Biomass and Bioenergy 178 (2023) 106940

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Biomass production and fuel characteristics from long rotation poplar plantations

Henrik Böhlenius [a,*], Marcus Öhman [b], Fredrik Granberg [b], Per-Ove Persson [c]

[a] Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, SE-234 56, Alnarp, Sweden
[b] Energy Engineering, Division of Energy Science, Luleå University of Technology, SE-97187, Luleå, Sweden
[c] Persson f.N.B. AB, SE-54197, Lerdala, Sweden

ABSTRACT

There is an increasing demand for biofuel to replace fossil fuels. One of the key elements in this transition is the securing of a large supply of sustainable biomass. In this study, the feedstock potential of long rotation poplar plantations (12–30 years with diameter of 15 of 30 cm) was determined and the properties of poplar biomass fuel were analyzed with the aim of using thermochemical conversion methods to produce biofuel. Our results demonstrate that Sweden has great potential for producing biofuels from long rotation poplar plantations, with a total of 1.8 million hectares (ha) consisting of arable (0.5 million ha) and forested arable land (1.3 million ha). Based on available land and biomass production potential, our results indicate that 10 million Mg DW could be produced annually. Regions in mid/southern Sweden have the largest potential (larger areas and higher biomass production. Our results further suggest that poplar biomass from these plantations has fuel characteristics similar to forest fuels from other conifer tree species, making the biomass suitable as feedstock for biofuel production based on thermochemical conversion methods. If 25% of the available land were used, 7.6 TWh methanol biofuels could be produced annually from 16 biofuel plants, using 160,000 Mg DW yr^{-1}, primarily located in the southern part of Sweden. Two counties (Skåne and Västra Götaland) would be able to support their biofuel plants using poplar plantations as feedstock. Stable biofuel production in the other counties would depend on collaborating with neighboring counties.

1. Introduction

The challenges of the increasing global demand for energy, decreasing use of fossil fuels, increasing fuel prices and global warming have led to the search for alternative strategies for energy supply. The substitution of fossil fuels for biofuel is one key method. In this transition, biomass can serve as a renewable feedstock for producing liquid and gaseous biofuels. In the European Union (E.U.), the Renewable Energy Directive II (REDII) set an overall renewable energy target of 32% and a 14% target for the transport sector by 2030 [1]. Sweden stands out among the E.U. member states, using more than 20% renewable fuels for domestic transport in 2015, with 85% imported [2,3]. In addition, the Swedish government has decided that, by the year 2030, CO_2 emissions from domestic transport i.e. road, railway and shipping, should be reduced by 70% compared to those in 2020 [4], be carbon neutral by 2045 and after that have negative CO_2 emissions [4]. In this transition, biomass usage could be an important component in reaching the goal of a carbon neutral energy system.

Biofuel production depends on large stable biomass supplies from agricultural or forest resources. However, the currently available biomass from forest/agricultural land may not be enough for biofuel production or current and future forest industries (paper and saw products), and the development of new industrial products such as dissolving pulp, and carbon neutral steel production. Overall, this means there could be a lack of available woody biomass.

Several investigations have reported a variation between 88,000 and 466,000 ha suitable for fast growing trees (FGT), mainly on available arable land, areas that are not used for food or feed production of [5–7]. In addition, over 1 million ha of forested arable land has been recorded [7], which currently has plantations of Norway spruce (*Picea abies* L.). However, as Norway spruce is damaged or killed by pests and pathogens as an effect of climate change, reforestation using other tree species is an attractive alternative when these plantations reach their rotation age, especially given that this land is suitable for high tree growth.

In several parts of the world, planting fast-growing trees of the genus *Populus* (Poplar and hybrid aspen) is one alternative to increase the feedstock of woody biomass, and is therefore frequently used in plantation forestry [8–13]. Currently, these plantations are mostly located on floodplains [14] and marginal abandoned agricultural land [8,15–20] but rarely planted on recently harvested forestland [21–23]. Poplars, *P. trichocarpa* (and their hybrids) are generally nutrient demanding [24] and suffer from growth reduction if soil pH is lower

---

* Corresponding author.
E-mail address: henrik.bohlenius@slu.se (H. Böhlenius).

https://doi.org/10.1016/j.biombioe.2023.106940
Received 17 March 2023; Received in revised form 20 June 2023; Accepted 28 August 2023
Available online 6 October 2023
0961-9534/Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

than 5 [8,20,24,25]. In Sweden, the arable/forested arable land are sites that show site conditions suitable for poplar plantations, such as high soil fertility and soil pH suitable for poplar and several studies has reported that poplars can be established at these sites [26,27] with a high biomass production.

At present, Swedish poplar plantations have a tree density of 1100–1600 plants per hectare and a rotation of approximately 20 years. A previous study has shown that, when grown on arable land, poplars have an annual mean biomass production of between 3.3 andto 9.2 Megagrams (Mg) dry weight (DW) ha^{-1} yr^{-1} [15,28]. Similar variation in production can be found from hybrid aspen, being 3–12 Mg $DWha^{-1}$ yr^{-1} [29,30]. This level of biomass is produced by poplar and hybrid aspen plantations with long rotations e.g. 20 years, resulting in trees with tree diameters of about 20 cm [28].

The use of poplar plantations on both arable and forested arable land does not conflict with RED II, as these areas are not being considered, or used, for food or feed production [1], making biomass production from poplar plantations an interesting option as a resource for biofuel production in these areas. The Swedish government highlighted in 2022 [31] that forested arable land should be considered for planting with species other than conifers, such as broad-leaved tree species, including poplars and hybrid aspen.

However, to make good predictions of biomass supply from these plantations, reliable biomass production numbers need to be combined with available land areas, something currently lacking. Thus, it is not known how poplar plantations can contribute as a feedstock for biofuel production and where such production might be based in each county, resulting in uncertainty in the potential of domestic biofuel production using cellulose-based biomass from poplar plantations as feedstock.

Downstream conversion of biomass to biofuel depends on several components, including biomass quality. Such conversion can be divided into methods based on thermochemical, biochemical and oleo-chemical processes. Earlier studies using poplars have focused on biomass from short rotation forestry (SRF) i.e. dense plantations (5000–10,000 trees ha^{-1}) that are harvested after 4–5 years. The characteristics of fuel derived from SRF are somewhat similar to those of willow [32], while the characteristics of poplar biomass produced from long rotation forestry have not previously been evaluated. As thicker trees should contain more stem wood and a smaller proportion of ash-rich components such as bark and branches, this should positively affect the fuel's properties. It is, above all, concerning the fuel's concentration of ash-forming elements that SRF poplars differ from traditional conifer stem wood and forest fuel-based assortments. SRF poplar's fuel ash is dominated by calcium (Ca), and potassium (K) and has a moderate content of phosphorus (P).

As the Swedish biomass production system with poplars uses long rotation plantations, i.e., trees with larger diameters compared to other SRF biomass production systems, it is not obvious how biomass from long rotation poplar plantations would function in biofuel production systems based on thermochemical conversion methods.

The objectives of this study were to.

i) identify and describe the geographical location of available arable and forested arable land areas in Sweden
ii) estimate biomass production potential in Sweden from long rotation poplar plantations in the different geographic regions (counties) and for different land types (arable and forested arable land)
iii) determine the fuel composition of biomass produced from long rotation poplar plantations with biofuel production using thermochemical conversion methods as a target process
iv) identify possible biofuel plant locations in Sweden based on available biomass feedstock from long rotation poplar plantations.

2. Materials and methods

2.1. Identification of available land

To identify arable land that could be used for poplar plantations at the county level, that is land not used for food or feed production, statistics from the Swedish Board of Agriculture were used. These statistics contain only the land that meets the requirements for financial support from the Swedish Board of Agriculture, thus identifying land areas that include fallow, extensive ley, and unspecified arable land. This type of land is referred to here as "unused arable land". To identify arable land areas that are not included in the Swedish Board of Agriculture support system, comparisons between statistics from the Swedish Board of Agriculture (total of agricultural area that is part of the support system [33] and total agricultural area from Lantmäteriet's property database [34] were used. This type of land is referred to as "Abandoned arable land", and includes areas not considered as forest or arable land. Unused and abandoned arable land areas are referred to as "arable land" in this study.

The areas of forested arable land were identified by comparing current (2019) total agricultural land areas [33] with historical agricultural land areas (1919 and 1937) [34], using statistics from the Swedish Board of Agriculture. The two time points selected represent the year when the highest arable land area was recorded: 1937 for the counties in Northern Sweden (county code BD., AC., Z, Y, W) and 1919 for the remaining counties. These areas are referred to as "forested arable land". At both arable and forested arable land, several poplar planation's have previously been established [26–28], demonstrating that soil fertility, water supply and the soil pH is suitable for poplar plantations at these sites.

In this study, all land areas were included for both arable and forest-arable land, as detailed statistics of area sizes are not available for all land types.

2.2. Biomass production from long rotation poplar plantations

The production capacity of poplar plantations on arable land and reforested arable/marginal land was determined by using information from scientific articles/reports, theses (bachelor and master) and reports. From this literature, studies that used known genetic material, similar age and stem density were included. OP42 was used in southern and mid Sweden as this clone has been shown to have high sustainable production and high vitality in various site conditions; it is the most planted clone in Sweden. In northern Sweden, we chose to include stands with clone mixtures as there is a lack of knowledge related to specific clones. For stem density, we included stands with similar stem numbers (549–1200 ha^{-1}) and similar stand ages (18–20 years). This stand age represents the threshold at which plantations need to be harvested in order to maintain agricultural subsidies [35]. For determining the production of plantations located on forested arable land, results from stands with a lower age (10 years) were included as reports of stands aged 18–20 years were lacking.

2.3. Regional biomass and biofuel production potential

The total biomass supply from the different counties was calculated by using the available land identified (Table 1) combined with annual biomass production (Table 2) In county U, C, T, D, E, O, AB, H, K, N, M (counties located in southern Sweden) an annual biomass production per hectare of 8 Mg DW for arable land and 6 Mg for forested-arable land were used. For counties BD, AC, Z, Y, W, X, (located in northern Sweden) and counties S, F, G (located in Souther/mid Sweden but with a northern climate condition), an annual biomass production of 6 Mg DW per hectare for arable land and 4 Mg DW for forested arable land were used. Results are presented as Mg dry weight (DW) ha^{-1} yr^{-1} In a report to the Swedish energy agency [36], it was suggested that 25% of the unused

Table 1
Poplar samples prepared for fuel analysis.

Fuel sample	Abbreviation
Site 1: 12-year-old stand	
Stem/Round wood - stem + bark	P12r
Branches with leaves	P12br + l
Branches without leaves	P12br
Site 2: 30-year-old stand	
Stem/Round wood - stem + bark	P30r
Stem/Round wood - without bark	P30s
Stem/Round wood - only bark	P30b
Branches without leaves	P30br

arable and marginal land could be considered for poplar plantations. Thus, in this work, 25% of the total available land was used to identify possible locations of biofuel plants. For conversion from biomass to energy (MWh), 4.8 MWh per Mg DW was used [35]; for conversion from biomass (MWh) to biofuel (MWh), e.g., methanol, a 61% conversion level was used, as described in Hannula and Kurkela [37].

2.4. Biomass samples collected from long rotation poplar plantations

In the analysis of the quality of biomass produced from poplar plantations, we analyzed the stem and branches from two different types of plantations to represent the possible biomass types that might be produced under Swedish and international conditions. The plantations were located in mid-Sweden N58 29.309 E13 48,960) county Västra Götaland (county code O) (Fig. 1). Clone OP42 (*P. trichocarpa x P. maximowiczii*) was planted at both sites. Both sites were similar in site conditions and showed similar site conditions within the sites. At the 12 year old stand, the stem density was 800 trees ha^{-1} with a mean diameter of 15 cm with a mean height of 18 m, and the soil was of sandy loam type. At the 30 year old stand, stem density was 408 trees ha^{-1}, with a mean diameter of 30 cm and 28 m in height. This stand was located on clay soil. Earlier studies have shown that there is a low variation in ash forming elemental composition between tress of similar sizes within sites [38], and thus, one tree representing a typical tree at the two sites was selected for the biomass sample; site one (12 years old plantation) tree diameter of 16 cm and site 2 (30 years old plantation) tree diameter was 32 cm. The selected trees was located within the stand to avoid edge effects and showed no sign of branch or stem damage. At both sites, stem samples were collected by cutting a four cm trunk disk every 5 m, thus containing both bark and stem wood. After air drying, wood discs were divided into wood chips (1 × 2 cm) and then ground to a fine powder before analysis. From the 30-year-old tree, the bark was also separated from the stem sample. Samples were also taken from six typical branches from the trees selected from sites 1 and 2. Two different samples were prepared from the branches from site 1, both with and without leaves. From site 2, only one sample without leaves was prepared. After air drying, the branch samples were also ground to a fine powder before analysis. Table 1 shows the analyzed samples. The stem trunk discs were also dried and weight to be able to calculate the average stem trunk bulk density resulting in a bulk density for both round wood samples of 350 kg/m^3, which also were used in the biomass calculations converting m^3 to kg.

2.5. Fuel analysis of poplar biomass samples

All samples were analyzed for the following parameters using the standard procedures shown in parentheses: total moisture (CSN EN ISO 18134-1), ash (SS-EN 15934 and CSN ISO 562), carbon (C) and nitrogen (N) (CEN/TS 15104), sulfur (S) (SS EN ISO 11885 mod), chlorine content (Cl) (SS EN ISO 17294-1 mod), heating value (CSN ISO 1928) and the concentrations of the main ash-forming elements sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), phosphorus (P) and silicon (Si) (SS EN ISO 11885 mod). In addition, the fuel characteristics of the samples were compared with poplar sample analysis results reported in one of the most up-to-date biomass fuel database [32].

3. Results and discussion

3.1. Available land area for poplar plantations in Sweden

The total available area that can be used for planting fast-growing broad-leaved tree species (FGB.) i.e. poplars and hybrid aspen, is approximately 479,000 ha of arable land and 1,200,000 ha of forested arable land (Table 2). The "Arable land" consists of "unused arable land" (289,000 ha) and "abandoned arable land" (190,000 ha). It should be

Table 2
Available land areas for poplar plantations as a resource for biofuel production. Data shown are in hectares (ha).

County Code	County name	Unused arable land	Abundant arable land	Forested arable land	Total available land
B.D.	Norrbottens län	4,600	2,700	38,200	45,500
AC	Västerbottens län	14,300	5,700	47,400	67,400
Z	Jämtlands län	2,000	1,700	28,200	31,900
Y	Västernorrlands län	11,800	8,500	53,200	73,500
W	Dalarnas län	6,900	6,000	49,900	62,800
X	Gävleborgs län	6,600	14,800	49,600	71,000
S	Värmlands län	16,600	11,000	90,300	117,900
C	Uppsala län*	21,000	7,600	−7,700	20,900
U	Västmanlands län	12,000	3,100	66,300	81,400
AB	Stockholms län	17,200	8,600	86,500	112,300
D	Södermanlands län	16,400	6,500	58,200	81,100
T	Örebro län	12,300	6,400	59,500	78,200
E	Östergötlands län	16,700	7,700	59,600	84,000
O	Västragötaland län	58,300	34,600	200,400	293,300
F	Jönköpings län	7,000	8,600	54,500	70,100
H	Kalmar län	9,600	10,100	78,400	98,100
G	Kronobergs län	3,600	7,200	55,800	66,600
K	Blekinge län	3,500	3,000	32,600	39,100
N	Hallands län	10,600	8,100	40,000	58,700
M	Skåne län	31,000	22,200	157,400	210,600
I	Gotlands län**	7,000	5,600	−2,000	10,600
Total area		**288,900**	**189,700**	**1,296,500**	**1,775,000**

Note: The areas in the table are located within growing zones 1–6 in Sweden, and correspond to a growing season of 140 days or more. * The municipality, Heby, was transferred from Uppsala to Västmanland, affecting the land area.

Fig. 1. Letter code for Swedish counties.
Letters represent the county codes for all counties in Sweden. The blue bullet point shows the location of the two sites selected for biomass analysis.

noted that unused arable land is not used at present to produce food or feed. There are, though, large regional differences in the area available. For example, unused arable land in Skåne and Västra Götaland counties cover 31,000 and 58,000 ha respectively, while 10 counties have an area available between 10,000 and 21,000 ha. The remaining nine counties have available areas of 4,000 to 9,600 ha. Similar variations were found for "abandoned arable land" but the areas are smaller (2700–34,600 ha). Together, these land types have available areas in excess of 18,000 ha in 13 counties (varying between 92,900 and 18,700 ha). Five counties have areas between 10,000 and 18,000 ha. The large available areas are found in the mid and southern parts of the country.

The total forested arable area is approximately 1,300,000 ha (Table 2). For this land type, Skåne and Västra Götaland counties have 157,000 and 200,000 ha, respectively (Table 1). Of all 21 counties, there are 14 counties with more than 38,000 ha available. In the remaining counties, five contain about 30,000 ha (Table 2). Like arable land, forested arable land is mainly found in the middle and southern part of Sweden.

Our findings relating to available land are in line with an earlier study [5], which identified a total of 446,000 ha of abandoned farmland. In contrast [6], identified only 88,000 ha of available abandoned arable land using GIS analysis of agricultural blocks. Moreover, this study has shown that an additional 1.3 million ha (Mha) of available land consists of arable land that has been reforested ("ara-for") over the last 100 years (Table 1). This means that Sweden has a potential of establishing poplar plantations on 1.8 million ha without interfering with food production. Internationally, different numbers of the available land for non-food crops have been reported. Krasuska et al. [39] recorded up to 13.2 million ha in the European Union, mostly located in eastern Europe, and [40] reported more than 20 million ha of agricultural land that risked being abandoned [41]. calculated that there are 9.5 million ha of such land in Canada.

It is often suggested that bioenergy production could use abandoned, marginal and degraded land [42,43] but often constraining factors, such as water, productivity, social aspects or nature conservation are not considered [44–47], resulting in difficulty in establishing large-scale poplar plantations.

One of the first problems is that the soil pH might be such in forested arable land that poplars have difficulty growing (soil pH needs to be higher than 5.5) [25,49]. However, Falvik et al. [26] suggested that cultivation of poplars on forested arable land is possible. In addition, recent studies [48] have shown that applying lime during establishment efficiently increases growth in acidic forest soils, thus making plantations on forested arable land possible.

Second, the Forest Stewardship Council (FSC) have rules concerning the replanting of natural forest land with non-native tree species (hybrid poplars are not native to Sweden). However, the FSC standard particularly highlights the potential for using non-native tree species, such as poplar, as a replacement for plantations on former arable land where intense forest management has been carried out, where trees have been planted in rows and where trenching has been done. Moreover, there is support from the Swedish government as planting broad-leaved tree species in these areas is favored [31]. On arable land, poplar plantations are not affected by FSC rules as they considered an energy crop.

Third, a land-use change is required, meaning that the reasons given by individual landowners for avoiding the establishment of poplar or other fast-growing broad-leaved tree species need to be resolved. Similar to other short rotation crops (SRCs), the lack of relevant knowledge of practitioners, a high initial investment cost [49,50] uncertainty of economic profitability or political aspects related to the introduction of certification systems [51–53] might all influence the potential use of the available land. In contrast to other biomass production systems (willow plantations, short rotation forestry of poplar plantations, energy grasses), increasing the rotation age (20 years) would increase the flexibility of biomass harvest time points, thus having a positive effect on available land area. In this respect, a possible scenario is that a larger proportion of the available area might be established with poplar plantations compared to other SRCs.

Compared to other SRF, long-rotation poplar plantation has the advantage that they can be managed by using existing forest operation machinery and transportation logistics. However, management of small plantation areas might result in a higher cost for biomass production as biomass transportation and transport of operation machinery might increase, thus reducing the available land areas. There could also be an increased transportation costs of the biomasses from small plantations resulting in an economically insufficient transportation chain to wood processing places. However, for Sweden, there is already a well-developed logistics including transportation and harvest operations for woody biomasses, thus, biomasses form small plantation areas can be integrated the current system.

Earlier studies into introducing biofuel production using SRCs have suggested that it might stimulate a land-use change leading to large amounts of carbon being released into the atmosphere. When considering land-use change, a distinction between direct and indirect land-use needs to be made. Converting land from one state to another (forested arable land to forested arable land with FGT or arable land to arable land with FGT) would be referred to as a direct land-use change. However, if agricultural land is used for food production, this might displace crop production in other areas elsewhere, resulting in an indirect land-use change (iLUC). iLUC can be coupled with the demand and supply of agricultural products, which can ultimately lead to market changes. In contrast, the establishment of poplar on arable land and forested arable land would be a direct change in land-use, resulting in a smaller system change than if agricultural land were to be used.

3.2. Biomass production from poplar plantations in Sweden

Table 3 shows a biomass production of 8 MMgg haha^{-1} yr^{-1} per ha and 9 Mg DW ha^{-1} yr^{-1} in Skåne county (M) when poplar plantations are located on arable/marginal land. In Uppland (O) and Västra Götaland (C) counties, located in mid Sweden, the production was 9 Mg DW ha^{-1} yr^{-1}. This suggests that biomass production in the south (Skåne) and mid Sweden (Uppland and Västragötaland) can reach a similar level, 8 and 9 MMgg haha^{-1} yr^{-1} respectively after 20 years of growth. For plantations located in the northern part of Sweden (Västerbotten (AC) and Västernorrland (Y) counties) mean biomass production was 4 Mg DW ha^{-1} yr^{-1} when grown on arable/marginal land (Table 2). For plantations located in forested arable land, mean biomass production was 6 Mg DW ha^{-1} yr^{-1} (Table 3) when planted in Halland county (N) in southern Sweden.

Biomass supply potential depends on several aspects: available land and accurate production for each land type/geographic location are the most important parameters. Our results indicate that, for arable land in southern Sweden, biomass production of 8 Mg DW ha^{-1}yr^{-1} can be expected. However, when plantations are located on arable land in northern Sweden, there was an annual production of 4.0 Mg DW ha^{-1} yr^{-1} (Table 2). However, comparisons between new poplar plantations [54] and older plantations [55,56] indicate that the mean biomass production of 4 Mg DW ha^{-1}yr^{-1} after 20 years is probably an underestimation (new plantations showed a biomass production of 6 Mg DW ha^{-1}yr^{-1}). The reasoning behind this is that, young plantations are still before the maximum production capacity that is found when plantations become older. In line with this argument plantations on forested arable land, a yearly biomass production of 4.5 Mg DW ha^{-1}yr^{-1} (Table 2) is probably also an underestimation, as the plantations have a stand age of 10 years. In fact, the production level is comparable to plantations on arable land with similar ages [57]. However, a recent biomass production in Falhvik et al. [26] indicated that biomass production of poplar planation's on forested arable land is possible and that biomass production is slightly lower compared to plantations located at arable land. It should be noted that these plantations are still young, e.g., 10 years, thus differences occur later in the rotation period.

Table 3
Biomass production of poplar plantations in Sweden. Data shown are stem numbers, trees ha^{-1}, biomass production ton dry weight (D.W.) ha^{-1}yr^{-1} land type, agricultural land (ara) and foresed arable land (For-ara). Stand age is given as years after planting.

Poplar genotype	Age	Stem numbers	Production	Site type	County	Reference
Poplar (OP42)	20	549	11	Ara	M	[28]
Poplar (OP42)	19	440	6,3	Ara	M	[28]
Poplar (OP42)	18	750	7	Ara	M	[15]
Poplar (OP42)	18	670	8	Ara	M	[15]
Poplar (OP42)	18	625	9	Ara	M	[15]
Poplar (OP42)	18	707	8.5	Ara	M	[28]
Mean	**19**	**624**	**8**			
Poplar (OP42)	12	1000	4	For-ara	N	[26]
Poplar (OP42)	10	1200	6	For-ara	N	[26]
Mean	**12**	**1100**	**5**			
Poplar (OP42)	19	1250	14,7	Ara	C	[28]
Poplar (OP42)	18	1026	6,3	Ara	C	[57]
Poplar (OP42)	23	1005	7,8	Ara	C	[28]
Poplar (OP42)	18	909	5,5	Ara	C	[28]
Poplar (OP42)	30	650	10,15	Ara	O	[57]
Poplar (OP42)	27	850	8,4	Ara	C	[57]
Mean	**23**	**948**	**9**	Ara		
910 and 58	27	600	5	Ara	AC	[56]
910 and 58	16	900	3	Ara	AC	[56]
910 and 58	18	900	4	Ara	AC	[56]
910 and 58	20	600	4	Ara	AC	[55]
Mixture	9	1100	6	Ara	Y	[54]
Mixture	9	1100	4	Ara	AC	[54]
Mean	**17**	**968**	**4**			

The availability of poplar biomass for biofuels is also dependent on price and competition for the biomass where the woody biomass is currently used as pulpwood. However, as these poplar plantations have a long rotation period (15–20 years), it is likely that the biomass will be used for several other purposes. A recent publication Adler 2023 [58] suggests that poplar biomass can be used to produce cellulose fibers to displace cotton. Thus economic viability is probably dependent on the products that are produced from the biomass, and as this biomass are produced from trees with large diameter (>15 cm), there is several more options for the biomass than only conversion to energy or biofuels.

3.3. Swedish feedstock resources from poplar plantations in different regions

In total, the biomass supply from poplar plantations in Sweden when using available arable land and forested arable land could be up to 10.9 Million Mg DW (Table 3). This corresponds to 52.6 TWh that can be produced from poplar plantations. The biomass and energy production can be twice as high when plantations are located on forested arable land, reaching 35.1 TWh and 7.3 million Mg DW of biomass (Table 4), while for arable land 3.7 million Mg DW could be produced, corresponding to 17.6 TWh.

Assuming a 25% usage of the available land, arable land could provide a total biomass supply of about 914,000 Mg DW yr^{-1} (Fig. 3A). However, there are large variations in each county. Västra Götaland and Skåne (county C and M) have a biomass production potential of 186,000 and 106,000 Mg DW yr$^{-1,}$ respectively. There are 11 counties, mostly located in the mid/southern part of Sweden, with annual biomass production of between 25,000 and 60,000 DW In counties located in northern areas, biomass production is the lowest, from 3,700 to 20,000 Mg DW yr^{-1} (Fig. 3A).

On forested arable land, biomass production can provide approximately 1,825,000* Mg DW yr^{-1} year (Fig. 3B). Similar to arable land, potential biomass production is largest in Skåne and Västra Götaland counties, followed by counties in mid/south Sweden, producing about 100,000 Mg DW yearly. In the northern counties, biomass production potential is about half, so 50,000 Mg DW yr^{-1} (Fig. 3B). Thus, the large potential for poplar plantation is not on arable land, but on arable land that was reforested during the 20th* century.

3.4. Fuel characteristics of woody biomass from long rotation poplar plantations

From previous poplar sample analyses reported in the Phyllis 2 database [32], the ash, N, S, and Cl concentrations vary greatly between the analyzed samples (see Table 5). The major reason for this is probably

Table 4
Total biomass production potential from poplar plantations in 1000 tons and TWh per county.

Code	County	Arable land		Forested arable land	
		(1000 Mg)	(TWh)	(1000 Mg)	(TWh)
BD	Norrbotten	44	0.21	153	0.73
AC	Västerbotten	120	0.58	190	0.91
Z	Jämtland	22	0.11	113	0.54
Y	Västernorrland	122	0.58	213	1.02
W	Dalarna	77	0.37	200	0.96
X	Gävleborg	128	0.62	198	0.95
S	Värmland	166	0.76	361	1.73
C	Uppsala*	229	1.10	0	0.00
U	Västmanlands län	121	0.58	398	1.91
AB	Stockholm	206	0.99	519	2.49
D	Södermanland	183	0.88	349	1.68
T	Örebro	150	0.72	357	1.71
E	Östergötland	195	0.94	358	1.72
O	Västragötaland	743	3.57	1202	5.77
F	Jönköping	94	0.45	218	1.05
H	Kalmar	158	0.76	470	2.26
G	Kronoberg	65	0.31	223	1.07
K	Blekinge	52	0.25	196	0.94
N	Halland	150	0.72	240	1.15
M	Skåne	426	2.04	944	4.53
I	Gotland	100	0.48	0	0.00
	Total	3,550	17	6902	33

Note: * The municipality Heby was transferred from Uppsala to Västmanland, affecting the total biomass production.

because different parts from the tree/bush have been analyzed, and bark and branch parts from trees have significantly higher ash, N, S, and Cl concentrations than, for example, the stem wood part. Differences in the age of the tree (since young trees possibly have a greater proportion of bark than stem wood), the clone, and the stand location probably also contribute to differences in these levels. Few analyses of the concentrations of main ash-forming elements in poplars can be found in the Phyllis 2 database (only four samples are reported) [33]. From reports in the Phyllis 2 database [32], it appears that the fuel ash of the analyzed samples was dominated by Ca (30–50% by weight calculated as CaO), K (10–24% by weight calculated as K2O), and P (0.2–15% by weight calculated as P2O5).

Table 5
Fuel characteristics of earlier published poplar samples [32]. Results show are mean values of 6–17 samples.

Fuel characteristics	Min	Max	Median	Average	SD	Number of samples
Ash content (wt%, dry basis)	0.4	2.7	1.22	1.28	0.69	17
Volatile content (wt%, dry and ash-free basis)	71.8	87.5	84.8	82.6	6.11	6
Lower heating value (MJ/kg, dry and ash-free basis)	17.3	19.5	18.4	18.5	64	12
C (wt%, dry and ash-free basis)	44.8	53	49.7	49.8	1.92	13
H (wt%, dry and ash-free basis)	5.6	6.34	6.07	6.05	0.2	13
O (wt%, dry and ash-free basis)	41.6	48.6	43.9	43.8	1.95	13
N (wt%, dry and ash-free basis)	0.1	1.02	0.32	0.39	0.28	11
S (wt%, dry and ash-free basis)	0.001	0.05	0.03	0.03	0.02	10
Cl (wt%, dry and ash-free basis)	0.008	0.1	0.012	0.034	0.039	9

Note: Standard deviations are given in the column SD.

Based on both the poplar analyses reported in the Phyllis 2 database (Table 5) and the analyzed samples from this work (Table 6), it appears that the C, H, and O concentrations, as well as the volatile component concentrations and the heating value, do not vary significantly compared to other wood fuel-based assortments (e.g. conifer stem wood) calculated on a dry and ash-free basis. The ash content, however, varies considerably between the different poplar samples analyzed in this work. The ash content in the stem wood of the analyzed poplar sample (P30s) was similar to conifer stem wood, while the two analyzed round/stem wood fractions (P12r and P30r) were more similar to willow (see Table 6 and 7). However, it should be noted that the analyzed poplar branch fractions (P12br, P12br + l, and P30br) had lower ash contents than typical conifer branches, with an ash content similar to willow. However, the analyzed poplar bark fraction (P30b) had a higher ash content than typical conifer bark. An interesting observation is that the round/stem wood fraction from the older poplar stand had a significantly higher ash content than in the younger stand, which may be because the bark was significantly thicker in the older stand. Based on the differences in the analyzed Ca and K concentrations of the round wood (stem + bark), stem wood, and bark of the older poplar (P30), the proportion of bark was estimated to be 15–18% by weight on a dry basis in the round wood.

The analyzed stem wood fraction from poplar (P30s) had similar N, S, and Cl concentrations as typical conifer stem wood (see Table 6 and 7). The N concentration of the analyzed branch poplar samples was similar to that of traditional conifer branch samples. The N concentration of the bark fraction (P30b) was similar to that of typical conifer bark. Cl levels were surprisingly low in all analyzed poplar samples and on a par with typical conifer stem wood. The S concentration of the poplar samples matched that of similar typical forest fuel fractions.

The dominant ash-forming elements in the studied poplar samples were Ca and K, similar to other conifer forest fuels (Fig. 2). Unlike typical conifer branches and bark, the poplar samples contained very little Si and other anions, but some P. The levels of trace elements such as Cd were of the same order of magnitude in the poplar samples as in typical forest fuels (0.2–0.5 mg/kg dry substance). By way of comparison, in willow, the Cd levels are often 10 times higher [59].

To summarize, the ash, N, S, and Cl concentrations of the studied poplar samples were similar to those of traditional conifer forest fuels,

Table 6
Fuel composition of the analyzsed poplar samples (P12/P30).

Fuel characteristics	P12r	P12br	P12br + l	P30r	P30s	P30b	P30br
Ash content (wt %, dry basis)	1.5	1.6	1.7	2.3	0.7	5.7	1.7
Volatile content (wt%, dry and ash-free basis)	84.9	83.2	81.3	83.4	86.8	75.8	85
Lower heating value (M.J./kg, dry and ash-free basis)	18.1	18.6	18.7	18.7	18.1	18.7	18.6
C (wt%, dry and ash-free basis)	48.5	50	49.9	50.2	48.6	53	49.8
H (wt%, dry and ash-free basis)	6.6	6.3	6.5	6.4	6.6	6.5	6.4
O (wt%, dry and ash-free basis)	44.5	43.2	42.1	43.4	44.7	40.3	43.6
N (wt%, dry and ash-free basis)	0.18	0.25	0.41	0.15	0.14	0.36	0.12
S (wt%, dry and ash-free basis)	0.02	0.02	0.036	0.011	0.01	0.04	0.01
Cl (wt%, dry and ash-free basis)	0.01	0.008	0.01	0.008	n.a.	0.02	0.01

Note: Analyzed samples are stem/Round wood - stem + bark (P12r), branches with leaves (P12br + l), branches without leaves (P12br), Stem/Round wood - stem + bark (P30r), stem/Round wood - without bark (P30s), stem/Round wood - only bark (P30b), branches without leaves (P30br + l).

Table 7
Fuel composition given as median values of more than 12, 6, 8, 11 and 12 characterized fuel samples of willow, straw, stem wood, bark and branches, respectively, reported in Ref. [59].

Fuel characteristics	Willow 1	Conifer			
		Straw	Stem wood	Bark	Branches
Ash content (wt%, dry basis)	2.1	4.95	0.6	3,0	2.65
Volatile content (wt%, dry and ash-free basis)	81.6	n.a.	84.3	n.a.	75.6
Lower heating value (M.J./kg, dry and ash-free basis)	18.6	17.6	19.1	20.3	19.5
C (wt%, dry and ash-free basis)	49.7	48.3	50.9	53.7	51.1
H (wt%, dry and ash-free basis)	6.1	5.9	6.1	6.1	6.1
O (wt%, dry and ash-free basis)	43.6	44.8	42.8	39.8	40.1
N (wt%, dry and ash-free basis)	0.5	0.6	0.1	0.3	0.4
S (wt%, dry and ash-free basis)	0.04	0.08	0.01	0.03	0.04
Cl (wt%, dry and ash-free basis)	0.02	0.12	0.01	0.02	0.02

where the stem wood fraction has very low concentrations, and the branch and bark fractions have significantly higher concentrations. The fuel ash of the poplar samples was dominated by Ca, K and, to a certain extent, P. Similar to previously characterized woody biomass fuels [61], the stem wood-based poplar fraction sample is the only fuel fraction that potentially meets the requirement for use as raw material in pellets for producing class A pellets according to ISO 17225–2:2014 or EN plusA1 standard. Thus, poplar grown with a 10 or 20 year rotation probably has similar fuel conversion behavior to traditional conifer forest fuels. However, this needs to be verified experimentally, especially concerning the reactivity of the char formed during gasification.

3.5. *Potential locations for biofuel production plants*

When converting biomass to biofuels, the amount of biomass that can be supplied is one of the most important parameters in deciding the location of the associated industrial plants. There are several publications [59,60] describing examples of biofuel plants using a biomass supply of 160,000 Mg DW yr^{-1}. Based on the possible biomass supply from poplar plantations located on both arable and forested arable land (Fig. 3 A and B), there could be 16.4 industrial sites, with most located in the mid and southern parts of Sweden. Only a few counties, such as Skåne and Västra Götaland (Fig. 2), could supply their own biofuel industry (160,000 Mg DW yr^{-1}), with the rest of the counties dependent on sharing biomass with neighboring counties. In the northern counties (BD, AC, Z, Y), biomass supply could only supply one biofuel plant using 160,000 Mg DW yr^{-1}.

The geographic location of a biofuel plant/industrial site depends on several factors, including energy supply, export of biofuel products, the technological maturity of the production method, and large amounts of high quality biomass. Currently, there are biofuel plants under construction based on thermochemical (gasification) conversion methods, with an estimated biomass usage of approximately 160,000 Mg DW yr^{-1} [60,61]. By using this figure as an indicator of the need for biofuel plants, our results suggest that most counties in mid and southern Sweden could supply a biofuel plant using 160,000 Mg DW annually. There are, though, counties (Skåne and Västra Götaland) that could support several biofuel plants with 160,000 Mg DW annually. However, additional sites would be possible, either by using a larger proportion of the land or by increasing biomass production. There is also potential to increase the biomass supply by increasing growth. Several studies have shown there is a large variation in growth between clones [62–64] in Scandinavian climate conditions. Thus, new and better-performing clones might increase biomass production. There has also been a development of management methods e.g. vegetation control treatments, plant types, or application of lime that changes soil pH, that can increase biomass production [19,22,48].

Our results do suggest that biofuel production based on thermochemical (gasification) methods using 25% of the available land with long rotation poplar could produce 7.7 TWh bio-methanol, with each biofuel plant producing 0.47 TWh. In comparison, Prade et al. [65] demonstrated a straw feedstock potential of 10 TWh biogas or 4.0 TWh ethanol from agricultural land. There is also available forest biomass for biofuel purposes that has been estimated to be 18 TWh [65]. Using biofuel production such as thermal gasification (with high energy and

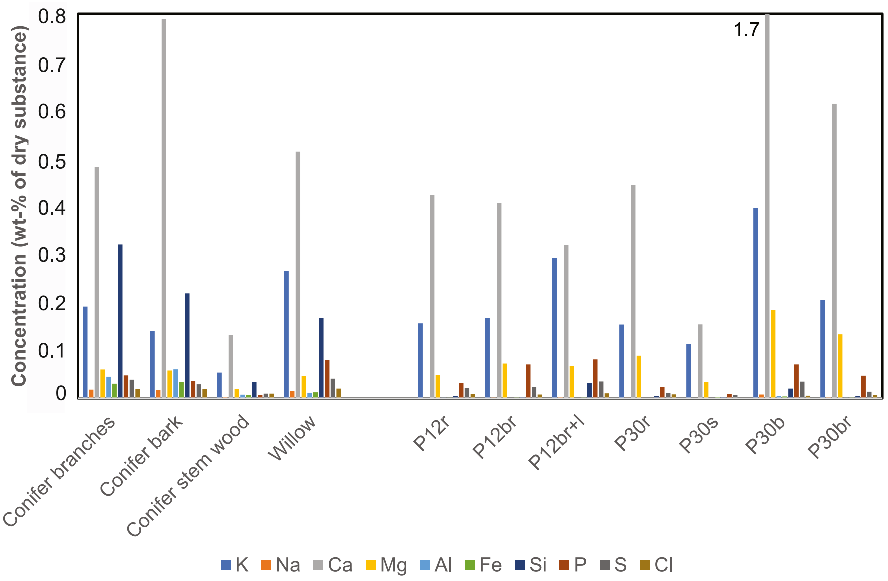

Fig. 2. Concentrations of ash-forming elements.
The different poplar samples studied in this work (P12/P30) and comparison with the typical composition of various wood-derived fuels (median values of several samples) taken from [16]. Analyzed samples are stem/Round wood - stem + bark (P12r), branches with leaves (P12br + l), branches without leaves (P12br), Stem/Round wood - stem + bark (P30r), stem/Round wood - without bark (P30s), stem/Round wood - only bark (P30b), branches without leaves (P30br).

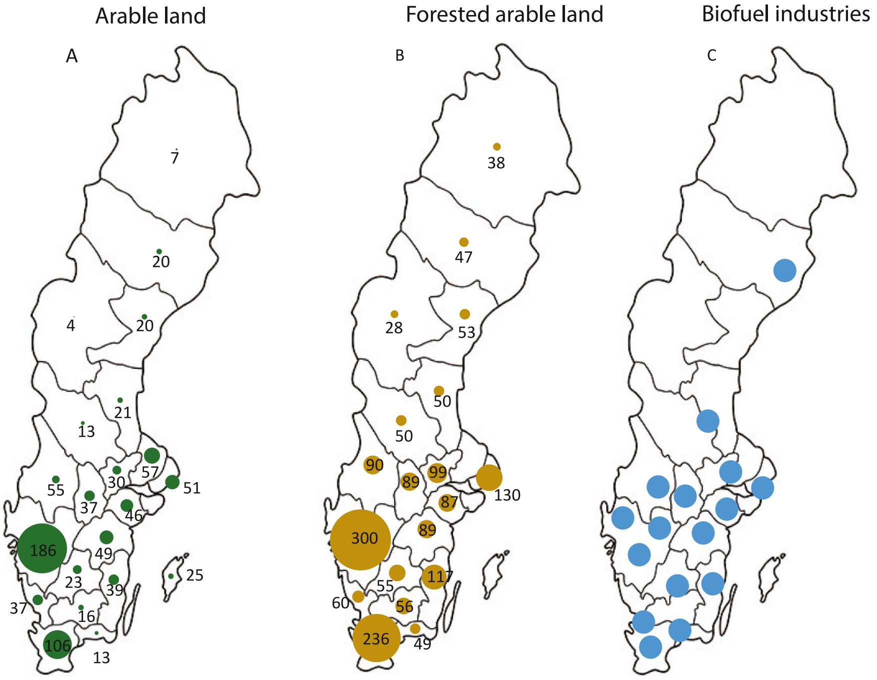

Fig. 3. Biomass production potential using 25% of available land and location of biofuel plants
A, Biomass production potential of arable land. B, Biomass production potential of forested arable land. Biomass production potential shown is in 1000 ton DW yr^{-1}. C, biofuel plant location (160,000 ton DW yr^{-1}) based on biomass supply from poplar plantation at each county.

resource efficiency) in the future, this biomass would yield a maximum theoretical biofuel production of 11–12 TWh. However, considering technical development and economic conditions, 4–6 TWh from biofuels has been suggested to be a more realistic production level [66]. Thus, a large proportion of the expected biofuel demand in 2030, that is, 20 TWh yr^{-1} [68] could be covered by production from poplar plantations. However, if plantation areas or biomass growth were to be increased, that proportion would increase and, together with forest, agricultural residues, Sweden could become a net producer and not an importer of biofuels.

4. Conclusion

This study estimated the potential of using poplar biomass as feedstock for domestic biofuel production. The results suggest that there are 1.8 million ha of land available, with forested arable land having the largest potential, with 1.3 million ha. When combined with production capacity for the different land types (arable land and forested arable land) and geographical regions, a total biomass production of 53 TWh is possible. However, a more realistic feedstock would be the usage of 25% of the available land areas: approximately 13 TWh biomass could be available mainly produced in the southern part of Sweden (Götaland). This feedstock can, on its own, support up to 16.4 biofuel plants (using 160,000 Mg DW yearly), resulting in 0.47 TWh biomethanol produced at each plant and a total production of 7.7 TWh. Fuel analysis of the biomass produced from poplar grown with a 10 or 20 year rotation length suggests that poplar stem wood is similar to the stem wood of other conifer tree species, allowing for multiple downstream biofuel conversion processes. This study was, nevertheless, only the first attempt to estimate the biomass potential at a geographical scale on available arable and forested arable land for poplar plantations in Sweden to meet the Swedish and E.U. climate and renewable biofuel targets.

Data availability

Data will be made available on request.

Acknowledgements

This work has been carried out with support from the Swedish Energy Agency and f3 (the Swedish Knowledge Center for Renewable Transportation Fuels), and in collaboration with Centerre of Excellence for fast growing deciduous TREES - sustainable FORest, Material, and Energy (TREES FOR ME) funded by the Swedish Energy Agency. The authors would also like to express their gratitude to the reference group in this project consisting of members from Skogssällskapet, Preem, Höganäs AB, Norra skog AB, private land owner and to Mats Högström at the Swedish University of Agricultural Science (SLU) for assistance with analyzing available land area.

References

[1] European Parliament, Renewable Energy Directive (RED II), 2022.
[2] Branchfakta SPBI (2019).
[3] ER 2019, Energimyndigheten Drivmedel, 2018, p. 14.
[4] Energimyndigheten, Komplettering till Kontrollstation 2019 För Reduktionsplikten, 2019.
[5] S. Larsson, T. Lundmark, G. Ståhl, Möjligheter till Intensiv Odling Av Skog, Slutrapport Från Regeringsuppdrag JO 2008/1885, 2009.
[6] J. Olofsson, P. Börjesson, Disused Arable Land for Biomass Production – Mapping and Potential Estimation, Report no. 2016:01, f3, Knowledge Center for Renewable Transport Fuels and Foundation, Sweden., 2016.
[7] H. Böhlenius, L. Petersson, M. Cleary, A. Karacic, E. Anander, K. Blennow, A. Adler, N. Fahlvik, M. Liziniewicz, P.-O. Persson, Snabbväxande Trädslag För Energi Och Andra Andamål -sammanställning Av Dagens Kunskapsläge Och Framtidens Utmaningar, 2021.
[8] L. Christersson, Poplar plantations for paper and energy in the south of Sweden, Biomass Bioenergy 32 (11) (2008) 997–1000.
[9] R. Mao, D.-H. Zeng, Y.-L. Hu, L.-J. Li, D. Yang, Soil organic carbon and nitrogen stocks in an age-sequence of poplar stands planted on marginal agricultural land in Northeast China, Plant Soil 332 (1–2) (2010) 277–287.
[10] A. Tullus, L. Rytter, T. Tullus, M. Weih, H. Tullus, Short-rotation forestry with hybrid aspen (Populus tremula L.×P. tremuloides Michx.) in Northern Europe, Scand. J. For. Res. 27 (1) (2011) 10–29.

[11] A. Tullus, H. Tullus, A. Vares, A. Kanal, Early growth of hybrid aspen (*Populus wettsteinii* Hämet-Ahti) plantations on former agricultural lands in Estonia, For. Ecol. Manag. 245 (1–3) (2007) 118–129.

[12] D.S. DeBell, C.A. Harrington, Productivity of Populus in monoclonal and polyclonal blocks at three spacings, Can. J. For. Res. 27 (7) (1997) 978–985.

[13] J.A. Stanturf, C. von Oosten, D.A. Netzer, M.D. Colman, C.J. Prtwood, Ecology and Silviculture of poplar plantations, in: D.I. Dickman, J.E. Eckenwald, J. Richardson (Eds.), Poplar Culture in North Amerika, National Council of Canada Research Press, Ottowa, Ontario, 2001, pp. 152–206.

[14] S.G. Pallardy, D.E. Gibbins, J.L. Rhoads, Biomass production by two-year-old poplar clones on floodplain sites in the Lower Midwest, USA, Agrofor. Syst. 59 (1) (2003) 21–26.

[15] L. Christersson, Wood production potential in poplar plantations in Sweden, Biomass Bioenergy 34 (9) (2010) 1289–1299.

[16] B.-G. Simon, P. David, M. Christian, N. Bélanger, Juvenile growth of hybrid poplars on acidic boreal soil determined by environmental effects of soil preparation, vegetation control, and fertilization, For. Ecol. Manag. 261 (3) (2011) 620–629.

[17] B. Truax, D. Gagnon, J. Fortier, F. Lambert, Yield in 8 year-old hybrid poplar plantations on abandoned farmland along climatic and soil fertility gradients, For. Ecol. Manag. 267 (2012) 228–239.

[18] B. Truax, D. Gagnon, J. Fortier, F. Lambert, Biomass and volume yield in mature hybrid poplar plantations on temperate abandoned farmland, Forests 5 (12) (2014) 3107–3130.

[19] B.D. Pinno, N. Bélanger, Competition control in juvenile hybrid poplar plantations across a range of site productivities in central Saskatchewan, Canada, N. For. 37 (2) (2009) 213–225.

[20] B.D. Pinno, B.R. Thomas, N. Bélanger, Predicting the productivity of a young hybrid poplar clone under intensive plantation management in northern Alberta, Canada using soil and site characteristics, N. For. 39 (1) (2009) 89–103.

[21] T. Guillemette, A. DesRochers, Early growth and nutrition of hybrid poplars fertilized at planting in the boreal forest of western Quebec, For. Ecol. Manag. 255 (7) (2008) 2981–2989.

[22] L.M. Coll, Christian Delagrange, Sylvain Berninger, Berninger Frank, Growth, allocation and leaf gas exchanges of hybrid poplar plants in their establishment phase on previously forested sites: effect of different vegetation management techniques, Ann. For. Sci. 64 (3) (2007) 275–285.

[23] R.L. Mc Carthy R, K. Hjelm, Effects of soil preparation methods and plant types on the establishment of poplars on forest land, Ann. For. Sci. 74 (47) (2017) 1–12.

[24] J. Jobling, Poplars for Wood Production and Amenity, the Forest Commition, Forest Research Station, Alice Holt Lodge, 1990, pp. 51–52.

[25] A.E. Bergstedt, Dyrkning Af Poppel, Statens forstlige Forsøgsvæsen, Danmark, 1981, p. 106.

[26] N. Falhvik, H Böhlenius. Hybrid Aspen and Poplar Planted on Forestland in Sweden after the Storm Gudrun 2021 Poster 26th Session IPC (International Poplar Commission).

[27] L. Olsoon, E. Månsson, Poppels Volymproduction På Granåkrar I Götaland, Poplar Volyme Production of Fareste Arable Land Bachlor Thesis, Swedish university of agricultural Science, 2023.

[28] A.V. Karacic, T. Weih M, Above-ground woody biomass production of short-rotation Populus plantations on agricultural land in Sweden, Scand. J. For. Res. (2003).

[29] L.S. Rytter, G. L, Clonal variation in nutrient content in woody biomass of hybrid aspen (Populus tremula L. x P. tremuloides Michx.), Silva Fenn. 37 (3) (2003).

[30] T. Johansson, Biomass production of hybrid aspen growing on former farm land in Sweden, J. For. Res. 24 (2) (2013) 237–246.

[31] 22:58, Regeringens Proposition Stärkt Äganderätt, Flexibla Skyddsformer Och Ökade Incitament För Naturvården I Skogen Med Frivillighet Som Grund, 2021.

[32] Phyllis2, Database for the Physico-Chemical Composition of (Treated) Lignocellulosic Biomass, Micro- and Macroalgae, Various Feedstocks for Biogas Production and Biochar, Available online:, 2021 https://phyllis.nl/. (Accessed 21 December 2021).

[33] The Swedish Board of Agriculture Statistical Database of Area, Crop and Geografic Area, 2020. https://statistik.sjv.se.

[34] The Real Estate Map of the Whole of Sweden, 2019. https://www.lantmateriet.se/en/about-lantmateriet/contact-us/.

[35] Energimyndigheten, Kvalitetesdeklaration Oförädlat Trädbränsle, SCB Statistics, 2019.

[36] H. Böhlenius, M. Öhman, F. Granberg, P.-O. Persson, Biodrivmedel från snabbväxande lövträd - en syntesstudie från råvara till drivmedel, Rapport nr FDOS 36:2022, 2022. Tillgänglig på, https://f3centre.se/sv/samverkansprogram/.

[37] I. Hannula, E. Kurkela, Liquid Transportation Fuels via Large-Scale Fluidised-Bed Gasification of Lignocellulosic Biomass, 2013.

[38] J. Werkelin, B.-J. Skrifvars, M. Hupa, Ash-forming elements in four Scandinavian wood species. Part 1: summer harvest, Biomass Bioenergy 29 (6) (2005) 451–466.

[39] E. Krasuska, C. Cadórniga, J.L. Tenorio, G. Testa, D. Scordia, Potential land availability for energy crops production in Europe, Biofuels Bioproduct.Biorefin. 4 (6) (2010) 658–673.

[40] E. Commission, LUISA Territorial Modelling Platform, 2018.

[41] T. Liu, T. Huffman, S. Kulshreshtha, B. McConkey, Y. Du, M. Green, J. Liu, J. Shang, X. Geng, Bioenergy production on marginal land in Canada: potential, economic feasibility, and greenhouse gas emissions impacts, Appl. Energy 205 (2017) 477–485.

[42] J. Dauber, C. Brown, A.L. Fernando, J. Finnan, E. Krasuska, J. Ponitka, D. Styles, D. Thrän, K.J. Van Groenigen, M. Weih, R. Zah, Bioenergy from “surplus” land: environmental and socio-economic implications, BioRisk 7 (2012) 5–50.

[43] I. Gelfand, R. Sahajpal, X. Zhang, R.C. Izaurralde, K.L. Gross, G.P. Robertson, Sustainable bioenergy production from marginal lands in the US Midwest, Nature 493 (7433) (2013) 514–517.

[44] D.P. van Vuuren, J. van Vliet, E. Stehfest, Future bio-energy potential under various natural constraints, Energy Pol. 37 (11) (2009) 4220–4230.

[45] H. Haberl, T. Beringer, S.C. Bhattacharya, K.-H. Erb, M. Hoogwijk, The global technical potential of bio-energy in 2050 considering sustainability constraints, Curr. Opin. Environ. Sustain. 2 (5) (2010) 394–403.

[46] T. Beringer, W. Lucht, S. Schaphoff, Bioenergy production potential of global biomass plantations under environmental and agricultural constraints, GCB Bioenergy 3 (4) (2011) 299–312.

[47] E. Sevigne, C.M. Gasol, F. Brun, L. Rovira, J.M. Pagés, F. Camps, J. Rieradevall, X. Gabarrell, Water and energy consumption of Populus spp. bioenergy systems: a case study in Southern Europe, Renew. Sustain. Energy Rev. 15 (2) (2011) 1133–1140.

[48] H. Böhlenius, U. Nilsson, C. Salk, Liming increases early growth of poplars on forest sites with low soil pH, Biomass Bioenergy 138 (2020), 105572.

[49] M. Ostwald, A. Jonsson, V. Wibeck, T. Asplund, Mapping energy crop cultivation and identifying motivational factors among Swedish farmers, Biomass Bioenergy 50 (2013) 25–34.

[50] C. Sherrington, J. Bartley, D. Moran, Farm-level constraints on the domestic supply of perennial energy crops in the UK, Energy Pol. 36 (7) (2008) 2504–2512.

[51] I. Lewandowski, A.P.C. Faaij, Steps towards the development of a certification system for sustainable bio-energy trade, Biomass Bioenergy 30 (2) (2006) 83–104.

[52] J. van Dam, M. Junginger, A. Faaij, I. Jürgens, G. Best, U. Fritsche, Overview of recent developments in sustainable biomass certification, Biomass Bioenergy 32 (8) (2008) 749–780.

[53] B. Mola-Yudego, P. Pelkonen, The effects of policy incentives in the adoption of willow short rotation coppice for bioenergy in Sweden, Energy Pol. 36 (8) (2008) 3062–3068.

[54] L. Rytter, R. Lutter, Early growth of different tree species on agricultural land along a latitudinal transect in Sweden, Forestry, Int. J. Financ. Res. 93 (3) (2019) 376–388.

[55] M. Boström, L. Linck, Poppel - en möjlighet i norra Sverige?. Masterthesis, SLU, epartment of forest management and ecology, 2012, 2012.

[56] B. Elfving, En Plantering Med Poppel, Björk Och Gran På Nedlagd Jordbruksmark Vid Umeå. , Institut¬ionen För Skogens Ekologi Och Skötsel, 2012 report 5 reviced 2012.

[57] T. Verwijst, Pilotstudie Av Tillväxtdynamik under Olika Planteringsförband Och Omloppstid För Poppelplanteringar. Opublicerat., Slutrapport, SLF Projekt O-15-22-561 (Opublicerat), 2019.

[58] A. Adler, I. Kumaniaev, A. Karacic, K.R. Baddigam, R.J. Hanes, E. Subbotina, A. W. Bartling, A.J. Huertas-Alonso, A. Moreno, H. Håkansson, A.P. Mathew, G. T. Beckham, J.S.M. Samec, Lignin-first biorefining of Nordic poplar to produce cellulose fibers could displace cotton production on agricultural lands, Joule 6 (8) (2022) 1845–1858.

[59] B. Strömberg, S. Herstad Svärd H, The Fuel Handbook, Värmeforsk, Stockholm, Sweden, 2012.

[60] Redrock Biofules. https://www.redrockbio.com/. September 2021.

[61] Fulcrum bioenergy. https://www.fulcrum-bioenergy.com. September 2020.

[62] U.B. Nielsen, P. Madsen, J.K. Hansen, T. Nord-Larsen, A.T. Nielsen, Production potential of 36 poplar clones grown at medium length rotation in Denmark, Biomass Bioenergy 64 (2014) 99–109.

[63] A. Adler, A. Karacic, A.-C. Ronnberg-Wastljung, U. Johansson, K. Liepins, A. Gradeckas, L. Christersson, Variation of growth and phenology traits in poplars planted in clonal trials in Northern Europe—implications for breeding, BioEnergy Res. 14 (2021) 1–19.

[64] B. Ilstedt, Genetics and performance of Belgian poplar clones tested in Sweden, For. Genet. 3 (1996).

[65] T. Prade, L. Björnsson, M. Lantz, S. Ahlgren, Can domestic production of iLUC-free feedstock from arable land supply Sweden’s future demand for biofuels? J. Land Use Sci. 12 (6) (2017) 407–441.

[66] AvfallSverige, Realiserbar Biogaspotential I Sverige År 2030 Genom Rötning Och Förgasning (Report No. B2013:02), AvfallSverige, Malmö, Sweden, 2013.