, biopharmaceutical, biofuels and bioenergy. These bioeconomy branches employ approx. 22 million people (Golembiewski et al., 2015).

High-value bioproducts can be made from lignocelluloses. Speciality cellulose is used in the manufacturing of cosmetics, textiles, pharmaceutical, tires, ethanol and more. Hemicelluloses are also used in the production of ethanol and furfural. Lignin can be potentially used as a feedstock for manufacturing high-value products, e.g. vanillin, biopolymers in petro-chemistry, pesticides and others, including as material for soil enrichment, especially poor sandy sites. Obviously, lignocellulosis can be used successfully - as it has been - in the generation of electricity and heat (Bozell and Petersen, 2010; Doherty et al., 2011; Serrano et al., 2012; Sjöde, 2013; Stolarski et al., 2016b).

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Abbreviations

C input carbon input
C unfertilized variant (control)
C:N carbon to nitrogen ratio
C_{above} aboveground carbon in crop residues (kg ha^{-1} C)
C_{above_Poplar} aboveground carbon in poplar crop residues (kg ha^{-1} C)
C_{above_Ref} aboveground carbon in reference crop residues (kg ha^{-1} C)
C_{below} belowground carbon in root residues (kg ha^{-1} C)
C_{below_Poplar} belowground carbon in poplar root residues (kg ha^{-1} C)
C_{below_Ref} belowground carbon in reference root residues (kg ha^{-1} C)
CH_4 methane
C_{lignin} lignin organic carbon (kg ha^{-1} C)
CO_2 carbon dioxide
$EF_{default}$ default emission factor
EF_{TS} technology-specific emission factor
F mineral fertilizers variant
FU functional unit
GHG greenhouse gases
IPCC Intergovernmental Panel on Climate Change
IRR internal rate of return
ISO International Organisation for Standardization
kg ha^{-1} C kilogram of carbon per hectare
kg GJ^{-1} CO_2 eq. kilogram of carbon dioxide equivalents per gigajoule of energy in fresh biomass
kg ha^{-1} $year^{-1}$ CO_2 eq. kilogram of carbon dioxide equivalents per hectare per year
kg Mg^{-1} d.m. 1,4-DB eq. kilogram of 1,4-dichlorobenzene equivalents per megagram of dry matter (dry biomass)
kg Mg^{-1} d.m. CO_2 eq. kilogram of carbon dioxide equivalents per megagram of dry matter (dry biomass)
kg Mg^{-1} d.m. oil eq. kilogram of oil equivalents per megagram of dry matter (dry biomass)
kg Mg^{-1} d.m. P eq. kilogram of phosphorus equivalents per megagram of dry matter (dry biomass)
kg Mg^{-1} d.m. PM10 eq. kilogram of particulate matter (10 μm or less in diameter) equivalents per megagram of dry matter (dry biomass)
kg Mg^{-1} d.m. SO_2 eq. kilogram of sulphur dioxide equivalents per megagram of dry matter (dry biomass)
L lignin variant
LCA Life Cycle Assessment
Mg ha^{-1} d.m. megagram of dry matter per hectare
Mg ha^{-1} f.m. megagram of fresh matter per hectare
LF mineral fertilizers plus lignin variant
N_2 nitrogen gas
N_2O nitrous oxide
N_{AD} precipitation nitrogen deposition (kg ha^{-1} N)
NH_3 ammonia
NMVOC non-methane volatile organic compounds
NO_x nitrogen oxides (NO and NO_2)
NPK nitrogen, phosphorus, potassium
NPV net present value
OECD Organisation for Economic Co-operation and Development
OM organic matter
PM10 particulate matter less than 10 μm
PM2.5 particulate matter less than 2.5 μm
R_{AG} ratio of above-ground residues dry matter to harvested yield d.m. for crop
R_{BG} ratio of below-ground residues dry matter to harvested yield d.m. for crop (root:shoot ratio)
SOC soil organic carbon
SRC short rotation coppice
UWM University of Warmia and Mazury in Olsztyn, Poland
α harvest index of main crop product relative to aboveground biomass
β root biomass carbon as proportion of yield of main crop product
ε concentration of carbon in biomass (kg C Mg^{-1} d.m.)

One of the species that provides lignocellulosic feedstock is poplar (*Populus* spp.). It includes 40–100 species and hundreds of cultivars grown all over the northern hemisphere; they can be cultivated both as a forest crop in long rotations (10–20 years) and as short rotation coppices (SRC) (2–5 years) (Barontini et al., 2014; Johansson and Karačić, 2011). Poplar yields (according to various authors) from 2 up to 25 Mg ha^{-1} $year^{-1}$ d.m. (Guidi et al., 2009; Guo and Zhang, 2010; Johansson and Karačić, 2011; Stolarski et al., 2015). The yield depends on a number of factors such as climate, soil, cultivar, planting density and rotation. Moreover, intensification is often a priority in the cultivation of poplar in short rotations. Irrigation, plant protection products and fertilisation is used in high-yield production technologies (Dimitriou and Mola-Yudego, 2017; Grella et al., 2017; Paris et al., 2018; Schweier et al., 2016; Yan et al., 2018). Since mineral fertilizers are expensive and their use in plantations of perennial energy crops is not always effective, alternative fertilisation methods are sought using waste materials, i.e. sewage sludge, animal manure, compost, biochar and others. The benefits of organic fertilizers include - apart from supplying nutrients to plants - improvement of soil fertility and fixing organic carbon in soil (Buss et al., 2016; Lafleur et al., 2012; Moreno et al., 2017). Therefore, a team of researchers at the University of Warmia and Mazury in Olsztyn is studying the use of alternative methods of fertilisation and soil enrichment in plantations of perennial lignocellulosic plants. The findings of studies have already been reported concerning the effect of fertilisation with various forms of biogas digestate on the yield of herbaceous crops, i.e. Jerusalem artichoke, giant miscanthus, willow leaf sunflower and Virginia mallow (Stolarski et al., 2017a). Studies have been conducted on the use of lignin for fertilisation of plantations of willow, poplar and black locust and found that the use of lignin usually increases the yield and has a beneficial effect on the economic and energy balance of lignocellulosic biomass production of these three crops (Stolarski et al., 2016a, 2017a). Scientific literature on crop production indicates that the application of mineral fertilisation is one of the main sources of emission to the environment. For instance, Gasol et al. (2009) found that in poplar production, the highest environmental impact was connected with the production and use of fertilizers, representing 51–67% of global warming, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity. Heller et al. (2003) reports that fertilizers constituted 75% of the greenhouse gas emissions included in agricultural inputs of willow production. The mineral fertilizers were also the main agricultural input with the highest environmental impact for