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Research paper

Energy analysis of poplar production for bioenergy in Sweden

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ABSTRACT

Poplar (*Populus* spp.) species are currently not widely grown in Sweden but offer interesting options for future large-scale biomass production for bioenergy. This study assesses the average annual net energy yield and the ratio between the gross energy yield and the total primary energy input for well-managed current commercial poplar production systems in Sweden, with and without fertilization with mineral nitrogen (N). The two systems perform similarly, mainly because the yield response to fertilization is estimated to be small. The average annual net energy yields with and without fertilization are estimated at 190 and 179 GJ ha^{-1} yr^{-1}, respectively. The corresponding energy ratios are 32 and 34, i.e., the total primary energy inputs correspond to only ca. 3% of the gross energy yield, in both cases. Therefore, improving the net energy yield by increasing the harvest level may be considered the most important objective from an energy performance point of view. To do this, more research is needed in order to develop poplar clones that are better adapted to the Swedish climate and identify in which situations poplar responds well to fertilization. At the same time, by reducing the energy inputs associated with the most fuel-intensive activities (wood-chip transportation, chipping, harvesting, forwarding, and stump lifting), greenhouse gas emissions can be reduced. The results should be interpreted with caution since several parameters, especially the yield response to fertilization and fuel consumption rates, are associated with considerable uncertainties.

1. Introduction

Sweden recently adopted a new climate law which binds all future governments to work for net zero greenhouse gas (GHG) emissions by 2045 [1]. The Government of Sweden has also set the goal of a fossil fuel independent vehicle fleet by 2030 [2]. Supply of energy from biomass (bioenergy) has been identified as critical to meeting these goals [3,4]. Willow species (*Salix* spp.) are already broadly cultivated in Sweden and utilized for production of heat and/or electricity [5,6]. Another tree species that has been identified as a potential candidate for large-scale bioenergy production in Sweden is poplar (*Populus* spp.) [7]. Poplar has been cultivated for wood production in Sweden since the 1930s [8], but as a bioenergy crop it is relatively new, and there are only a few large commercial plantations [7,9]. The societal interest in poplar as a bioenergy feedstock is, however, increasing as shown by studies of the future biomass production potential in poplar plantations [10,11]. The area used for cultivating poplar, mainly arable land in the southern and central parts of the country, has increased from ca. 1300 ha in 2014 [5], to ca. 1700 ha in 2017, an area about 22% the size of that used for willow [12].

Poplar species are characterized by fast growth, high survival rates, and large production potential [13]. Growth rates in intensively managed poplar plantations are among the highest in the world [13]. Swedish poplar plantations yield between 3 and 10 Mg dry matter (DM) ha^{-1} yr^{-1} [14–16], referring to the mean annual biomass increment measured from the ground to the top bud including bark but excluding branches. A recent review of poplar production in Sweden reports that an average value of the annual stem biomass increment is 6.9 Mg DM ha^{-1} yr^{-1} including bark but excluding tops and branches [5]. Due to limited experience with poplar cultivation in Sweden, there is relatively little knowledge available concerning management and performance. One important management aspect that has been found to strongly influence the energy performance of willow-based bioenergy production is fertilization with mineral nitrogen (N) [17]. While willow generally responds well and rather consistently to fertilization [6,18,19], poplar demonstrates a highly variable yield response to fertilization

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Research on poplar cultivation in Sweden is limited, and lack of information and scientific knowledge is one of the greatest obstacles to increased poplar production [7]. More research is needed within several areas to support a future large-scale poplar cultivation program in Sweden, including clone breeding, regeneration methods, cultivation systems, management methods, growth potentials, harvest technology, environmental impacts, and GHG performance [7].

Only a few studies have assessed the energy performance of Swedish poplar production systems for bioenergy. A comparison with willow suggests that poplar-based bioenergy production is more energy efficient, i.e., has a higher energy output:input ratio than willow-based bioenergy production [22]. A simplified analysis of the energy performance of poplar production on cropland in southern Sweden by Börjesson [23] found that the average annual net energy yield (the energy content of the harvested biomass minus the total primary energy inputs) was ca. 125 GJ ha^{-1} yr^{-1}, with an energy ratio of 53 (only unfertilized poplar was considered). Rytter et al. [7] presented energy analyses of several hypothetical poplar production systems with net energy yields between 122 and 190 GJ ha^{-1} yr^{-1} and energy ratios between 32 and 82 depending on management method, end use, etc. Neither Rytter et al. [7] nor Börjesson [23] was, however, published in a peer-reviewed journal.

This study aims at determining the average annual net energy yield (referred to as the *net energy yield*), and the ratio between the gross energy yield and the total primary energy input (referred to as the *energy ratio*), of well-managed current commercial Swedish poplar production systems for bioenergy, with and without fertilization with mineral N. At the same time, it aims at updating and improving previous assessments.

2. Material and methods

The method consists of four steps: 1) definition of the poplar production systems (Section 2.1); 2) inventory of management operations and material inputs in the studied production systems (Section 2.2); 3) energy analysis providing a complete overview of energy inputs and energy outputs (Section 2.3); and 4) assessment of performance based on the two indicators (i) average annual net energy yield and (ii) energy ratio (Section 2.4). The work is based on a detailed and thorough inventory of management operations and energy use, using predominantly empirical data collected from a wide range of published sources and experts.

2.1. Poplar production systems and system boundaries

Poplar production with and without fertilization with mineral N is included (Table 1). The studied production systems are both considered representative of well-managed current commercial plantations (although recommendations for best practice regarding all aspects of management are not available). Fertilized and unfertilized poplar are also both considered realistic and feasible future management options. Production in southern/central Sweden is considered, but the analysis is not specific to any particular site or soil type.

The system boundaries include all management operations performed in the production stage including upstream processes (primary production of energy carriers and material inputs) as well as transportation of wood chips to the bioenergy-conversion site (heat plant or combined heat-and-power plant), see Fig. 1. The distance from the plantation to the bioenergy-conversion site was assumed to be 30 km, based on Rosenqvist et al. [24] and Baky et al. [25]. The energy embodied in machines and implements (e.g., boom sprayers, cultivators, etc.) is also included. Energy use is fully allocated to the studied production systems. Biomass conversion to secondary energy carriers (heat/electricity), human labor, and infrastructure for transportation are not included.

Table 1
Definitions of the production systems.

Case	Definition
Fertilized poplar	75 kg ha^{-1} yr^{-1} of mineral nitrogen (N) applied in two consecutive years (year 7 and 8); 150 kg N ha^{-1} in total.
Unfertilized poplar	Mineral N is never applied (0 kg N ha^{-1} yr^{-1}).

2.2. Inventory of management operations and material inputs

Table 2 presents the management operations, time of performance, and machines used in the studied production systems. Management operations and choice of machinery were determined based on information from the literature, experts, and a number of assumptions: 1) plantations are established on existing cropland previously cultivated with annual crops on private commercial farms; 2) the farms have access to their own or hired machinery; 3) the soil has an average production potential; 4) management operations are not hindered by any physical conditions of the fields, such as shape, size, or drainage; 5) good agricultural practice, regarding, e.g., soil preparation, planting, and weed control, is applied at all stages of the plantation life cycle; 6) irrigation is never used; 7) the planting density is 1350 trees ha^{-1}, and 8) all plantations are harvested and terminated after 24 years based on Rytter et al. [7] and the Swedish Board of Agriculture [26], although current regulations preempt plantations harvested at age above 20 years from receiving economic support from the Single Payment Scheme [27]. The planting density is the average value of the range from 1100 and 1600 trees ha^{-1} as reported in Rytter et al. [7] and Persson et al. [9]. Other than fertilization, the two cases are subject to the same management operations. More information about the management operations is given in the Supporting Information, Section S1.

After harvest, the plantations are terminated and the initial field conditions are restored, i.e., the fields are prepared for the sowing of an annual crop. In reality, fields can be re-planted with a second rotation of poplar or stumps can be allowed to re-sprout, in which case a large part of the energy used in the restoration phase can be avoided. Short-rotation forestry, i.e., multiple harvests from the same stump, is not considered since 1) most Swedish poplar production systems are not managed as such, but rather as long-rotation, no-coppice systems [5], and 2) although a few experimental and commercial Swedish short-rotation poplar plantations do exist, they are currently too few and not sufficiently studied to be considered an appropriate basis for yield estimates [9]. Terminating and restoring the field is also the most energy-intensive option, thus does not risk overestimating the energy performance and efficiency.

2.2.1. Data on yields and fertilization

The yield level is one of the most important parameters determining energy performance. Dimitriou and Mola-Yudego [5] represents the most recent attempt to synthesize the available knowledge concerning the growth potential of poplar in Sweden by collecting empirical data on location, age, diameter, height, volume, plantation density, soil, etc. from four previous publications and 26 of their own measurements, encompassing in total 67 plots. When data on tree diameters and age were available, the stem standing crop biomass was estimated.

In this paper, the yield in the unfertilized case was set based on data from an updated version of the database of Dimitriou and Mola-Yudego [5] in which errors were corrected and yields re-estimated using an improved model. Also, in order to better represent the conditions considered here, only plantations of ages 18–23 years with a plantation density between 1000 and 1600 trees ha^{-1} were included. The seven plantations that fulfilled these selection criteria had annual yield increments between 6.1 and 14.8 Mg DM ha^{-1} yr^{-1} with an average value of 9.1 Mg DM ha^{-1} yr^{-1} (Table 3). This yield level represents a