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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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[20,21].

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

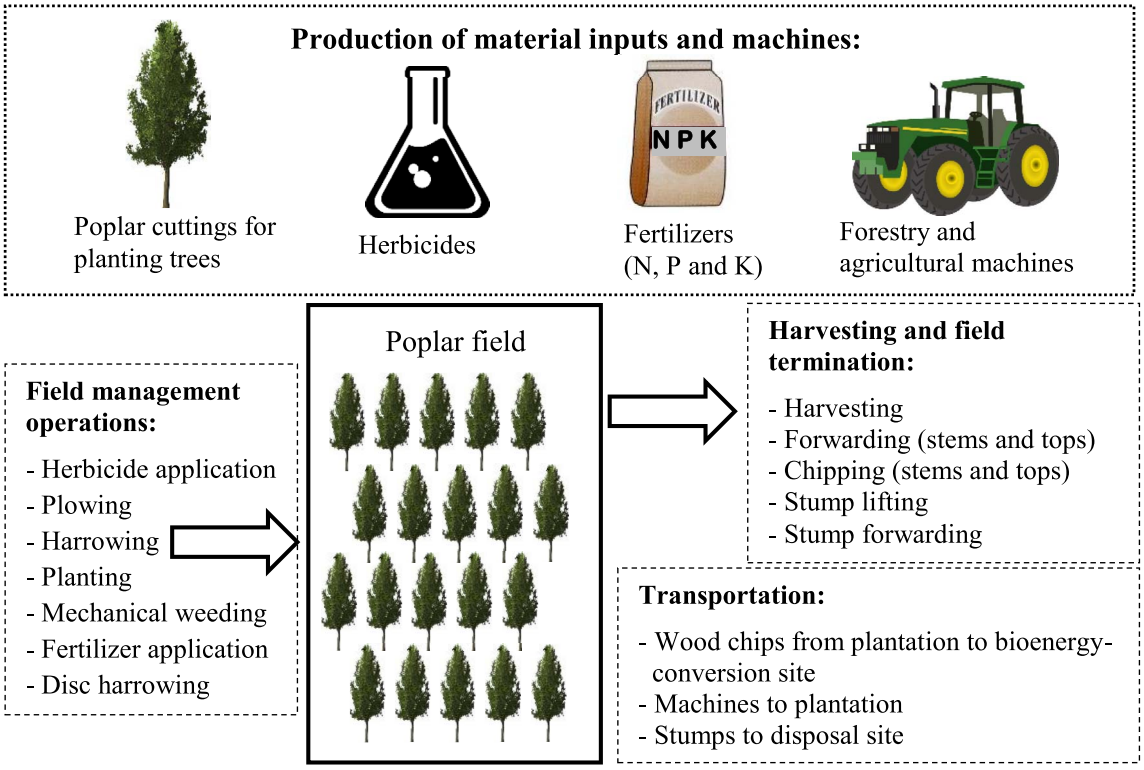



**Fig. 1.** Production system boundaries and processes. Table 2 specifies which operations are performed in each case. A detailed description of management operations is available in the Supporting Information, Section S1.

**Table 2**
Management operations, time of performance, and machines used. Only field operations are listed. Off-field activities, such as transport, are not included here but are included in the energy analysis. More information about the management operations is available in the Supporting Information, Section S1. N/A = not applicable.

| Management operation | | Time of operation (year) | | Machine | Implement |
|---|---|---|---|---|---|
| | | Fertilized poplar | Unfertilized poplar | | |
| Field preparation | Herbicide application | −1 | −1 | Tractor, 90 kW | Boom sprayer |
| | Plowing | −1 | −1 | Tractor, 160 kW | Plow |
| Establishment phase | Harrowing | 0 | 0 | Tractor, 160 kW | Cultivator |
| | Herbicide application | 0 | 0 | Tractor, 90 kW | Boom sprayer |
| | Planting[a] | 0 | 0 | N/A | N/A |
| | Mechanical weeding | 0 | 0 | Tractor, 90 kW | Small row cultivator |
| | Mechanical weeding | 1 | 1 | Tractor, 90 kW | Small row cultivator |
| | Mechanical weeding | 2 | 2 | Tractor, 90 kW | Small row cultivator |
| Fertilization | Fertilizer application (N) | 7 | N/A | Tractor, 90 kW | Small fertilizer spreader |
| | Fertilizer application (N) | 8 | N/A | Tractor, 90 kW | Small fertilizer spreader |
| Harvesting | Harvesting | 24 | 24 | Harvester | Accumulating harvester head |
| | Forwarding (stems and tops) | 24 | 24 | Forwarder | N/A |
| | Chipping (stems and tops) | 24 | 24 | Mobile chipper | N/A |
| Field termination & restoration | Herbicide application[a] | 24 | 24 | N/A | N/A |
| | Stump lifting [b] | 24 | 24 | Excavator | N/A |
| | Stump forwarding [b] | 24 | 24 | Forwarder | N/A |
| | Disc harrowing | 24 | 24 | Tractor, 160 kW | Disc harrow |
| | Disc harrowing | 24 | 24 | Tractor, 160 kW | Disc harrow |
| | Herbicide application | 24 | 24 | Tractor, 90 kW | Boom sprayer |
| | Fertilizer application (P, K) | 24 | 24 | Tractor, 90 kW | Normal fertilizer spreader |

[a] Manual operation.
[b] Stumps are not utilized for bioenergy production due to low fuel quality.

model estimate of the average annual increment of stem standing crop biomass including bark but excluding tops and branches and is considered representative of an average Swedish unfertilized commercial poplar plantation. Self-thinning, i.e., a certain degree of deceased trees, is implicitly considered, since the yield level is based on data from real plantations which almost certainly have undergone self-thinning, although it not known to which degree. Stumps are not utilized for bioenergy production due to low fuel quality.

In order to account for losses associated with harvest, a correction factor of 0.9 was applied (the biomass harvest-loss fraction is thus 10%). In addition to stems, tops and branches are also harvested and utilized for bioenergy production. The biomass in tops and branches was estimated to be 20% of the stem biomass, based on Rytter [28]. Potential biomass losses associated with post-harvest drying at the roadside were considered minor, hence disregarded.

The yield in the fertilized case depends on the yield response to

**Table 3**
Yields of unfertilized and fertilized poplar expressed as mass of dry and fresh biomass, volume of biomass, over and under bark, for stems, tops and branches, and their combined totals. Different metrics are used to match data on time and fuel consumption associated with harvesting, forwarding, and chipping (see Section S2 in the Supporting Information). DM = dry matter. Mg = $10^6$ g = 1 metric ton. Numbers may not add up due to rounding.

| | Unit | Unfertilized poplar | | | Fertilized poplar | | |
|---|---|---|---|---|---|---|---|
| | | Stems | Tops and branches | Total | Stems | Tops and branches | Total |
| Standing biomass over bark, average annual yield increment | Mg DM $ha^{-1}$ $yr^{-1}$ | 9.1 [a] | 1.8 [b] | 11.0 | 9.7 | 1.9 [b] | 11.6 |
| Standing biomass over bark, total yield | Mg DM $ha^{-1}$ | 219 [c] | 44 | 263 | 233 [d] | 47 | 279 |
| Harvested biomass over bark [e] | Mg DM $ha^{-1}$ | 197 | 39 | 237 | 209 | 42 | 251 |
| Harvested biomass under bark [f] | Mg DM $ha^{-1}$ | 174 | 35 | 208 | 184 | 37 | 221 |
| Harvested biomass over bark (fresh weight) [g] | Mg fresh biomass $ha^{-1}$ | 377 | 86 | 463 | 401 | 91 | 492 |
| Volume of fresh harvested biomass over bark [h] | $m^3$ fresh biomass $ha^{-1}$ | 613 | 123 | 735 | 651 | 130 | 781 |
| Volume of fresh harvested biomass under bark [h] | $m^3$ fresh biomass $ha^{-1}$ | 539 | 108 | 647 | 572 | 114 | 687 |

[a] The average annual yield increment in Swedish poplar plantations of ages 18–23 years with a plantation density between 1000 and 1600 trees $ha^{-1}$ obtained from an updated version of the database of Dimitriou and Mola-Yudego [5] in which errors have been corrected and yields re-estimated using an improved model (data from 7 plantations). This yield level represents a model estimate of stem standing crop biomass including bark but excluding tops and branches.
[b] Calculated as 20% of the stem standing biomass over bark, based on Rytter [28].
[c] Calculated as the product of the age of the trees at the time of harvest (24 years) and the average annual yield increment of standing biomass over bark (9.1 Mg DM $ha^{-1}$ $yr^{-1}$).
[d] Calculated as 106% of the corresponding value in the unfertilized case, based on empirical data from the fertilization trial at Stöpen [29]. For more information, see Section 2.2.1.
[e] Calculated as 90% of the mass of standing biomass over bark, accounting for losses associated with harvest.
[f] Calculated assuming that the bark represents 12% of the total tree mass at the time of harvest based on Klasnja et al. [30].
[g] Calculated based on data from Barontini et al. [31], according to which the average moisture content is 47.7 and 54.2% for fresh wood chips made from stems and tops, respectively.
[h] Calculated using the poplar density from Stener [32], according to which 1 $m^3$ of fresh wood corresponds to 0.322 Mg DM.

fertilization. Defined as the percentage change in harvest yield for fertilized relative to unfertilized poplar at age 24, the yield response to fertilization was set based on empirical data from the fertilization trials by Dimitriou and Mola-Yudego [29]. Using a randomized block design and three different fertilization levels (0, 75, and 150 kg N $ha^{-1}$ $yr^{-1}$ applied in two consecutive years), Dimitriou and Mola-Yudego [29] studied the effects of fertilization on tree diameter growth in four poplar plantations established on cropland in southern and central Sweden (Billinge, Stora Vallskog, Sätuna, and Stöpen).

We used data from Stöpen, corresponding to the fertilization level 75 kg N $ha^{-1}$ $yr^{-1}$ applied in two consecutive years (i.e., 150 kg N $ha^{-1}$ in total over the plantation life cycle), since this was the site and fertilization level that exhibited the greatest (albeit rather low) yield response to fertilization. Dimitriou and Mola-Yudego [29] found that at Stöpen, the stem standing crop biomass was 6% greater in plots fertilized with 75 kg N $ha^{-1}$ $yr^{-1}$ in two consecutive years compared to unfertilized plots, when evaluated at the end of the trial period (6.1 and 5.7 Mg DM $ha^{-1}$ $yr^{-1}$ on average in fertilized and unfertilized plots, respectively). This percentage value was used to represent the yield response to fertilization, i.e., fertilized poplar was assumed to yield 6% more when harvested at age 24, compared to unfertilized poplar (Table 3). We acknowledge that this approach is associated with large uncertainties, see the sensitivity analysis in Section 2.5 and the discussion in Section 4.2.

The trial at Stöpen was conducted between 2013 and 2015 on a light clay soil, and mineral N was applied as urea when the trees were 7 and 8 years old [29]. The same application timing was used here, to match that trial. Fertilizer was applied using a small tractor-pulled fertilizer spreader.

The unfertilized and fertilized cases yield 11.0 and 11.6 Mg DM $ha^{-1}$ $yr^{-1}$, respectively (Table 3); this is more than the average commercial unfertilized Swedish poplar plantation, which yields 6.9 Mg DM $ha^{-1}$ $yr^{-1}$, with a standard deviation of 2.7 Mg DM $ha^{-1}$ $yr^{-1}$ [5], mainly because our yield estimates also include tops and branches. Excluding tops and branches, the unfertilized and fertilized cases yield 9.1 and 9.7 Mg DM $ha^{-1}$ $yr^{-1}$, respectively, which is in line with yield levels in high-performing Swedish poplar plantations [5]. We stress that individual plantations can perform very differently depending on site-specific conditions such as soil quality, clones, climate, weather, management (e.g., weed control and fertilization), age of plantation, experience and engagement of farmers, pests, diseases, and browsing animals.

Recommendations regarding fertilization of poplar are largely missing, presumably because fertilization trials have produced mixed and inconclusive results, see Section 4.2. A best management-practice manual for poplar from Minnesota recommends annual application of 56 kg N $ha^{-1}$ [33], but does not mention for how many years. Literature values for "sustained growth" of poplar range between 95 and 276 kg N $ha^{-1}$ $yr^{-1}$ [13]. No Swedish poplar growing manual clearly recommends that plantations should be fertilized [29]. One manual states that poplar generally responds well to fertilization but that it is hardly economically motivated and that growth is normally good even without fertilization, when grown on former cropland [9]. Along the same lines, Rytter [34] states that high yields can be achieved without fertilization, but that adequate fertilization "likely" results in higher yields.

The only explicit recommendation regarding fertilization of poplar in Sweden, to our knowledge, is Weih [35], according to which ca. 60–80 kg N $ha^{-1}$ should be applied annually to maintain soil N levels. This recommendation was derived based on the atmospheric N-deposition rate, the N content of poplar wood, the N-removal rate via biomass harvest, and typical harvest levels. The cumulative application over the plantation life cycle in this study (150 kg N $ha^{-1}$) is far below the level suggested by Weih [35], thus likely causing a net removal of soil N. However, when determining a suitable level of fertilization, farmers consider many aspects in addition to soil health, such as the prices on biomass and mineral fertilizers. We also note that, currently, most Swedish poplar plantations are not fertilized at all [5]. The application level considered here can be considered a compromise between what is biologically optimal and standard practice.

### 2.3. Energy analysis

#### 2.3.1. Energy inputs

Direct and indirect energy inputs are considered. The former inputs include diesel and oil required to fuel machines. The latter inputs include all forms of energy used to extract, refine, process, transport, and/or produce energy or materials that are used in the studied production systems, e.g., energy used to produce machines, planting material, and herbicides. The indirect energy inputs associated with a product or material are also referred to as *embodied* or *virtual energy*, typically given as MJ $kg^{-1}$, i.e., the energy needed to produce 1 kg product or material. It should be noted that data on energy embodied in products and materials are associated with large uncertainties [36,37]. Solar

energy incorporated in the biomass through photosynthesis is not considered.

The energy analysis produces a complete overview of the energy inputs and outputs during a specified reference period. Here, energy flows are expressed as gigajoule (GJ) $ha^{-1}$ $yr^{-1}$ or as GJ $ha^{-1}$ over 24 years (the plantation lifespan). Energy from all sources, not just fossil energy, is included. All energy inputs are aggregated, i.e., no differentiation is made among different types of energy sources, and expressed as primary energy. Higher heating values are used, based on Bossel [38] and Frischknecht et al. [39]. The heating value is defined as the energy released as heat when a substance undergoes complete combustion with oxygen [38]. The difference between the higher and lower heating value is that the latter subtracts the evaporation energy of water, since it is not released as heat and therefore not considered useful. Bossel [38] argued that the higher heating value should always be used in energy assessments since the lower heating value 1) violates the energy conservation principle, and 2) represents an outdated concept from a time with less advanced technology. In a few cases, we used data from sources that did not specify if lower or higher heating values were used. A detailed description of the assessment of energy inputs, and the data used, is given in the Supporting Information, Section S2.

#### 2.3.2. Energy outputs

The energy outputs refer to the gross energy yields of the studied production systems and were calculated as the product of the DM harvest yields from Table 3 and the energy content of the harvested biomass (18.7 MJ $kg^{-1}$ DM biomass, from Börjesson [22], referring to the higher heating value of harvested poplar biomass from established plantations in the second or subsequent cutting cycle).

### 2.4. Energy performance indicators

Performance is measured by two main indicators: the average annual net energy yield (called the *net energy yield*, for short) and the *energy ratio*. The net energy yield is calculated as the difference between the gross energy yield (the energy contained in the harvested biomass) and the total primary energy input, divided by the plantation lifespan (24 years). The energy ratio is calculated as the dimensionless ratio between the gross energy yield and the total primary energy input. The net energy yield indicates the productivity of a system, while the energy ratio indicates the energy efficiency of a system. Higher net energy yields and energy ratios correspond to better performance.

### 2.5. Sensitivity analysis

Several input parameters are associated with large uncertainties and/or natural variability. Sensitivity analyses (by varying parameter values one at a time) were performed for a selection of parameters considered to be highly uncertain: 1) the yield response to fertilization; 2) the transport distance from the plantation to the bioenergy-conversion site; 3) the fuel consumption rates of energy-intensive activities (wood-chip transportation, chipping, harvesting, forwarding, and stump lifting); 4) the biomass harvest-loss fraction, and 5) the energy use in ammonia production. A detailed description of the sensitivity analysis is given in the Supporting Information, Section S3.1, where parameter ranges are also presented. We also evaluated the effect on the total primary energy input by setting the N-application rate to 70 kg $ha^{-1}$ $yr^{-1}$ for 24 years, based on Weih [35], see Section 2.2.1.

## 3. Results

### 3.1. Net energy yields and energy ratios

The net energy yields and energy ratios are presented in Table 4, along with additional performance indicators. The net energy yields are estimated at 190 and 179 GJ $ha^{-1}$ $yr^{-1}$ and the energy ratios are estimated at 32 and 34 for fertilized and unfertilized poplar, respectively. The two systems thus perform similarly. N fertilization causes the net energy yield to increase by 6% (relative to the unfertilized case) and the energy ratio to decrease by 4%, indicating that there is a (weak) inverse correlation between productivity and energy efficiency. The total primary energy inputs correspond to ca. 3% of the gross energy yields in both cases (Table 4).

**Table 4**
Energy performance of the studied production systems. The results for the fertilized poplar case should be considered indicative due to existing uncertainties associated primarily with the yield response, see the sensitivity analysis in Section 2.5 and the discussion in Section 4.2. Numbers may not add up due to rounding.

| Performance indicator | Unit | Fertilized poplar | Unfertilized poplar |
|---|---|---|---|
| Total primary energy input over plantation life cycle[a] | GJ $ha^{-1}$ | 145 | 131 |
| Gross energy yield over plantation life cycle[b] | GJ $ha^{-1}$ | 4710 | 4430 |
| Net energy yield over plantation life cycle[c] | GJ $ha^{-1}$ | 4560 | 4300 |
| Average annual net energy yield[d] | GJ $ha^{-1}$ $yr^{-1}$ | 190 | 179 |
| Energy ratio[e] | Dimensionless | 32 | 34 |
| Total primary energy input as percentage of gross energy yield[f] | % | 3.1 | 3.0 |

[a] The sum of direct and indirect energy inputs including energy required to produce material inputs and energy embodied in machines and implements.
[b] The energy contained in the harvested biomass, calculated as the product of the DM harvest yields from Table 3 and the energy content of the harvested biomass (18.7 MJ $kg^{-1}$ of DM biomass from Börjesson [22]), see Section 2.3.2.
[c] Calculated as the gross energy yield (the energy contained in the harvested biomass) minus the total primary energy input.
[d] Calculated as the net energy yield divided by the plantation lifespan (24 years in both cases).
[e] Calculated as the dimensionless ratio between the gross energy yield and the total primary energy input.
[f] Calculated as the reciprocal of the energy ratio.

Fig. 2 presents a breakdown of the total primary energy inputs. The total primary energy inputs are, in descending order: 1) transport, 2) wood chipping, and 3) harvesting, in both cases. Transport represents 20 and 21% of the total primary energy inputs in the fertilized and unfertilized cases, respectively, and includes the transport of wood

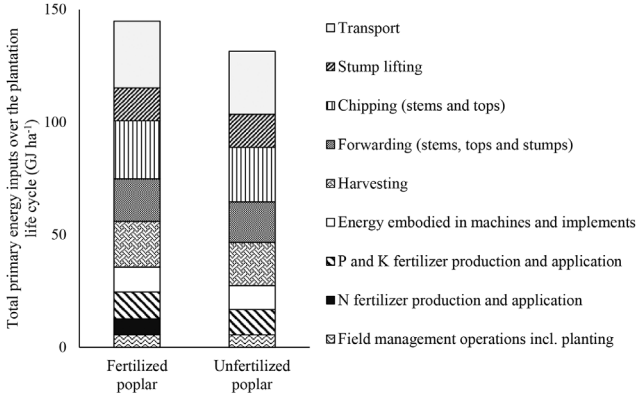



**Fig. 2.** Total primary energy inputs over the plantation life cycle and contribution from management operations and/or material inputs. The category "Transport" includes transport of wood chips, machines, and stumps. The category "Field management operations incl. planting" includes plowing, harrowing, mechanical weeding, disc harrowing, herbicide application, and production of planting material. A more detailed breakdown of categories is available in the Supporting Information, Table S4.1. The results for the fertilized poplar case should be considered indicative due to existing uncertainties associated primarily with the yield response, see the sensitivity analysis in Section 2.5 and the discussion in Section 4.2.

chips to the bioenergy-conversion site (30 km); the return trip of the empty wood-chip truck to the plantation; the transport of the harvester, forwarder, mobile chipper, and excavator to the plantation (by truck), and the transport of the stumps to a disposal site (10 km). Of these activities, the energy use associated with wood-chip transportation represents ca. 75% of the energy use associated with transport in both cases. Wood chipping (of stems, tops, and branches) represents 18% of the total primary energy inputs in both cases. Harvesting represents 14 and 15% of the total primary energy inputs in the fertilized and unfertilized cases, respectively.

The energy inputs are unevenly distributed over the plantation life cycle. The direct energy inputs (diesel and oil) associated with operations performed in the final year (harvesting, forwarding, stump lifting, chipping, transport, etc.) dominate the total primary energy inputs in both cases (75 and 79% in the fertilized and unfertilized cases, respectively).

### 3.2. Sensitivity analysis

The results of the sensitivity analysis are presented in Fig. S3.1 and Table S3.2 in the Supporting Information. Productivity increases considerably when the yield response to fertilization increases and the losses associated with harvest decrease, and vice versa. Energy efficiency increases considerably when fuel consumption and transport distances decrease, and vice versa. The energy use in ammonia production does not affect the energy efficiency or productivity since the application rate is low (the energy inputs associated with ammonia production only represent ca. 5% of the total primary energy inputs in the fertilized case). However, if application rates were to increase, this parameter would likely influence energy efficiencies considerably [17]. When the N-fertilization rate is set to 70 kg ha$^{-1}$ yr$^{-1}$ for 24 years, based on the recommendation in Weih [35], the total primary energy input in the fertilized case increases by 47%. However, the effects on net energy yields and energy ratios could not be assessed since the yield response to fertilization is not known, see Section 4.2.

The net energy yield is rather insensitive to small changes in the total primary energy input. However, the energy ratio is highly sensitive to small changes in the total primary energy input. Therefore, parameters that mainly affect the gross yield (i.e., the yield response to fertilization and the biomass harvest-loss fraction) also mainly influence productivity, while parameters that mainly affect the total primary energy input (i.e., the distance from plantation to bioenergy-conversion site and the fuel consumption rate) also mainly influence energy efficiency.

In conclusion, the sensitivity analysis indicates rather stable performance despite uncertainties in parameter values. The energy ratios always remain above 26, while parameter values vary within reasonable ranges (the lowest value is reached when the fuel consumption rates associated with energy-intensive activities are assumed to be 30% above the base-case values), and fluctuate by at most 28% relative to the base-case values. The net energy yields always remain above 159 GJ ha$^{-1}$ yr$^{-1}$ (the lowest value is reached when the biomass harvest-loss fraction is assumed to be 20%, instead of 10% as in the base case), and fluctuate by at most 23% relative to the base-case values. Overall, there are no large differences between the cases in terms of the results from the sensitivity analysis. More information is available in the Supporting Information, Section S3.2.

## 4. Discussion

### 4.1. Comparison to other studies

Table 5 presents the results from a selection of similar studies identified in our literature review. Our results are well within the (wide) range of results from other studies: net energy yields are between 67 and 299 GJ ha$^{-1}$ yr$^{-1}$, and energy ratios are between 9 and 270. Only two other studies (to our knowledge) have assessed the energy performance of poplar grown with different levels of N fertilization. Scholz and Ellerbrock [40] found that the level of fertilization did not significantly affect the net energy yield but had a strong (negative) influence on energy ratios, which decreased as fertilization increased. The same relationship, albeit not as strong, was observed here.

Nassi o di Nasso et al. [44] also assessed the energy performance of poplar subject to different levels of N fertilization, but the cases also differed regarding other management aspects, preventing attribution of the observed effects to the level of fertilization alone. The management operations and/or material inputs that contribute most to the total primary energy inputs (Fig. 2) mostly align well with corresponding results in similar studies compiled by Djomo et al. [42], see Table 6.

Diverging results among studies are expected due to differences with regard to geographical location (related to soil properties, climate, etc.), cultivation practices (use of machinery, management methods, level of fertilization, etc.), yield levels, transport of materials (means, distances), data sources, system boundaries, and allocation methods [45]. For example, Swedish poplar production systems are typically managed as long-rotation, no-coppice systems, while plantations located further south are typically managed as short-rotation coppice. Djomo et al. [42] identified fertilization (amount and type), harvesting method, and yield level as the three parameters mainly responsible for diverging results among studies. Noting that differences among studies and lack of transparency hamper meaningful comparisons, Djomo et al. [42] called for increased methodological standardization to support more robust and comparable future assessments of bioenergy production systems.

### 4.2. Yield response to fertilization

The yield response to fertilization is defined here as the percentage change in harvest yield for fertilized relative to unfertilized poplar at age 24, and was set to 6%, see Section 2.2.1. The productivity of the fertilized case strongly depends on the value of this parameter (Section 3.2), which is highly uncertain, since 1) long-term studies on the yield response to fertilization are not available, and 2) the studies that exist show highly variable results.

Many studies have investigated how poplar responds to fertilization, reaching different conclusions. Several field experiments in Canada and the USA found that fertilizers increase poplar growth [46–50]. Other field experiments from Germany found no effect of fertilization on poplar growth [40,51–53]. Some studies found a mixed, or even negative, effect [54,55].

Dimitriou and Mola-Yudego [29] is the most thorough attempt to quantify the yield response to fertilization of poplar in Sweden. Fertilization was found to positively affect the growth when all four test sites were evaluated together. However, the response differed considerably among these sites, and plantations in two sites did not show any statistically significant response to fertilization. Other Swedish studies report similar findings. A field trial on cropland in southern Sweden found that 150 kg N ha$^{-1}$ yr$^{-1}$ did not affect poplar yields [56]. Limited evidence from two Swedish poplar plantations showed that fertilization had no effect in one plantation and an initial effect, which disappeared after 3–4 years, in the other plantation [14].

The yield response appears to be highly site-dependent, but it is not yet fully known which factors most strongly control the yield in each situation. Berguson [21] suggests that the soil, cropping history, climate, and genetic composition of the stand are important factors. Recent research suggests that the soil microbiome may play a key role for the ability of poplar to acquire N, thus partly explaining the divergent results from fertilization trials [57]. Several studies suggest that poplar established on poor soils (e.g., former forest land) generally responds well to fertilization, whereas plantations established on former cropland (or soils with a high organic matter content) often show no or little response to fertilization [20,21,52,54]. This can be explained by the

**Table 5**
Average annual net energy yields (the gross energy yield, i.e., the energy contained in the harvested biomass, minus the total primary energy input, divided by the plantation lifespan) and energy ratios (the ratio between the gross energy yield and the total primary energy input) reported in energy analyses of poplar production. The system boundaries are approximately similar in all studies (cradle-to-farm gate). HHV/LHV = higher/lower heating value.

| Reference | Country | Average annual net energy yield (GJ $ha^{-1}$ $yr^{-1}$) | Energy ratio | Fertilization | Comments |
|---|---|---|---|---|---|
| This study | Sweden | 190/179 | 32/34 | 0 and 150 kg $ha^{-1}$ over the plantation life cycle, respectively. | Fertilized and unfertilized poplar, respectively. |
| Börjesson [22] | Sweden | ca. 122–155 (average: 138) | ca. 29–39 (average: 33) | It is not stated if fertilizers are used or not. | HHVs were used. Model study based on data from the literature and statistics. Trees were harvested when fully grown. Primary energy, including direct and indirect energy inputs, was considered. Values are partly based on visual inspection of Fig. 9.1–9.3 in the report, hence approximate. Three regions in Sweden were studied; ranges depend on production region (production is generally more favourable in the south). Not peer-reviewed. |
| Börjesson [23] | Sweden | ca. 125 | 53 | Fertilizers were not applied. | Model study of a poplar plantation established on agricultural land in the south of Sweden. Stems, as well as tops and branches were harvested. Primary energy, including direct and indirect energy inputs, was considered. The energy ratio was calculated based on data in the paper. Calculations presented at a seminar; brief method description. Not peer-reviewed. |
| Dillen et al. [41] | Belgium | 89 | 30 | Fertilizers were not applied. | Field study with a plantation established on degraded land managed as short-rotation coppice during 16 years (harvested 4 times). The plantation was maintained as a low-energy input system with as few inputs as possible. The net energy yield was calculated based on data presented in the paper. |
| Djomo et al. [42] | Various, see comments | 67–236 | 13–55 | A majority of the reviewed studies include fertilization but information about application levels is not available. | Review. Results are from 10 reviewed studies and refer to cradle-to-farm gate system boundaries. Net energy yields were calculated based on data presented in Tables 2 and 3 in the paper. |
| Gasol et al. [43] | Spain | 240 | 46 | The crop was fertilized in each cutting cycle. | LHVs were used. Study based on data from a field trial with poplar managed as short-rotation coppice. The plantation was harvested three times (the cutting cycle was 5 years). The net energy yield and energy ratio were calculated based on data presented in Table 5 in the paper. |
| Nassi o di Nasso et al. [44] | Italy | 172/249/299 | 17/39/59 | Each case was fertilized with 100 kg N $ha^{-1}$ after each harvest (≈86, 42, and 25 kg N $ha^{-1}$ $yr^{-1}$, on average, for the 1, 2, and 3-year cycles, respectively). | LHVs were used. Study based on data from field trials with poplar managed as short-rotation coppice and three different harvest frequencies; 1, 2 and 3-year cutting cycles, respectively. The plantation lifespans were 7, 12, and 12 years, respectively. Energy ratios were calculated based on data presented in Tables 4 and 5 in the paper. |
| Rytter et al. [7] | Sweden | 122/178/190 | 32/79/82 | Fertilizers were not applied. | Model study of hypothetical poplar production systems constructed based on empirical data from Sweden and information from the literature. Values refer to 1) “PB3:2”: poplar for biomass production with harvest after 15 years, 2) “PT1:1”: poplar for production of pulpwood and timber with two thinnings and harvest after 25 years, and 3) “PT1:2”: poplar for production of pulpwood and timber with one thinning and harvest after 25 years. The net energy yields were calculated based on data presented in Table 8.15 in the report. Not peer-reviewed. |
| Scholz and Ellerbrock [40] | Germany | 71/88/83/135/128/135 | 142/19/9/270/27/15 | Three different fertilization levels were tested: 0, 75, and 150 kg N $ha^{-1}$ applied once (≈0, 12.5, and 25 kg N $ha^{-1}$ $yr^{-1}$, respectively). | Study based on data from a 6-year field trial with poplar managed as short-rotation coppice (12,000 plants $ha^{-1}$). Net energy yields and energy ratios were calculated based on data obtained from visual inspection of Fig. 7 in the paper, hence approximate. Values refer to poplar fertilized with 0, 75, and 150 kg N $ha^{-1}$ with an undersown crop, and poplar fertilized with 0, 75, and 150 kg N $ha^{-1}$ without an undersown crop. |

**Table 6**
Contribution to total primary energy input from management operations and/or material inputs, results from this study and from other energy analyses of poplar production compiled in the review by Djomo et al. [42]. A somewhat different categorization is used here compared to in Fig. 2 in order to better match the categorization used by Djomo et al. [42], e.g., all fertilizers are grouped together. N/A = not applicable. Numbers may not add up due to rounding.

| Category of management operations and/or material inputs | Contribution to total primary energy input from category (%) | | |
|---|---|---|---|
| | Results from this study | | Results from other studies, compiled by, and adopted from, Djomo et al. [42]. n = number of studies |
| | Fertilized poplar | Unfertilized poplar | |
| Cuttings for planting | 1 | 2 | N/A |
| Field management operations[a] | 2 | 2 | 3-9 (6) |
| Production and application of herbicides | 2 | 2 | 2-8 (6) |
| Production and application of fertilizers[b] | 13 | 9 | 10-64 (7) |
| Energy embodied in machines and implements[c] | 6 | 6 | 1-5 (3) |
| Harvesting, forwarding, chipping, stump lifting | 55 | 58 | 19-82 (7) |
| Transport[d] | 20 | 21 | 3-10 (2) |
| Field termination[e] | < 0.5 | < 0.5 | 1-2 (2) |
| Total | 100 | 100 | N/A |

[a] Results from this study include plowing, harrowing, and mechanical weeding (operations performed in the establishment phase). The corresponding category in Djomo et al. [42] is called "tillage/planting."
[b] Results from this study include production and application of N, P and K fertilizers.
[c] The corresponding category in Djomo et al. [42] is called "capital equipment."
[d] Results from this study include transport of the wood chips to the bioenergy-conversion site (30 km); the return trip of the empty wood-chip truck to the plantation; the transport of the harvester, forwarder, mobile chipper and excavator to the plantation (by truck), and the transport of the stumps to a disposal site (10 km).
[e] Results from this study include two rounds of disc harrowing. The corresponding category in Djomo et al. [42] is called "grubbing up."

fact that poplar has an excellent capacity to acquire nutrients that are available in the soil, e.g., from previous fertilization [51].

The second reason why the yield response to fertilization is uncertain is that most fertilization trials have evaluated the effect after a relatively short time, while in this study, we wanted to estimate the effect at the time of harvest (16 years after the last application). The longest poplar fertilization trial, to our knowledge, is a French study from 1947, cited in van Oosten [20], which measured the effect after 13 years. Most studies evaluate the effect after considerably shorter time. Extrapolating the observed effect beyond the trial period, e.g., by assuming that it persists, is associated with large uncertainties.

### 4.3. Improvement options

Poplar harvest yields and energy inputs associated with fuel-intensive activities (wood-chip transportation, chipping, harvesting, forwarding, and stump lifting) were identified as important determinants of energy performance (Section 3.2).

As noted above, poplar demonstrates a highly variable yield response to fertilization. A better understanding of the relationships between bio-geophysical factors and poplar growth is needed to develop fertilization recommendations and support plant-breeding research developing clones with better yield performance, with or without fertilization. Poplar has been cultivated and periodically bred in Sweden since the 1930s [8]. Breeding efforts increased in the 1980s in parallel with increased interest in bioenergy.

Poplar species are not native to Sweden and a lack of suitable clones has been an important obstacle to increased production in large parts of the country [7]. Until 2010, essentially only one clone, "OP42," was commercially available. In recent trials, only five out of 38 poplar clones were found to have acceptable resistance against leaf rust (*Melampsora larici-populina*) and bacterial canker (*Xanthomonas populi*), two of the most devastating diseases affecting poplar [58]. These five clones were recommended for use in southern Sweden, while no clone was found suitable for cultivation in the north. The use of only a few clones increases the risk of infection, and intensified breeding efforts are considered a prerequisite for increased poplar production in Sweden [58].

Swedish poplar breeding programs currently focus on developing clones better adapted to the Swedish climate, improving biomass production and wood quality, and identifying genes that may influence the energy conversion efficiency [8]. The Climate-Adapted Poplar (CLAP) project, for example, is a collaboration among the Swedish University of Agricultural Sciences, the Umeå Plant Science Centre, and the company SweTree Technologies that aims to develop clones adapted to the current and future climates in the Baltic region, including Sweden [59].

Besides increasing poplar yields, the energy performance can also be improved by reducing the energy inputs associated with wood-chip transportation, chipping, harvesting, forwarding, and stump lifting, which together represent between 70 and 75% of the total primary energy inputs in both cases.

Transport represents ca. 20% of the total primary energy inputs in both cases (Fig. 2). Measures aimed at minimizing fuel consumption associated with transport by, e.g., optimizing biomass logistics, will therefore contribute considerably to improving the energy efficiencies of the systems, while also reducing costs and GHG emissions. Fuel-efficient tires, fuel-efficiency standards, and eco-driving programs have been identified as critical in achieving more energy-efficient transport systems [60]. Also, when establishing new plantations, the distance to the bioenergy-conversion site is an important parameter to consider. Other measures that can contribute to lowering the transport-related energy inputs include using vehicles capable of carrying larger loads [61] and using ship and railway transport where this is possible [62].

Concerning wood chipping, significant efficiency improvements have been made over the past ten years, and further improvements can be achieved by increasing machinery utilization rates, improving chipping technology, and optimizing handling of wood-chips [63]. If a wood chipper or crusher is available at the bioenergy-conversion site, it may be fuel efficient to chip the stems there, while chipping the tops and branches at the plantation using a mobile chipper, since the crushers/chippers that are available at bioenergy-conversion sites are often more energy efficient than their mobile counterparts, and since it is hard to reach the maximal loading capacity when transporting tops and branches [63]. By chipping larger fractions and maintaining the sharpness of the knives, the fuel use associated with chipping can also be reduced [64].

Poplar trees are harvested and forwarded using the same machines and technology as in conventional forestry [65]. The technology is considered mature, hence the room for efficiency improvements is rather limited [66]. Nevertheless, planning tools can help to rationalize operations, and efficiency gains can be made by improving head grips and the handling of tops and branches [66]. Existing stump extraction

techniques are relatively immature, and further development is needed to find an optimal method with regard to economic costs, fuel consumption, and soil disturbance [67]. Concerning stump transportation, compaction (e.g., crushing) and removal of contaminants (soil, stones, etc.) prior to transport can help reduce energy inputs [68].

## 5. Conclusions

This study determined the net energy yields and the energy ratios for current well-managed, N-fertilized and unfertilized, commercial poplar production systems in Sweden. The two systems perform similarly, and the results are rather stable despite uncertainties in parameter values. As has been shown for willow [17], there is a trade-off between achieving a high net energy yield and a high energy ratio, but the results presented in this paper indicate that this trade-off is weaker for poplar than for willow, mainly because the N-application level is lower for poplar.

General recommendations on whether a high net energy yield or a high energy ratio is more important cannot be given. It can, however, be argued that a high net energy yield is more important than a high energy ratio if land is the limiting resource. If energy is instead the limiting resource, then a high energy ratio may be considered more important, although both indicators are relevant since the availability of energy depends on the net energy yield. In practice, since the total primary energy input correspond to just a few percent of the gross energy yield in both cases, it might be advisable to primarily strive towards improving the net energy yield by increasing poplar harvest levels. At the same time, the energy ratio depends on the amount of land cultivated with poplar, due to scale-effects: larger areas of cultivation with similarly aged stands in a region reduces the energy inputs in production due to larger availability of machines and shorter transportation distances. Measures aimed at increasing the poplar cultivation area can therefore also contribute to increasing both the total bioenergy output and the energy ratio, even if harvest levels remain stable. Larger scales also contribute to faster learning and progress in technology and operations, which can contribute positively to the energy performance. Regardless of whether a high net energy yield or a high energy ratio is considered more important, GHG emissions can be reduced by reducing the energy inputs associated with the most fuel-intensive activities (wood-chip transportation, chipping, harvesting, forwarding, and stump lifting).

Research, including long-term fertilization studies, is needed to determine the nutrient requirements of poplar, identify the conditions under which fertilization becomes economically and environmentally favorable [20,21], and develop guidelines that can help farmers decide how much fertilizer to apply, and when [54]. Specifically for Sweden, where poplar plantations are rarely managed as short-rotation coppice [5], future studies on both coppice and single-stem systems can improve the knowledge about performance under different management regimes [7,9]. Research is also needed to develop poplar clones suitable for cultivation in different parts of Sweden, especially the north.

This study assessed the energy performance of biomass supply chains up to the gate of the bioenergy-conversion site. Studies that include the conversion to secondary energy carriers (heat/electricity/biofuels) and possible co-products (e.g., animal feed, biomaterials) can evaluate alternative uses of harvested biomass relative to various objectives, e.g., GHG emission reductions or fossil fuel displacement. Depending on priority among objectives, biomass supply chains with less favorable energy performance may be preferred if they better meet requirements at the conversion stage (e.g., mechanical, chemical and nutritional properties of the biomass). Future studies of the bioenergy production potential should also consider alternative uses of poplar and the demand- and policy-driven competition among various assortments, such as pulpwood, stemwood and bioenergy.

Bioenergy is an important ecosystem service that multifunctional landscapes provide [69]. If strategically located, biomass production systems can support many other ecosystem services, as well as biodiversity [69–72]. Policy-makers, farmers and other stakeholders involved in the governance of multifunctional landscapes can gain valuable insights from energy analyses of bioenergy production systems but also need information about multiple environmental, legal, economic, and social aspects of production.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2018.01.021.

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