Dissertationes Forestales 337

Land-use patterns of energy crops in the agricultural landscape

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Academic dissertation

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ABSTRACT

Lignocellulosic energy crops can produce substantial amounts of biomass for energy purposes, but their introduction implies land-use changes as they are mainly cultivated in agriculturally dominated landscapes. This thesis presents a land-use analysis of lignocellulosic energy crops in the agricultural landscape in Sweden, specifically aiming to i) assess different energy crops' regarding production, location and climatic profiles, ii) characterise and define the surrounding agricultural landscape, and iii) study the overall land-use changes derived from the establishment of energy crops in the country. The analysis is based on empirical data from commercial fast-growing tree plantations (willow, poplar, and hybrid aspen) and energy grasses (reed canary grass) at multiple spatial scales from field to landscape level, during the period 1986-2018. At field level, there is a trend for smaller and more regular fields dedicated to energy crops, with cultivation patterns moving towards more productive lands, reflecting an intensification in the land-use management. Willow was initially established mainly on fallow lands, but many plantations were subsequently replaced by cereals due to changes in global cereal prices. In the case of grasses, this pattern was similar, although changes appeared later and not so markedly. At landscape level, energy crops significantly diversify the agricultural landscape, as fast-growing tree plantations are largely introduced in cereal areas and grasses in forest-dominated landscapes. The methods and analysis of this thesis contribute to a better understanding of land-use changes associated to energy crops, and help define their contribution to diversifying the agricultural landscape.

Keywords: bioenergy, biomass production system, fast-growing plantations, land-use change, lignocellulosic biomass

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November 2022, Joensuu

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on data presented in the following articles, referred to by the Roman Numerals I-III.

I **Xu X**, Mola-Yudego B. (2021). Where and when are plantations established? Land-use replacement patterns of fast-growing plantations on agricultural land. Biomass and Bioenergy 144: 105921.

II Mola-Yudego B, **Xu X**, Englund O, Dimitriou I. (2021). Reed Canary Grass for Energy in Sweden: Yields, Land-Use Patterns, and Climatic Profile. Forests 12(7): 897.

III **Xu X**, Englund O, Dimitriou I, Rosenqvist H, Liu G, Mola-Yudego B. Landscape metrics and land-use patterns of energy crops in the agricultural landscape. Manuscript.

Author's contribution

The author is responsible for the compilation of this thesis. For all the articles, the author was responsible for conceptualisation, formal analyses, visualisations, and drafting of the articles jointly with the co-authors. B. Mola-Yudego and X. Xu shared the first authorship in article II. Papers I and II are reprinted with kind permission from the concerned journals.

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ABBREVIATIONS AND DEFINITIONS

Abbreviations

CO_2	carbon dioxide
EC	European Commission
EEA	European Environment Agency
Eq	Equation
EU	European Union
LUC	Land-use change
NSCP	Number of Shape Characterising Points
Mha	million hectares
odt	oven dry ton
RCG	Reed canary grass
RED	Renewable Energy Directive
RR	Rectangularity Ratio
SCB	Swedish Official Statistics
SEK	Swedish krona
SI	Shape Index
Svebio	Swedish Bioenergy Association
TWh	Tera Watt hour
Energimyndigheten	Swedish Energy Agency
Jordbruksverket	Swedish Board of Agriculture
Regeringskansliet	Government Offices of Sweden

INTRODUCTION

Producing biomass for energy purposes

Lignocellulosic energy crops offer an alternative source of biomass for traditional and emerging bioeconomic uses (Brown et al. 2014). These are non-food crops often established on agricultural land for the production of biomass for energy and include fast-growing tree species in short rotations as well as perennial grasses (Dimitriou et al. 2018; Cronin et al. 2020). Historically, these plants have played an important role in the production of biomass for energy, as there are records concerning the use of coppice for the production of firewood since medieval times (Evans 1992). In Europe, their industrial use of energy traces back to the 1960s (Venendaal 1997). Concerning woody plants, willow (*Salix* sp.), poplar (*Populus* sp.) and eucalypt (*Eucalyptus* sp.) have been the most broadly planted, and among grasses, miscanthus (*Miscanthus* spp.) and reed canary grass (*Phalaris arundinacea* L.) (RCG) were among the most cultivated (Venendaal 1997).

In recent years, the role of energy crops as a solution for mitigating climate change, combined with the contribution from other renewable energy alternatives, have attracted attention. Lignocellulosic biomass production for energy purposes contributes to reducing net carbon dioxide (CO_2) emissions when compared to fossil fuel consumption (European Commission, EC 2016). In this sense, the European Union (EU) has set several goals related to the drastic reduction of greenhouse gas emissions, such as expanding the use of renewable energy (EC 2018) and the carbon-neutrality goal by 2050. The EU's effort to combat climate change and increase the share of renewable energy resulted in the Renewable Energy Directives (REDs). In the most recent EU RED, the renewable energy target has been increased to 40% by 2030 (EC 2021). Therefore, developing domestic bioenergy production, in alignment to other renewable energy alternatives, is perceived as an essential and urgent step to cope with the imminent needs. Arguably, the recent geopolitical developments affecting energy markets are not but accelerating this trend.

In addition, modern technologies enable biomass to be applied to different energy purposes, including generating electricity and heat, and producing vehicle fuels (Slade et al. 2014). Based on the origin of biomass, it can be transformed into i) biofuels which are directly burnt biomass for heating and power generation (e.g., wood pellets, wood chips, and lignocellulosic biomass residues), and ii) biofuels which are processed biomass in the form of bioethanol and biodiesel (Anderson and Fergusson 2006; Dragone et al. 2010). These modern technologies enable processing several sources of agricultural and forest biomass (as well as wastes, and residues) enlarging the uses of biomass for energy and thus the demand (Slade et al. 2014; Magazzino et al. 2021).

Planting lignocellulosic energy crops on agricultural land presents several advantages. For example, their management is less intensive than traditional agricultural crops, and requires fewer management practices (Rytter et al. 2011; Johansson and Hjelm 2012) and lower production costs (Rosenqvist et al. 2013). In fact, already over 3 million hectares (Mha) of cropland have been converted to bioenergy production in the EU (Gabrielle et al. 2014), and about 17–21 Mha of additional land are expected to be converted to energy crop cultivation in order to achieve the bioenergy goals of the EU policies (Don et al. 2012). At least 25 Mha of arable land are estimated to be available for energy crops by 2030 in the EU (Swedish Bioenergy Association, Svebio 2022) and it is forecasted that the increasing demand for biomass will result in a share of this available land to be effectively converted to energy crops before 2050 (Perpiña Castillo et al. 2015).

Domestic bioenergy production could nearly meet the national energy demand (EC 2019), particularly in Northern Europe. There, many countries have already shown a preference to develop biomass production for energy purposes, and present a large potential for perennial lignocellulosic energy crops (Stolarski et al. 2020). In that region, fast-growing tree species have been cultivated to a certain extent in Denmark, Latvia, Lithuania, Poland, and Sweden, and energy grasses in Germany and Finland (Stolarski et al. 2020).

Lignocellulosic energy crops in Sweden

Sweden is one of the leading countries in Europe concerning biomass share in the total energy production (Stolarski et al. 2020). Nearly 40% of Swedish energy use comes directly or indirectly from bioenergy, up to 140 TWh (Svebio 2020). To explain this success, three main factors have been proposed: the availability of raw biomass, a good tax system e.g., carbon tax on fossil fuels to encourage using biofuels (McCormick and Kåberger 2005), and the general use of district heating systems in the main urban areas (Parikka 2004; Amiandamhen et al. 2020).

Regarding energy crops, Sweden has established plantations of fast-growing tree species since the 1970s, being one of the pioneer countries in Europe (Helby et al. 2004), and several successful examples of using energy crops have been implemented (Wright 2006). This makes Sweden a suitable country to study questions related to the establishment of energy crops from different angles (Mola-Yudego 2010). At the same time, Svebio estimates that around 900 000 ha could be used for energy crops by 2050 (Andersson 2017), as they can be established not only on agricultural land but in surplus grassland, abandoned agricultural land, and degraded soil (Abreu et al. 2022).

The main fast-growing tree species in Sweden are willow and poplar (Helby et al. 2004). Willow is one of the most widely cultivated lignocellulosic energy crops in Europe (Rowe et al. 2013), and it presents high productivity despite the adverse climatic conditions in Sweden (Mola-Yudego 2010). In Sweden, about 14% of arable land is suitable for willow cultivation (Börjesson 2001; Ericsson et al. 2004) and over 10 new varieties have been registered by 2022 (SalixEnergi 2022). The first experimental plots for willow were established in the 1970s and the commercial cultivation started in the early 1980s (Mola-Yudego and González-Olabarria 2008) with financial support from the Swedish Government (Johansson and Karačić 2011). Willow cultivation can provide a maximum 25-year economic lifespan (Stolarski et al. 2019), and the rotation period is about 3-5 years (Aronsson et al. 2000). After harvesting, willow will usually be converted into wood chips for combustion (Helby et al. 2006).

Poplar has a high survival rate with considerable biomass production potential (Stanturf and van Oosten 2014; Nordborg et al. 2018). The rotation period of poplar is usually shorter than 20 years (Mc Carthy 2016). Poplar plantations have been established in the 1980s on set-aside agricultural land (Dimitriou and Mola-Yudego 2017). Although poplar cultivation was traditionally used for non-energetic uses, interest in bioenergy has increased in recent years (Nordborg et al. 2018). For instance, poplar presents several benefits, such as being more energy-efficient compared with willow (Nordborg et al. 2018).

Hybrid aspen with the parental species of European aspen (*P. tremula* L.) and American aspen (*tremuloides* Michx.), grows fast and straight, providing biomass in a short period

(Rytter and Stener 2005; Hytönen et al. 2020). The cultivation of hybrid aspen has also been used in the match (Mc Carthy 2016) and pulp industries (Ericsson and Nilsson 2006). More recently, it has been identified as a biomass alternative for energy use (Rytter and Stener 2005). Hybrid aspen has a rotation length of about 20-25 years (Rytter and Stener 2005), and commercial stands have been established since the 1990s (Mc Carthy and Rytter 2015).

Finally, perennial energy grasses are considered for bioenergy production because of their high yield and low water content (Ustak et al. 2019). Several grass systems have been applied for biomass production, such as switchgrass (*Panicum virgatum* L.), RCG, and mixed prairie plantings (Werling et al. 2014). Among these, RCG is more suitable in cold climatic areas (Larsson 2003), and it is a native species in Sweden (Venendaal et al. 1997). Studies on RCG for energy purposes started in 1981 (Venendaal et al. 1997), and a steady increase in cultivation started shortly after due to the adjustment of the Swedish agricultural policy in 1991 (Larsson 2006). RCG has been used in pellet production (Jasinskas et al. 2020) and biogas generation (Roj-Rojewski et al. 2019). It has been studied that the costs of RCG cultivation are lower than willow, which has already shown promising potential for commercial production in energy use (Venendaal et al. 1997). Other grasses may also be suitable for growing in Sweden’s climate for energy purposes, for instance, hemp (*Cannabis sativa* L.) (Andersson 2012; Prade et al. 2012). However, the cultivation has been limited, and the costs associated have been estimated to be higher, as it is not a perennial species (Andersson 2012).

Landscape diversity and land-use changes

The relatively large extent of energy crops and long period of experience in Sweden provides a basis for the study of the development of energy crops, particularly concerning their effects on the nearby agricultural landscape. Landscape can be defined as a spatial unit resulting from human practices and natural factors which has become more essential in spatial planning and management (Moss 2000; Vejre et al. 2007; Vallés-Planells et al. 2014; Englund et al. 2017). Visible and physical elements in the landscape, such as land uses, together with ecological function, economic contribution, social connection, and cultural-historical value provision bring in different levels of landscape homogeneity (Englund et al. 2017). Over the years, agricultural landscapes may be modified due to the introduction of energy crops. Studying the landscape surrounding the crops can provide information on land expansion, configuration, fragmentation, and diversity patterns (Dadashpoor et al. 2019; Wang and Wen 2021). In addition, studying energy crops in the context of their agricultural landscape can reveal the cultivation preferences for crop alternatives, such as between energy crops or between lignocellulosic energy crops and food crops (Ericsson et al. 2006; Vasile et al. 2016).

Suitable methods based on landscape metrics provide precise details from aspects related to land area, edge, shape, patch density, and neighbour areas. These metrics enable the quantification of land transition and can also be used for analysing landscape structures. The selection of the methods and indicators to describe regional landscape patterns should be done according to the main research focus, as there is a large pool of indicators and metrics (see an example from southern Finland by Oksanen (2013)). In this sense, previous studies have applied shape-based metrics for Swedish energy crops, such as using indicators or regularity in field shapes in willow (Nilsson et al. 2015) and energy grass (Nilsson and Rosenqvist 2018), since these metrics act as proxy indicators of more complex activities related to energy crops; for example, economic efficiency and management practices in individual fields.

Additionally, fields are in a landscape, where land availability is limited, and its establishment is subject to several constraints (Bentsen and Felby 2012). Whereas the growing need for biomass encourages the establishment of energy crops, it is at the same time influenced by multiple factors, such as risk aversion, traditional practices, and the competing demand of other agricultural crops, among others (Ericsson et al. 2013). For example, the establishment of heating plants can increase the motivation of farmers to expand energy crops in the area, leading to significant land-use changes (LUCs) in the agricultural land (Mola-Yudego and Pelkonen 2011), which can lead to reduced production of other agricultural crops. In some cases, LUC occurs in non-agricultural land, when forest lands are being replaced by energy crops (Börjesson and Tufvesson 2011). But in other cases, increments in agricultural prices or the use of marginal lands (see a definition of "marginal lands" for bioenergy cropping by Arshad et al. 2021) can lead to the abandonment of energy crops in the area (Dimitriou et al. 2011).

LUCs derived from lignocellulosic energy crop cultivation bring both negative and positive impacts (Langeveld et al. 2012). Regarding negative effects, the increasing demand for bioenergy from lignocellulosic energy crops can result in land-use pressure on agricultural land (Zscheischler et al. 2016), particularly when cultivating the crops on a large scale (Vepsäläinen 2010). On the other hand, LUCs of lignocellulosic energy crops can enhance local land-use diversity, leading to higher biodiversity clusters (Immerzeel et al. 2013). For instance, species richness is higher in willow or poplar plantations on agricultural land than in areas dominated by cereal or even in many forest lands (Berg 2002; Weih et al. 2003; Baum et al. 2009; Baum et al. 2012).

Knowing the spatial distribution of lignocellulosic energy crops and the land-use replacement patterns could facilitate the integration of biomass production systems with other land uses and provide an environmentally beneficial system to reduce other negative impacts (Englund et al. 2020a; Englund et al. 2020b). Besides, the analysis of LUC can provide references to environmental assessment, such as Life Cycle Assessment, providing a realistic status-quo scenario prior to the energy crops for effective comparisons (Jungk et al. 2002). Finally, assessing the spatial patterns of energy crops can also deliver economic assessments in the local agricultural markets and have policy implications for their sustainable development.

Aims of the study

The establishment of energy crops supposes changes in the local agricultural land use. At the same time, previous agricultural practices and land use are important references which have an effect on the farmers' decisions concerning energy crops. There is a need to define and characterise those areas where energy crops are located and to profile previous land uses and ongoing trends in LUCs. It is also important to identify relevant climatic and economic variables and estimate the interactions of energy crops with the existing agricultural landscape from different angles.

This thesis presents a spatial analysis of lignocellulosic energy crops in Sweden, using empirical data from commercial plantations, grasses, and agricultural crops. Different approaches are taken to assess their interactions. The research addresses the following aims, from the field level to larger spatial scales:

i) to assess the energy crops' fields regarding production, location and climatic profiles;

ii) to characterise and define the agricultural landscape surrounding energy crops;

iii) to study the overall LUCs derived from the establishment of energy crops in the country.

MATERIAL AND METHODS

Data sources

Data concerning willow plantations was collected from previous studies, with records during the period 1986-2004 (Mola-Yudego and Aronsson 2008), concerning location and field area. Data concerning willow, poplar, hybrid aspen, RCG, as well as other agricultural crops used for references was retrieved from the Swedish land register for the period 2001–2018 (Figure 1). This data is based on the Integrated Administration and Control System maintained by the Jordbruksverket (2019), and includes detailed records concerning land uses, locations and spatial features of agricultural fields presented as individual polygons (1:10 000). The information about cultivated crops is registered in a uniform land area, which is called a *block* in the dataset (see definition of *block* in Owen et al. 2016). Each *block* contains agricultural field details regarding locations, areas, and cultivated crops.

Additional land-use data was retrieved from the Copernicus land datasets, supported by the Copernicus Land Monitoring Service. The specific layers used were the CORINE Land Cover 2006 and 2018 (EEA 2006; EEA 2018). The CORINE datasets allowed for land use comparison between 2006 and 2018, and provided further information concerning non-agricultural land uses, such as forest lands or urban areas, not included in the land register. This part was especially used for landscape-level analysis around energy crops.

Historical monthly climatic data were retrieved from the WorldClim database (Fick and Hijmans 2017). This dataset contained a 1 km^2 spatial resolution with global records from the most recent available climate normal period (1960–1990) including minimum, maximum, and average values of the monthly temperature, precipitation, solar radiation, and other climatic information (Fick and Hijmans 2017).

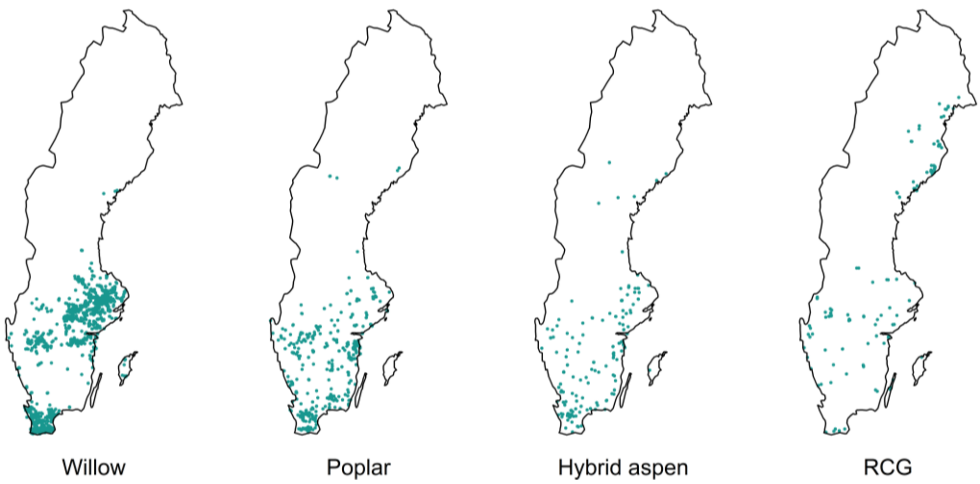

Figure 1. Locations of willow, poplar, hybrid aspen, and reed canary grass (RCG) in Sweden in 2018.

Yields of energy crops

Energy crops present a large variability in biomass yields because of the species and growing conditions (Gabrielle et al. 2014). The estimation of the yields was based on experimental plots and commercial plantations. The data included public sources and prior studies. The annual commercial yields of RCG were accessed from the Eurostat database (Eurostat 2021) for Sweden and LUKE (2021) for Finland. In addition, the RCG yields from experimental plots were retrieved from Landström et al. (1996), Lindvall (2012), Lindvall et al. (2012), Lindvall et al. (2015), and Nilsson et al. (2015), including 201 plots. Willow yields were retrieved from Mola-Yudego et al. (2015), including 290 plots in total. Poplar and hybrid aspen yields were retrieved from Dimitriou and Mola-Yudego (2017) including 58 plots. The average standard yields of barley from 2003 to 2017 were accessed from the Swedish Official Statistics (SCB 2017) to provide a reference for land productivity where energy crops were mostly cultivated. Besides this, the prices of wheat, barley, and oats were accessed from FAOSTAT (2019).

Analysis of spatial features

The thesis studied the total cultivated area, average field size, and core cultivation area for energy crops. Identifying the core area of energy crop distributions was based on kernel density estimation (Worton 1989). Kernel density estimation is a way to create a continuous density surface for a service area (Lewis 2015). The algorithms of this research were derived from the study of Mola-Yudego and González-Olabarria (2010). This research transformed the discrete distribution of the plantation locations (coordinates) into continuous areas. The core areas of cultivated energy crops were identified by two fixed contour levels, the smallest possible area and almost the total area. The percentages indicated the number of plantations inside the kernel boundaries. For instance, 50% meant that it contained 50% of the studied plantations and 90% represented that it involved 90% of the plantations. These two density levels presented the smallest concentration share of total cultivated areas and nearly all of the planting areas for willow, poplar, hybrid aspen, and RCG. Besides this, cereal prices were used as an economic indicator to reveal the agricultural market’s effect on energy crop alternatives.

Agro-climatic profiles

Climatic indices regarding monthly temperature and precipitation of the agricultural lands where crops are growing were analysed in the thesis to depict agro-climatic profiles for the biomass production systems. Besides this, an estimation of the land productivity range was conducted to describe the average agricultural productivity for each studied crop. The annual average barley yield was used as an indicator for calculating land productivity over the research years since it is a typical cereal in Sweden, widely cultivated in the studied areas. The barley yields were collected at the district level, and the analysis of land productivity only included field numbers with over 100 *blocks* to get a representative estimation (SCB 2017).

Surrounding landscape

This part of the analysis focused on the field and landscape levels. At field level, the analysis selected common and effective landscape metrics to describe the geometrical complexity of field borders and shapes for energy crop planting in a concise way. Landscape metrics have been classified at three levels, patch, class, and landscape level for different analysis purposes (Khan et al. 2021). This thesis uses landscape metrics at the patch level for individual plantations of fast-growing tree species, RCG land, and agricultural fields cultivated for wheat and barley. At the landscape level, the analysis focused on the surrounding land-use identification. The overall landscape analysis used 2006 and 2018 as two reference years, representing the initial and last land-use situation. Data from Jordbruksverket was used for the field and landscape level, and data from CORINE Land Cover 2006 and 2018 was for the landscape level.

At the field level, landscape metrics related to land shape diversity and land aggregation were chosen to analyse the land complexity of energy crops from the geometrical perspective (McGarigal et al. 2012; Lausch and Herzog 2002). These metrics are the Number of Shape Characterising Points (NSCP), Shape Index (SI), and Rectangularity Ratio (RR) (Eq1, Eq2, Eq3). The NSCP, SI, and RR were applied in previous studies related to species richness (Moser et al. 2002), landscape ecology (Forman and Godron 1986; McGarigal et al. 2012), and land management profits (Oksanen 2013). In this research, the NSCP, SI, and RR explain the edge and shape diversity of the lands. Among these, the NSCP was to explain the boundary's complexity; the larger the values of NSCP per ha, the more land borders. The SI was to analyse the shape complex. When the SI value is close to 1, the shape is close to a square; when the value is smaller, the land shape is more random. The RR was based on the minimum bounding area. When the RR value is close to 100%, the land is close to a rectangle; when the value is smaller, the land shape is more random. Software and analysing tools were developed to calculate the values of these metrics using digitised materials. For instance, using raster files in the Fragstats software enables calculating the metrics at three levels: patch, class, and landscape (McGarigal et al. 2012). The R package landscapemetrics (Hesselbarth et al. 2019) and the ArcGIS tool PolyFrag (MacLean and Congalton 2013) also provide similar algorithms to compute the metrics' values. In this research, the overall data were analysed through ArcGIS v10.5 (ESRI 2016) and R v4.0.4 (R core team 2020).

$$NSCP_i = N_i \qquad \text{(Eq1)}$$

$$SI_i = \frac{0.25 * Perimeter_i}{\sqrt{Area_i}} \qquad \text{(Eq2)}$$

$$RR_i = \frac{Area_i}{min.Area_i} \qquad \text{(Eq3)}$$

Where i is the ID of the plantation (*block* ID); N is the number of vertices of the plantation (e.g., triangle: NSCP=3-gon; rectangle: NSCP=4-gon; pentagon: NSCP=5-gon); $Perimeter$ is the length of the perimeter of the plantation; $Area$ is the area of the plantation; and $min.Area$ is the minimum bounding area in a rectangle (algorithm sources: McGarigal et al. 2012; Moser et al. 2002; Lombardo 2014).

At the landscape level, the surrounding land-use identification of energy crop plantations and energy grassland were also analysed to determine the surrounding changes over the years. The land use in this part focused not only on the energy crops on agricultural land (including grassland) but also on forests, water bodies, artificial land (e.g., urban areas, industrial areas, and transport infrastructures), and wetlands. The research areas are the surrounding buffers of the energy crops, with a radius of 500 m, 1000 m, 2000 m, and 5000 m, respectively. First, the dominant types of land use were analysed to know which energy crops are mainly located in which type of landscape. Second, the dominant land use proportions were analysed to know which proportions are more common.

Land-use changes

This part aimed to analyse land-use replacement patterns of energy crops during the research period. The replacement patterns include which types of land use replaced the energy crop fields and which types of land use were replaced by the energy crop fields. Besides land use for energy crops, other types of land use were grouped into three categories in order to classify the LUC patterns: cereal land, meadow, and fallow.

The land-use replacement was analysed annually during the research period and specific field locations for crops were studied. Some *blocks* had more than one crop cultivated in the registered uniform land area, and this research only considered the major cultivation in the *block* according to the land size.

RESULTS

Yield performance

Estimated yields from experimental plots of RCG, willow, and poplar/hybrid aspen had extensive ranges (Figure 2). RCG and poplar/hybrid aspen showed their largest yields of nearly 15 odt ha^{-1} year^{-1}; the maximum yield of willow was larger than RCG and poplar/hybrid aspen, over 20 odt ha^{-1} year^{-1}. Willow and poplar/hybrid aspen also had a few plantations with low yields, around 4 odt ha^{-1} year^{-1}. Despite this, the annual yields of RCG were mostly between 7–9 odt ha^{-1} year^{-1}, which was similar to the average yields of willow and poplar/hybrid aspen. This average yield of RCG from experimental plots (estimated as 6 odt ha^{-1} year^{-1}) had a large chance to overestimate the commercial yields plots (estimated as 3.5 odt ha^{-1} year^{-1}), particularly when compared with the official records in Finland at 3.1 odt ha^{-1} year^{-1}. Willow had a similar overestimation referring to its commercial yields.

Location patterns

Plantations of fast-growing tree species expanded from eastern and central Sweden to southern areas (Figure 3). Poplar plantations were mainly located in the east and the south, with a few changes during the studied years. Hybrid aspen plantations were distributed more northwards than willow plantations and closer to poplar plantations. RCG lands were distributed more widely in the country than others, which could be found in the northeast.

The total agricultural area cultivated with plantations of fast-growing tree species showed a decreasing trend throughout the years, meanwhile, cereal prices were rising. The area of the willow plantation dropped from 14 000 ha to 7785 ha from 2001 to 2017. However, poplar and hybrid aspen increased slightly, covering 1738 ha and 676 ha in 2017, respectively. The total area of RCG land rapidly increased from 675 ha to 800 ha from 2005 to 2009, then declined to 550 ha in 2013.

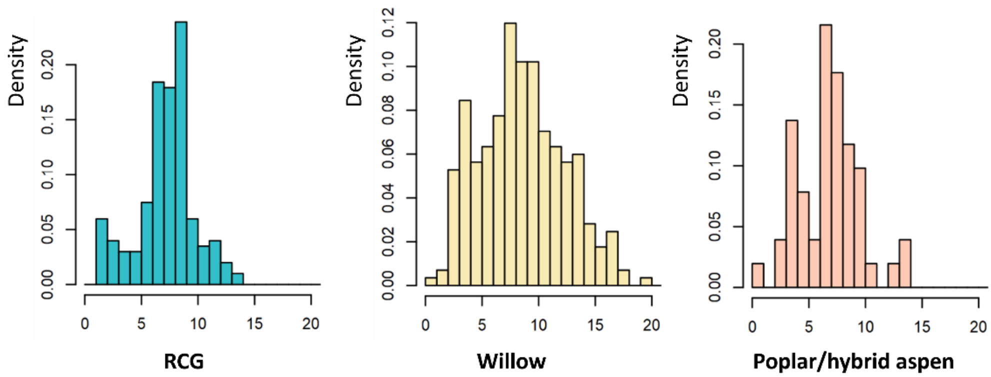

Figure 2. Annual yields for reed canary grass (RCG), willow, and poplar/hybrid aspen. The x-axis is the estimated distribution of yields (odt ha^{-1} $year^{-1}$), and the y-axis is the density of the yields.

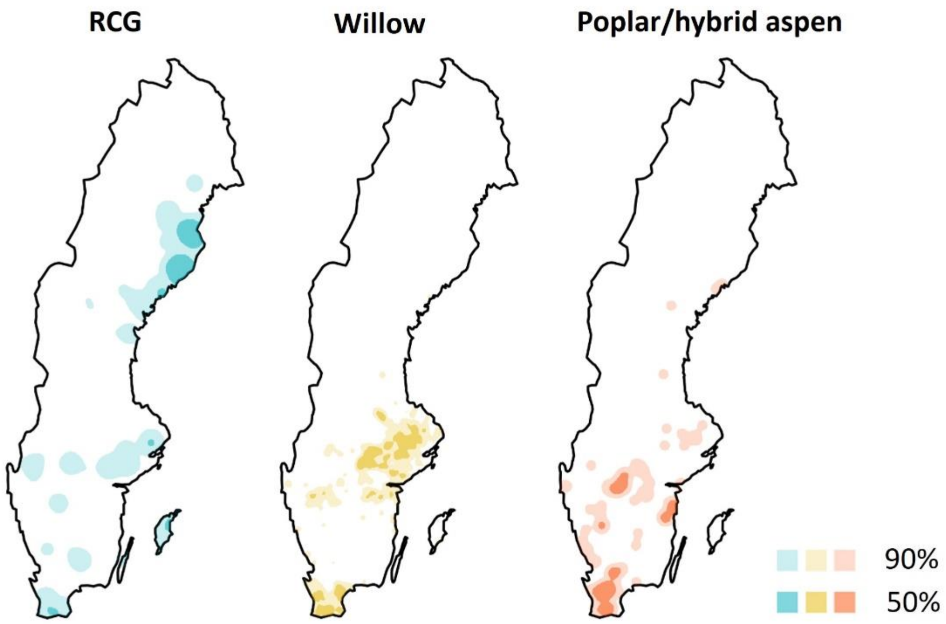

Figure 3. Locations of the main areas of reed canary grass (RCG), willow, poplar/hybrid aspen (1986-2018). Shade colours represent the areas including 90% (fair) and 50% (dark) of the planted area.

In recent years, the average land size for energy crops was about 4 ha. For the individual plantation area of willow, smaller size (less than 1 ha) was more prevalent than larger size (over 10 ha). Poplar plantations had a similar trend to willow in recent years. The average size of poplar plantations reduced from 2.5 ha to around 2 ha, and 50% of the plantations were less than 1 ha. The average plantation size of hybrid aspen was around 2.2 ha and recently increased to 3 ha. Sizes of RCG land presented a similar trend to the plantations. The RCG was more common in smaller sizes (around 2 ha) than in larger sizes (over 5 ha).

Climatic and land productivity profiles

The climatic profiles presented the growing conditions of willow, poplar/hybrid aspen, and RCG. In general, RCG was cultivated in less favourable climatic areas than the other studied crops (Figure 4). Concerning the mean annual temperature, RCG was cultivated in colder areas than other energy crops, with annual temperatures from −0.4°C to 7.6 °C. The annual temperature range for willow was 2.8 °C to 10.0 °C and for poplar/hybrid aspen was 3.2 °C to 10.1 °C. RCG fields had lower average annual precipitation, at around 582 mm. For willow and poplar, the precipitation was about 606 mm and 655 mm, respectively.

The studied energy crops were cultivated in different land productivity areas. The plantations were mainly established on the more productive lands, estimated with the standard barley yield, was 4500 kg ha^{-1} yr^{-1}, 4100 kg ha^{-1} yr^{-1} and 3800 kg ha^{-1} yr^{-1} for willow, poplar and hybrid aspen, respectively. RCG was planted mainly on lands with lower productivity, which was lower than 2500 kg ha^{-1} yr^{-1}.

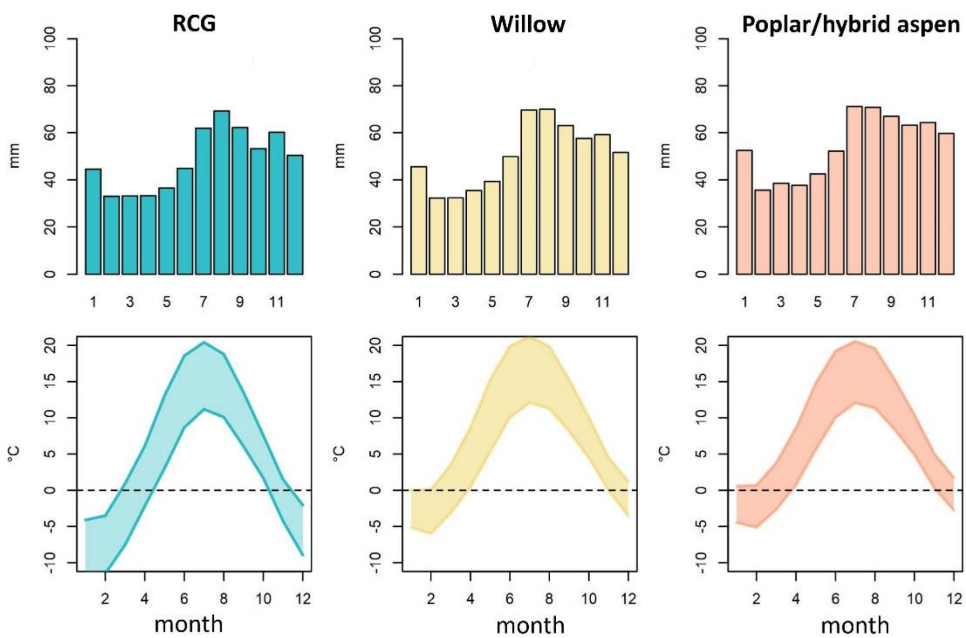

Figure 4. Agro-climatic profiles of reed canary grass (RCG) fields compared with plantations of fast-growing tree species.

Diversity in the surrounding landscape

In the 2006 dataset, 1560 fields with energy crops and 58 246 fields with cereal crops were analysed; in the 2018 dataset, 3416 fields with energy crops and 131 354 fields with cereal crops were analysed, which included winter wheat, spring wheat, winter barley, and spring barley. At the field level, the NSCP per ha, SI, and RR of energy crops showed a distinct spatial pattern, especially in willow (Figure 5). In general, the geometric edges of the fields showed a decreasing trend for both energy crops and cereals between 2006 and 2018. The values of the NSCP per ha of energy crops decreased between 2006 and 2018, although they were higher than the cereals. Concerning the SI, a high proportion of regular shapes for energy crop lands were observed, which concentrated around a value of 1, particularly for willow, with around 30% plantations. The RR showed that energy crops were mainly distributed between 63% to 70%, which was a high ratio of the minimum bounding area in a rectangular shape.

The surrounding landscape of energy crops was identified by different buffer scales with radius 500 m, 1000 m, 2000 m, and 5000 m, respectively (Figure 6). Willow had more stable adjacent land uses between 2006 and 2018 compared with other crops. In 2006, willow and poplar were mainly dedicated to agricultural land (around 65%) regarding the four buffer scales; hybrid aspen and RCG were mainly located in the forest-dominated landscape. The share of agricultural land around energy crops decreased within the buffers in 2018 except for willow. Agricultural areas around poplar, hybrid aspen, and RCG dropped to around 40%, particularly on the larger buffer scales (2000 m and 5000 m). In 2018, the forest share had increased, particularly around poplar, hybrid aspen, and RCG; water bodies, artificial areas, and wetlands generally rose around poplar and RCG, although the share was still small.

When the buffer radius increased to a larger scale, the distribution trends of land uses were more evident. A clear tendency of agricultural areas was observed, particularly when the radius reached 5000 m (Figure 7). The agricultural land percentage in the buffer area of a willow plantation mainly concentrated around 40% in 2006, then reduced to 35% in 2018 when the buffer radii were 2000 m and 5000 m. Poplar had more plantations with about 70–80% of the agricultural land share in 2006 but rapidly dropped to 20% in 2018. Similar share distributions were observed for hybrid aspen and RCG in 2018. However, hybrid aspen and RCG did not present a clear trend for the agricultural land percentage in 2006.

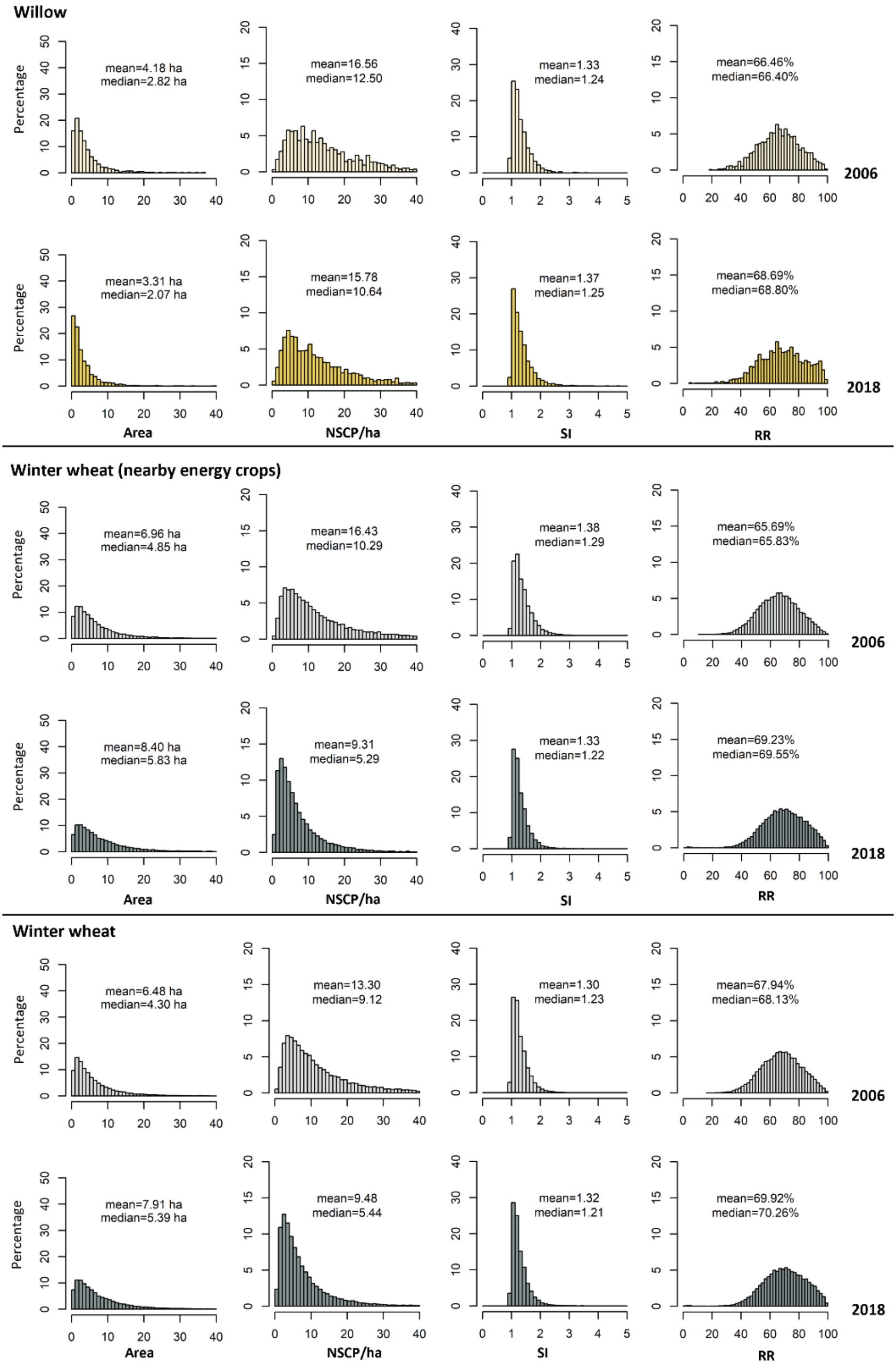

Figure 5. Distribution of plantation area, Number of Shape Characterising Points (NSCP) per ha, Shape Index (SI), Rectangularity Ratio (RR) of willow and winter wheat in 2006 and 2018. The x-axis is the metric value, and the y-axis is the proportion of the value.

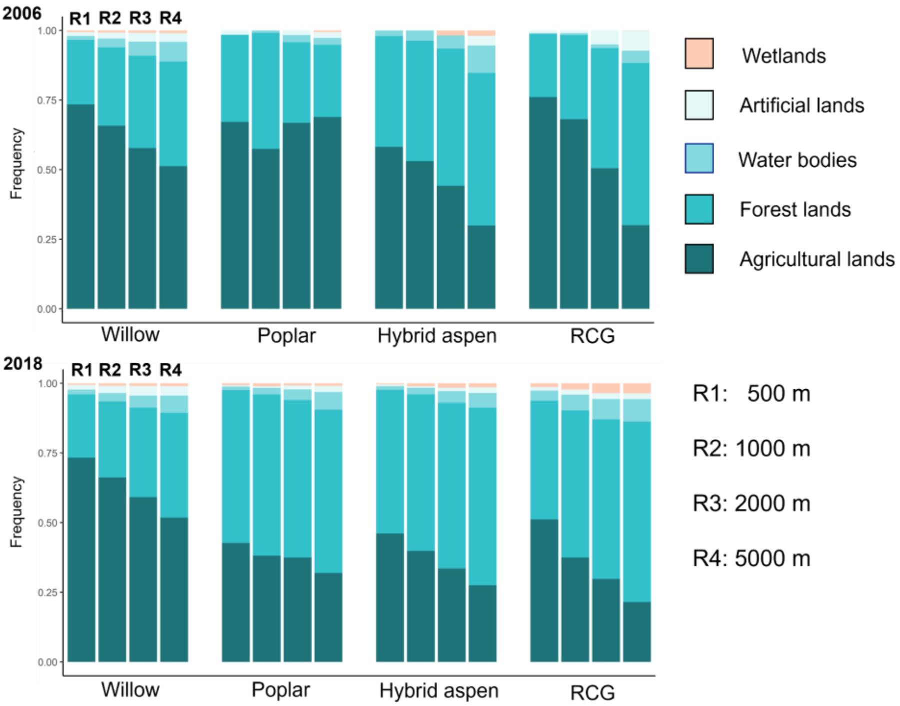

Figure 6. Surrounding land-use (Agricultural lands, Forest lands, Water bodies, Artificial lands, and Wetlands) patterns in mean proportions from energy crop lands in 2006 and 2018. Buffer areas are with a radius of 500 m (R1), 1000 m (R2), 2000 m (R3), and 5000 m (R4), respectively.

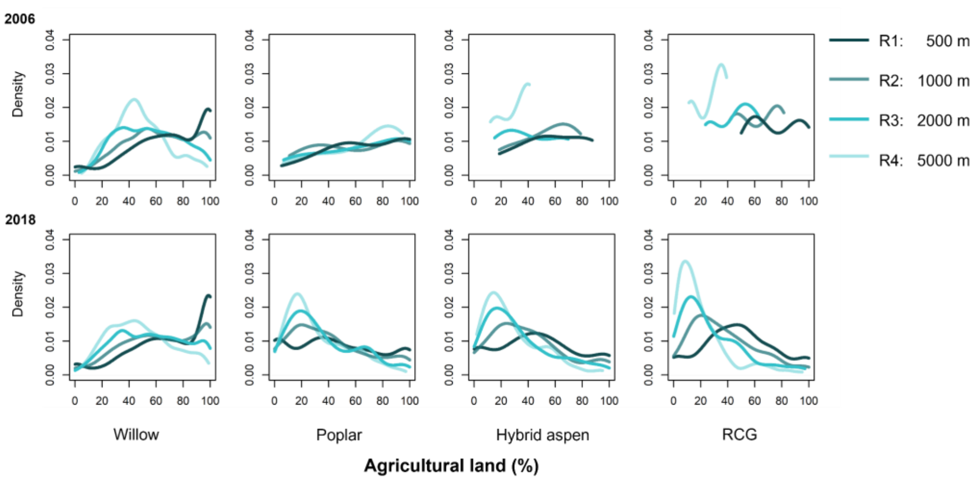

Figure 7. Agricultural land shares in the buffer areas (radius: 500 m, 1000 m, 2000 m, and 5000 m) of willow, poplar, hybrid aspen, and reed canary grass (RCG).

Land-use transition

The land use of the energy crops changed during the research period and several new plantations on agricultural land have been established recently. For instance, over 90% of current poplar and hybrid aspen plantations were newly established compared with the land use in 2001. In the case of willow, around 50% of the current plantations were newly established when compared with the situation in 2001.

Distinct LUC patterns were observed in willow and RCG; however, poplar and hybrid aspen did not represent similar dynamics in LUCs. In the case of willow plantations, the newly established plantations were mainly on former cereal lands. The replaced lands were mainly for cultivating spring barley, winter wheat, and oats (Figure 8). This trend changed after 2007, and willow plantations were progressively established in meadow and fallow lands. Similar replacement patterns were observed in RCG lands, which were mainly established on former cereal lands and meadowlands. To a lesser extent, RCG was also replacing fallow lands after 2005.

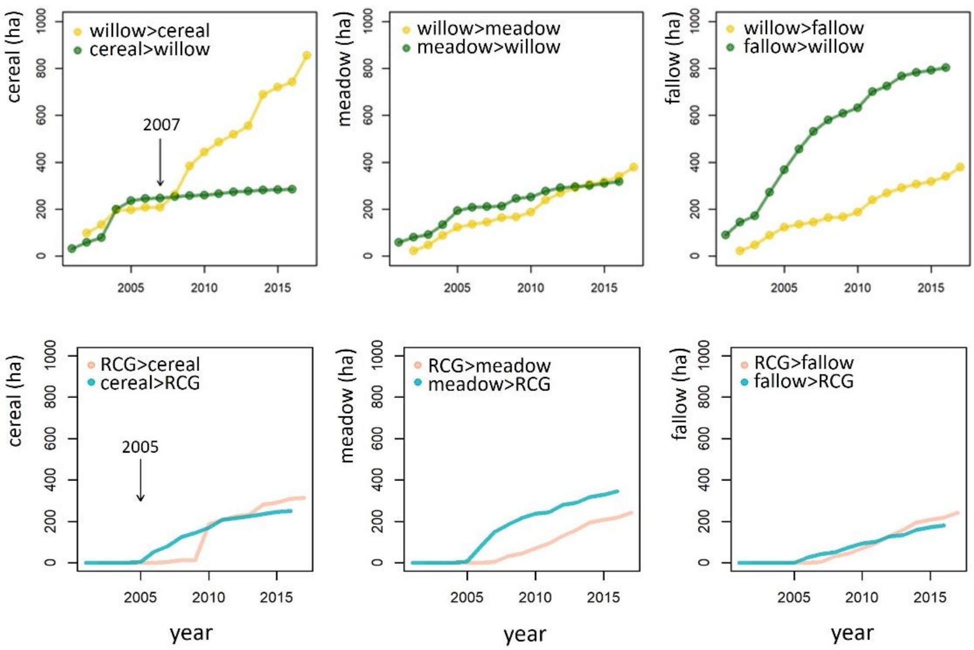

Figure 8. Land-use replacement of willow and reed canary grass (RCG). > refers to the land-use transition (e.g., willow>cereal, willow plantation replaced by cereal lands).

DISCUSSION

The establishment of lignocellulosic biomass production on agricultural land could reflect interactions between natural conditions and human agricultural practices, providing references for future land-use management to stakeholders. The focus of this thesis was to address both the characteristics of energy crops, including yield performance, overall agro-climatic profiles, and location factors, as well as the land-use patterns resulting in the agricultural landscape where energy crops are grown.

The cultivation of energy crops is a rather new practice in the European agricultural landscape, and Sweden is an interesting case for studying long-term dynamics due to its long experience in the cultivation of fast-growing woody and herbaceous plants. It provides the necessary land data, in the land registry as well as from the European CORINE land-cover maps, which conform two data both reliable and extensive sources for analysis. There are, however, limitations in the use of these data sources: the Swedish land registry used in the study does not have information on other land uses other than agriculture, earlier records of the land register have a lack of records concerning cultivated crops, the CORINE land-cover presents different spatial resolution and land-use categories, and there is limited information, all together, concerning the management uses and yield levels of the plots at such a detail level. Other sources, such as the Swedish national land-cover data, was only available for 2018, which made the dataset unsuitable for temporal comparisons. Despite these limitations, the timeframe, number of fields and level of spatial detail included in the study was quantitatively large, providing a solid basis for the analysis presented.

Energy crops fields

The spatial analysis combined multiple approaches to evaluate the biomass production system from the land-use aspect. The patterns and dynamics of these features reflect somehow the farmers' decision-making on the adoption and management of biomass plantations. The average size of willow plantations was 3.7 ha during the studied period, which differs from some other studies. Rosenqvist et al. (2000) estimated the average size of willow farm was 11.5 ha, with most of the plantations being larger than 10 ha; this disagreement might be because of the different research period, as the study by Rosenqvist et al. (2000) focused on a single year (studying in 1995), as well as the definitions of farm versus field used. However, beyond the individual size of the energy crop fields, there were obvious trends towards smaller fields, which may reflect important changes in plantation management. Previous research demonstrated that smaller plantations presented higher yields (discussed by Mola-Yudego et al. 2015), and this trend was parallel to the reduction of planting subsidies. A possible explanation could be that, because of the subsidy schemes, farmers aimed to have larger fields on low-productive land (Helby et al. 2004; Mola-Yudego and Aronsson 2008). In this line, the reduction of field size could indicate overall management intensification and productivity-oriented agriculture, as it would agree with the overall yield trends observed in the country (Mola-Yudego 2011). The reasons might be that farmers also cultivated energy crops on marginal lands, such as surplus lands (Miyake et al. 2012). However, this could be disputed as it could also mean farmers are no longer interested in investing large land areas, using only small fields or spare land. In either case, the results indicate changes in the profile and goals of energy crop farmers, confirmed in previous studies (Roos et al. 2000; Rosenqvist et al. 2000; Lindegaard et al. 2016).

The thesis also analysed the locations where energy crops were established, and the main trends linked to this. The overall land quality was established using cereal yield as a proxy, assuming high-yield areas reflect higher quality land and more intensive farming. This is a simple way to define the agro-climatic conditions of energy crops (Mola-Yudego and Aronsson 2008), socio-economic situations, and local policy implementations (Mola-Yudego 2010). All indicators suggested that wiilow and hybrid aspen in Sweden are moving towards more productive areas, which was also reflected in the results concerning the shape complexity of energy crops, presenting more regular shapes along time, suggesting a trend towards more cost-efficient management (Nilsson and Rosenqvist 2018), in line with the previous conclusions, and converging to a certain extent, to other agricultural crops features.

At field level, regular land edges and shapes could reduce input costs, maximise the economic benefits, and increase biomass yields. Spatially coherent field shapes are more efficient from the management point of view as the regular shape of the plantation could save machinery time and enhance machinery performance when harvesting (Nilsson et al. 2015). By studying energy crop cultivation on marginal lands in Sweden, Nilsson and Rosenqvist (2018) revealed that irregular plantation shapes could lead to lower economic profits. In general, the results showed that energy crop lands have started to become less complex in their borders and shapes, which was in line with the Swedish agricultural policies on restructuring farms resulting in more efficient cultivation (Marquardt et al. 2022; Griffel et al. 2020). It can also be an effect that willow farmers who gain more experience have realised that a way to reduce management costs from planting or harvesting is to have long rectangular fields.

Compared with cereal lands, energy crops had more irregular fields presented by larger variances in their NSCP values than cereals, which might be because energy crops have large differences in their areas (Moser et al. 2002). In the case of the SI and RR, greater values indicated lower machinery operation efficiency (Nilsson et al. 2015). From this perspective, perimeter-based financial support was suggested to be applied by Nilsson and Rosenqvist (2021) in order to compensate for the difficulties when harvesting biomass, especially for small areas.

The different core locations of the four crops analysed, ranging from north to south, did not significantly affect the biomass yields. Willow and poplar plantations concentrated more on higher productivity in southern Sweden, particularly in recent years (see land productivity in Sweden by Mola-Yudego 2011) whereas RCG was more widely cultivated in different areas of Sweden, particularly in northern areas where willow is not suitable for growing (Andersson 2012). Despite the different plantation locations and varied climatic profiles of the growing areas, the four crops were similar in terms of yield levels. However, it must be noted that the research also had overestimations in the yields from the experimental plots. These overestimations could result from optimal management of the plots, the edge effect, the harvesting ages of the crops, and experimental designs (see a yield divergence analysis in Mola-Yudego et al. 2015).

Energy crops expansion

Several factors impact farmers' decision-making regarding biomass production (Convery et al. 2012). Among the factors, financial support from the government can help to compensate for the cost and encourage farmers to participate in the production. Biomass production requires financial investment in plantation management, transportation, and storage. The results showed that the studied biomass production systems were sensitive to policy incentives. A case study in the UK also agreed that financial support could help to engage farmers in the medium-term biomass production of energy crops (Convery et al. 2012). The support in Sweden has been implemented in several energy production fields, such as combined heat and power, district heating, and research projects (Mahapatra et al. 2007). Sweden had the first energy programme to support biomass and other renewable energies in 1975 (Ericsson et al. 2004). Since then, financial support has also been applied for the production facility investment and pilot project implementation related to electricity production from biofuels (Hillring 1998). Over the years, the Swedish government has applied different tax exemptions to the different types of biofuels to encourage their consumption (Amiandamhen et al. 2020). Besides this, introducing a CO_2 tax has helped the prices of biofuels to be more competitive with fossil fuels (Hillring 1998; Mahapatra et al. 2007).

In the results, a clear increasing trend was observed concerning the total area of willow plantations after planting subsidies were introduced. Farmers received subsidies for energy crops established in the early 1990s to encourage cultivation (Hadders and Olssen 1996), which was 10 000 SEK ha^{-1} for a new willow plantation (Helby et al. 2006). During this period, the number of farmers growing willow increased around 70% (Mola-Yudego and Pelkonen 2008). However, after 1996 subsidies were reduced to 3300 SEK ha^{-1}, and the expansion of willow plantations started to slow down (Helby et al. 2006; Mola-Yudego and González-Olabarria 2010, Dimitriou et al. 2011). During the late 1990s, subsidies were increased again, and so did the area planted with willow, although at lower levels than in the 1990s. In 2007, another turning point was identified, as cereal prices peaked. Notwithstanding, the willow area was larger than poplar and hybrid aspen. This situation indicated willow cultivation was more resilient to changes in the policy framework than other energy crops, and a share of farmers demonstrated long-term interest in willow cultivation, due to a higher net income and yield in relation to management and investment, compared to other energy crops (Paulrud and Laitila 2010). The differing trend of poplar and hybrid aspen during this period is explained because they are often used for other purposes besides energy, such as the pulp industry (Christersson 2008), and therefore react to other economic factors.

While nowadays biomass production mainly relies on woody crops, herbaceous crops also provide a complementary option for biomass production as solid fuels or for generating biogas according to previous studies (Heinsoo et al. 2011; Melts et al. 2013). A series of policies encouraged the development of RCG: the early expansion of RCG was a result of financial support to replace food crops with non-food crops in the 1990s (Larsson 2006). But the lack of an established energy market for grass combustion precluded further development of the sector (Venendaal et al. 1997). Another main reason for not reaching the goals in RCG cultivation was the early disruption of support policies (Finell 2003; Olsson et al. 2008). For instance, the EU removed the requirement for farmers to set aside land for industrial crops (non-food crops) in 2009 (Official Journal of the European Union 2008), and the results showed that RCG areas started to reduce in the same year. This was confirmed partially in Finland as well, since the total land area dedicated to RCG was also reduced due to drastic changes in the policy framework and support schemes (LUKE 2021). The decreasing effects in the land area indicated that RCG cultivation was very sensitive to energy policy, in relative terms, more than short-rotation plantations.

Besides the effects of energy policy, the agricultural market and the farmers' cultivation experience also play important roles in biomass production. A study by Mola-Yudego and González-Olabarria (2010) showed that establishing successful willow plantations is associated with local energy demand and market development. Concerning the fuel market in Sweden, the low price of wood chips would reduce the motivation of farmers towards willow growing (Helby et al. 2006). Besides this, the personal cultivation experience with different plants affects farmers' attitudes towards cultivating energy crops (Roos et al. 2000). A study in Sweden showed that landowners with large forests (over 25 ha) had a higher chance of planting willow, while grassland owners had a negative attitude towards the cultivation (Roos et al. 2000), although the results indicate that this profile may have been substantially different in recent years. A survey in Sweden (Paulrud and Laitila 2010) indicated that the planting characteristics relating to the rotation length of the crops, machinery requirements in the fields, and surrounding landscape impact could also influence farmers' decisions on crop adoption.

Energy crops in the landscape

At landscape level, energy crops can increase the surrounding landscape diversity (Berndes et al. 2008; Rakovic et al. 2020). Furthermore, spatial heterogeneity could contribute to more sustainable agricultural systems (Dale et al. 2013). The results show that energy crops mainly replaced agricultural land use; in particular, willow and RCG replaced cereal crops primarily, and to a lesser extent, meadows or fallow land, and create more diverse landscape units in areas previously dominated by cereal, which has an overall positive effect on biodiversity as well as on multiple ecosystem services.

Linking LUC due to energy crops with ecosystem services and environmental issues has been discussed in many studies (Metzger et al. 2006), but the capacity of these ecosystem services in the agricultural landscape is influenced by energy crop selection, land location and its nearby habitat, and local landscape (Werling et al. 2014). The generally longer rotation period of energy crops, especially plantations in cereal-dominated landscapes, contributes to higher diversity, compared with annual crops (Baum et al. 2012). In Sweden, a case study showed that willow on fallow land has a large positive effect on climate change mitigation (Hammar et al. 2017); in Estonia, an experimental study showed that planting RCG on abandoned peat extraction areas could significantly reduce greenhouse gas emissions (Shurpali et al. 2010; Mander et al. 2012; Järveoja et al. 2013). The results also indicated that several other land uses appeared in the landscape, which might link to the management of plantations and its association to phytoremediation practices (locating crops nearby lakes) or to facilitate transportation (locating crops nearby power plants and urban centres). Likely, more complex environmental benefits could be identified when exploring the effects of energy crops in the landscape context.

The wide concept of LUC not only refers to energy crops growing on other former land uses but also refers to changes in land management, such as harvesting or rotations (Englund et al. 2020b). A study by Asbjornsen et al. (2014) proposed that the strategic integration of perennial vegetation in the agricultural landscape can enhance ecosystem services and Englund et al. (2020a) also indicated that perennial grass and fast-growing tree species could be used for purposes such as pest control, habitat provision, and erosion control. Spartz et al. (2015) proved that farmers were more concerned about environmental issues than having high economic profits when producing energy crops, which could be a basis for better landscape planning of biomass production systems. In the future, planning energy crop cultivation could consider how to increase the capacity for ecosystem services in agricultural and nearby landscapes as a whole.

Future perspectives

The current geopolitical developments and energy shortages could alter the availability, demand, and price of both agricultural products (for an increasing demand of food) as well as energy crops (for an increasing demand of energy), leading to potential conflicts in the agricultural sector. This research indicated that biomass production is strongly linked to agricultural markets. Domestic cereal production is essential, and the increasing prices of cereals might lead to more land areas being used for cereal cultivation. Based on this, future analysis of land-use planning between lignocellulosic energy crops for energy purposes and food production crops should be discussed in detail, analysing the strategic deployment of energy crops in order to make it compatible with other agricultural produce.

Uncertainty in the current Swedish energy market has brought several issues, such as tightening energy resource supply (e.g., natural gas, coal, and oil) and increasing electricity prices (Energimyndigheten 2022). Therefore, future analysis concerning energy sources from lignocellulosic biomass at the national and regional levels should be addressed to help to meet the self-sufficiency target in energy supply. Compared with other renewable energy alternatives (e.g., wind or hydro energy), establishing biomass plantations has the strengths of being cost- and time-saving when preparing the land and other facilities, so it could be interesting to continue analysis towards cost-efficient perspectives.

Analysing the land-use distribution of energy crops and their spatial interactions with the surrounding landscape is complex, requiring research input into large-scale commercial production for energy use. Plantations for fast-growing tree species and energy grasses might contribute differently to their surrounding landscape structures, which should be assessed in future studies. For instance, details could be analysed concerning species richness and biological homogenisation in different dominated landscapes (Immerzeel et al. 2013). Yield variability should also be linked with landscape diversity in future research, in order to give a prediction for biomass production system design.

According to the national goal, Sweden aims to achieve carbon neutrality by 2045 (Regeringskansliet 2017). Involving environmental targets in policies which support biomass production could provide solutions to climate change and other environmental issues. The use of multifunctional biomass production system could be a solution in this direction (Englund et al. 2020b). Co-benefits from biomass production could be created if management schemes are designed properly, although the current share from agricultural land is still small (the Swedish annual biomass production for energy purposes was around 2.5 to 3 TWh, Svebio 2020). For instance, about 20 sites have used landfill leachate in willow irrigation in Sweden, and wastewater treatment through establishing plantations of fast-growing trees at Enköping has been successful (Zalesny et al. 2019), which would be an important line for further research.

CONCLUSIONS

This thesis presented research on land-use patterns of energy crops, regarding core locations, LUCs over the years, and the surrounding agricultural landscape in Sweden from the field level to larger spatial scales. The research indicated that the total cultivation area of the energy crops decreased during the research period, particularly in willow plantations and RCG lands. This situation was compensated by a slight increase in poplar and hybrid aspen plantations, although the current shares are still small. At field level, the smaller size of plantations of fast-growing tree species and RCG lands are prevalent. Concerning the locations, new willow plantations were mainly established in the southern region with more productive land; poplar plantations were mainly established on less-productive land, often with hybrid aspen nearby. RCG lands were more widely located across the country compared with fast-growing tree species.

Despite RCG being located in less favourable climatic areas with colder temperatures, less precipitation, and less-productive land compared with the plantations of fast-growing tree species, the biomass yields of RCG had a similar range to the fast-growing tree species. The compensatory geographical locations enable RCG to offer an alternative for producing biomass in harsh climatic regions.

The energy crops generally showed a distinct spatial structure in the agricultural landscape. Willow plantations were mainly located in the agricultural-dominated landscape; poplar, hybrid aspen and RCG were mainly in the forestry-dominated landscape, particularly in 2018. This diversity of crop locations would be expected to contribute to the existing land-use patterns with essential effects on different ecosystem services. The borders and shapes of the fields became more regular, indicating cost-efficient agricultural practices and land planning.

LUCs occurred derived from cultivating energy crops, partially replacing cereal, meadow and fallow lands. Willow plantations were mainly established on former cereal lands, replacing spring barley and winter wheat. This LUC pattern was not presented in poplar and hybrid aspen plantations. RCG lands were mainly established on the former meadow and cereal lands; more RCG was replaced by cereals after 2009.

Biomass production expansion showed sensitivity to agricultural policies and market prices, which could influence spatial patterns. Therefore, future biomass production system planning should take the policy impact and agricultural market into consideration. The overall thesis could be the basis for future discussion on the spatial distribution and structure of energy crops grown in the agricultural landscape. The research findings could also be translated into the planning of biomass production systems and relevant policy-making in Northern Europe or elsewhere.

REFERENCES

Abreu M, Silva L, Ribeiro B, Ferreira A, Alves L, Paixão SM, Gouveia L, Moura P, Carvalheiro F, Duarte LC, Fernando AL, Reis A, Gírio F (2022) Low Indirect Land Use Change (ILUC) Energy Crops to Bioenergy and Biofuels—A Review. Energies 15(12): 4348. https://doi.org/10.3390/en15124348.

Amiandamhen SO, Kumar A, Adamopoulos S, Jones D, Nilsson B (2020) Bioenergy production and utilization in different sectors in Sweden: A state of the art review. BioResources 15(4): 9834. https://doi.org/10.15376/biores.15.4.Amiandamhen.

Anderson GQ, Fergusson MJ (2006) Energy from biomass in the UK: sources, processes and biodiversity implications. Ibis (London), 148(Suppl. 1): 180-183. https://doi.org/10.1111/j.1474-919X.2006.00535.x.

Andersson K. (2012) Bioenergy: The Swedish Experience. Stockholm: Swedish Bioenergy Association (Svebio). https://www.svebio.se/wp-content/uploads/2017/06/Bioenergy_Swedish_experice_3rded_web.pdf. Accessed 18 October 2022

Andersson K (2017) Is there enough land for growing energy crops? Swedish Bioenergy Association (Svebio). https://www.svebio.se/wp-content/uploads/2017/03/Is-there-enough-land-for-growing-energy-crops-March-2017.pdf. Accessed 18 October 2022

Aronsson PG, Bergström LF, Elowson SNE (2000) Long-term influence of intensively cultured short-rotation Willow Coppice on nitrogen concentrations in groundwater. Journal of Environmental Management 58(2): 135-145. https://doi.org/10.1006/jema.1999.0319.

Arshad MN, Donnison I, Rowe RL (2021) Marginal Lands: Concept, classification criteria and management. Supergen Bioenergy Hub report no. 02/2021. https://www.supergen-bioenergy.net/wp-content/uploads/2021/09/Marginal-Land-Report.pdf. Accessed 18 October 2022

Asbjornsen H, Hernandez-Santana V, Liebman M, Bayala J, Chen J, Helmers M, Ong CK, Schulte LA (2014). Targeting perennial vegetation in agricultural landscapes for enhancing ecosystem services. Renewable Agriculture and Food Systems 29(2): 101-125. https://doi.org/10.1017/S1742170512000385.

Baum S, Bolte A, Weih M (2012) High value of short rotation coppice plantations for phytodiversity in rural landscapes. GCB Bioenergy 4(6):728-738. https://doi.org/10.1111/j.1757-1707.2012.01162.x.

Baum S, Weih M, Busch G, Kroiher F, Bolte A (2009) The impact of short rotation coppice plantations on phytodiversity. Landbauforschung Volkenrode 59(3):163-170. https://literatur.thuenen.de/digbib_extern/bitv/dk042570.pdf. Accessed 18 October 2022

Bentsen NS, Felby C (2012) Biomass for energy in the European Union-a review of bioenergy resource assessments. Biotechnology for Biofuels 5(1): 1-10. https://doi.org/10.1186/1754-6834-5-25.

Berg Å (2002). Breeding birds in short-rotation coppices on farmland in central Sweden—the importance of Salix height and adjacent habitats. Agriculture, Ecosystems & Environment 90(3): 265-276. https://doi.org/10.1016/S0167-8809(01)00212-2.

Berndes G, Börjesson P, Ostwald M, Palm M (2008) Multifunctional biomass production systems–an overview with presentation of specific applications in India and Sweden. Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy 2(1): 16-25. https://doi.org/10.1002/bbb.52.

Börjesson P (2001) Framtida tillförsel och avsättning för biobränsle i Sverige-regionala analyser (Future supply and demand for biofuels in Sweden—Regional analyses). Report No. 34, The Department for Environmental and Energy System Studies, Lund University, Lund. pp 1-49.

Börjesson P, Tufvesson LM (2011) Agricultural crop-based biofuels–resource efficiency and environmental performance including direct land use changes. Journal of Cleaner Production 19(2-3): 108-120. https://doi.org/10.1016/j.jclepro.2010.01.001.

Brown TR, Wright MM, Román-Leshkov Y, Brown RC (2014) Techno-economic assessment (TEA) of advanced biochemical and thermochemical biorefineries. In Advances in biorefineries (pp. 34-66). Woodhead Publishing. https://doi.org/10.1533/9780857097385.1.34.

Christersson L (2008) Poplar plantations for paper and energy in the south of Sweden. Biomass and Bioenergy 32(11): 997-1000. https://doi.org/10.1016/j.biombioe.2007.12.018.

Convery I, Robson D, Ottitsch A, Long M (2012) The willingness of farmers to engage with bioenergy and woody biomass production: A regional case study from Cumbria. Energy Policy 40: 293-300. https://doi.org/10.1016/j.enpol.2011.10.009.

Cronin J, Zabel F, Dessens O, Anandarajah G (2020) Land suitability for energy crops under scenarios of climate change and land-use. GCB Bioenergy 12(8): 648-665. https://doi.org/10.1111/gcbb.12697.

Dadashpoor H, Azizi P, Moghadasi M (2019). Land use change, urbanization, and change in landscape pattern in a metropolitan area. Science of the Total Environment 655: 707-719. https://doi.org/10.1016/j.scitotenv.2018.11.267.

Dale VH, Kline KL, Kaffka SR, Langeveld JWA (2013) A landscape perspective on sustainability of agricultural systems. Landscape ecology 28(6): 1111-1123. https://doi.org/10.1007/s10980-012-9814-4.

Dimitriou I, Berndes G, Englund O, Murphy F (2018) Lignocellulosic crops in agricultural landscapes: Production systems for biomass and other environmental benefits–Examples, incentives, and barriers. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2019/01/TR2018-05.pdf. Accessed 18 October 2022

Dimitriou I, Mola-Yudego B (2017) Poplar and willow plantations on agricultural land in Sweden: Area, yield, groundwater quality and soil organic carbon. Forest Ecology and Management 383: 99-107. https://doi.org/10.1016/j.foreco.2016.08.022.

Dimitriou I, Rosenqvist H, Berndes G (2011) Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies. Biomass and Bioenergy 35(11): 4613-4618. https://doi.org/10.1016/j.biombioe.2011.09.006.

Don A, Osborne B, Hastings A, Skiba U, Carter MS, Drewer J, Flessa H, Freibauer A, Hyvönen N, Jones MB, Lanigan GJ (2012) Land-use change to bioenergy production in E urope: implications for the greenhouse gas balance and soil carbon. Gcb Bioenergy 4(4): 372-391. https://doi.org/10.1111/j.1757-1707.2011.01116.x.

Dragone G, Fernandes BD, Vicente AA, Teixeira JA (2010) Third generation biofuels from microalgae. https://repositorium.sdum.uminho.pt/bitstream/1822/16807/1/3067.pdf. Accessed 18 October 2022

Englund O, Berndes G, Cederberg C (2017) How to analyse ecosystem services in landscapes—A systematic review. Ecological Indicators 73: 492-504. https://doi.org/10.1016/j.ecolind.2016.10.009.

Englund O, Börjesson P, Berndes G, Scarlat N, Dallemand JF, Grizzetti B, Dimitriou I, Mola-Yudego B, Fahl F (2020a) Beneficial land use change: Strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. Global environmental change 60: 101990. https://doi.org/10.1016/j.gloenvcha.2019.101990.

Englund O, Dimitriou I, Dale VH, Kline KL, Mola-Yudego B, Murphy F, English B, McGrath J, Busch G, Negri MC, Brown M, Goss K, Jackson S, Parish ES, Cacho J, Zumpf C, Quinn J, Mishra SK (2020b) Multifunctional perennial production systems for bioenergy: performance and progress. Wiley Interdisciplinary Reviews: Energy and Environment 9(5): e375. https://doi.org/10.1002/wene.375.

Ericsson K, Huttunen S, Nilsson LJ, Svenningsson P (2004) Bioenergy policy and market development in Finland and Sweden. Energy policy 32(15): 1707-1721. https://doi.org/10.1016/S0301-4215(03)00161-7.

Ericsson K, Nilsson LJ (2006). Assessment of the potential biomass supply in Europe using a resource-focused approach. Biomass and Bioenergy 30(1): 1-15. https://doi.org/10.1016/j.biombioe.2005.09.001.

Ericsson K, Rosenqvist H, Ganko E, Pisarek M, Nilsson L (2006) An agro-economic analysis of willow cultivation in Poland. Biomass and Bioenergy 30(1): 16-27. https://doi.org/10.1016/j.biombioe.2005.09.002.

Ericsson N, Porsö C, Ahlgren S, Nordberg Å, Sundberg C, Hansson PA (2013) Time-dependent climate impact of a bioenergy system–methodology development and application to Swedish conditions. Gcb Bioenergy 5(5): 580-590. https://doi.org/10.1111/gcbb.12031.

ESRI (2016) ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute. European Environment Agency.

European Commission (EC) (2016) The Road from Paris: assessing the implications of the Paris Agreement and accompanying the proposal for a Council decision on the signing, on behalf of the EU, of the Paris agreement adopted under the UN Framework Convention on Climate Change. Brussels, Belgium. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2016:110:FIN. Accessed 18 October 2022

European Commission (EC) (2018) 2050 long-term strategy. In-depth analysis in support of the commission communication COM(2018) 773. A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://ec.europa.eu/clima/policies/strategies/2050_en. Accessed 15 January 2022

European Commission (EC) (2019). European Commission's Knowledge Centre for Bioeconomy Brief on biomass for energy in the European Union. https://publications.jrc.ec.europa.eu/repository/bitstream/JRC109354/biomass_4_energy_brief_online_1.pdf. Accessed 15 January 2022

European Commission (EC) (2021) Directive of the European Parliament and of The Council. Brussels. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0557. Accessed 1 September 2022

European Environment Agency (EEA) (2006) European Union, Copernicus Land Monitoring Service 2006. https://land.copernicus.eu/. Accessed 1 September 2021

European Environment Agency (EEA) (2018) European Union, Copernicus Land Monitoring Service 2018. https://land.copernicus.eu/. Accessed 1 September 2021

Eurostat (2021) Crop Production in EU Standard Humidity, Code: Apro_cpsh1. https://ec.europa.eu/eurostat. Accessed on 6 April 2021

Evans J (1992) Coppice forestry—an overview. Ecology and management of coppice woodlands: 18-27. https://doi.org/10.1007/978-94-011-2362-4_2.

FAOSTAT (2019) Food and Agriculture Organization of the United Nations http://www.fao.org/faostat/en/#data/PP. Accessed 27 May 2020

Fick SE, Hijmans RJ (2017) WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. International journal of climatology 37(12): 4302-4315. https://doi.org/10.1002/joc.5086.

Finell M (2003) The Use of Reed Canary-Grass (Phalaris arundinacea) as a Short Fibre Raw Material for the Pulp and Paper Industry. Doctoral Thesis, Swedish University of Agricultural

Sciences, Umeå, pp 1-53. http://urn.kb.se/resolve?urn=urn:nbn:se:slu:epsilon-95. Accessed 18 October 2022

Forman RTT, Godron M (1986) Landscape Ecology. John Wiley & Sons, New York. 619 pp.

Gabrielle B, Bamière L, Caldes N, De Cara S, Decocq G, Ferchaud F, Loyce C, Pelzer E, Perez Y, Wohlfahrt J, Richard G (2014) Paving the way for sustainable bioenergy in Europe: technological options and research avenues for large-scale biomass feedstock supply. Renewable and Sustainable Energy Reviews 33: 11-25. https://doi.org/10.1016/j.rser.2014.01.050.

Government Offices of Sweden (Regeringskansliet) (2017) Ett klimatpolitiskt ramverk för Sverige. Regeringskansliet https://www.regeringen.se/rattsliga-dokument/proposition/2017/03/prop.-201617146/. Accessed 15 February 2022

Griffel LM, Vazhnik V, Hartley DS, Hansen JK, Roni M (2020) Agricultural field shape descriptors as predictors of field efficiency for perennial grass harvesting: An empirical proof. Computers and Electronics in Agriculture 168: 105088. https://doi.org/10.1016/j.compag.2019.105088.

Hadders G, Olssen R (1996) European Energy Crops Overview, Country Report for Sweden. https://www.diva-portal.org/smash/get/diva2:959639/FULLTEXT01.pdf. Accessed on 26 January 2021

Hammar T, Hansson PA, Sundberg C (2017) Climate impact assessment of willow energy from a landscape perspective: a Swedish case study. GCB Bioenergy 9(5): 973-985. https://doi.org/10.1111/gcbb.12399.

Heinsoo K, Hein K, Melts I, Holm B, Ivask M (2011) Reed canary grass yield and fuel quality in Estonian farmers' fields. Biomass and Bioenergy 35(1): 617-625. https://doi.org/10.1016/j.biombioe.2010.10.022.

Helby P, Börjesson P, Hansen AC, Roos A, Rosenqvist H, Takeuchi L (2004) Market development problems for sustainable bio-energy systems in Sweden: (The BIOMARK project). Environmental and Energy Systems Studies, Lund University. https://inis.iaea.org/collection/NCLCollectionStore/_Public/35/018/35018132.pdf. Accessed 18 October 2022

Helby P, Rosenqvist H, Roos A (2006) Retreat from Salix—Swedish experience with energy crops in the 1990s. Biomass and Bioenergy 30(5): 422-427. https://doi.org/10.1016/j.biombioe.2005.12.002.

Hesselbarth MH, Sciaini M, With KA, Wiegand K, Nowosad J (2019) landscapemetrics: An open-source R tool to calculate landscape metrics. Ecography 42(10): 1648-1657. https://doi.org/10.1111/ecog.04617.

Hillring B (1998) National strategies for stimulating the use of bioenergy: policy instruments in Sweden. Biomass and Bioenergy 14(5-6): 425-437. https://doi.org/10.1016/S0961-9534(97)10036-8.

Hytönen J, Beuker E, Viherä-Aarnio A (2020) Biomass allocation and nutrient content of hybrid aspen clones grown on former agricultural land in Finland. Scandinavian Journal of Forest Research 35(3-4): 147-155. https://doi.org/10.1080/02827581.2020.1751269.

Immerzeel DJ, Verweij PA, Van Der Hilst F, Faaij AP (2013) Biodiversity impacts of bioenergy crop production: A state-of-the-art review. Gcb Bioenergy 6(3): 183-209. https://doi.org/10.1111/gcbb.12067.

Jasinskas A, Streikus D, Šarauskis E, Palšauskas M, Venslauskas K (2020) Energy evaluation and greenhouse gas emissions of reed plant pelletizing and utilization as solid biofuel. Energies 13(6): 1516. https://doi.org/10.3390/en13061516.

Johansson T, Hjelm B (2012) Stump and root biomass of poplar stands. Forests 3(2): 166-178. https://doi.org/10.3390/f3020166.

Johansson T, Karačić A (2011) Increment and biomass in hybrid poplar and some practical implications. Biomass and Bioenergy 35(5): 1925-1934. https://doi.org/10.1016/j.biombioe.2011.01.040.

Jungk NC, Reinhardt GA, Gärtner SO (2002) Agricultural reference systems in life cycle assessments. In Economics of sustainable energy in agriculture. Springer, Dordrecht, pp 105-119. https://link.springer.com/content/pdf/10.1007/0-306-48018-2.pdf. Accessed 18 October 2022

Järveoja J, Laht J, Maddison M, Soosaar K, Ostonen I, Mander Ü (2013) Mitigation of greenhouse gas emissions from an abandoned Baltic peat extraction area by growing reed canary grass: life-cycle assessment. Regional Environmental Change 13(4): 781-795. https://doi.org/10.1007/s10113-012-0355-9.

Khan A, Chatterjee S, Weng Y (2021) 2-Characterizing thermal fields and evaluating UHI effects. Urban Heat Island Modeling for Tropical Climates; Khan A, Chatterjee S, Weng Y, Eds, 37-67.

Landström S, Lomakka L, Andersson S (1996) Harvest in spring improves yield and quality of reed canary grass as a bioenergy crop. Biomass and Bioenergy 11(4): 333-341. https://doi.org/10.1016/0961-9534(96)00041-4.

Langeveld H, Quist-Wessel F, Dimitriou I, Aronsson P, Baum C, Schulz U, Bolte A, Baum S, Köhn J, Weih M, Gruss H, Leinweber P, Lamersdorf P, Schmidt-Walter P, Berndes G (2012) Assessing environmental impacts of short rotation coppice (SRC) expansion: model definition and preliminary results. BioEnergy Research 5(3): 621-635. https://doi.org/10.1007/s12155-012-9235-x.

Larsson S (2003) Modelling of the potential for energy crop utilisation in northern Sweden. https://pub.epsilon.slu.se/1067/1/Epsilon.pdf. Accessed 18 October 2022

Larsson S (2006) Supply curves of reed canary grass (*Phalaris arundinacea* L.) in Västerbotten County, northern Sweden, under different EU subsidy schemes. Biomass and Bioenergy 30(1): 28-37. https://doi.org/10.1016/j.biombioe.2005.06.008.

Lausch A, Herzog F (2002) Applicability of landscape metrics for the monitoring of landscape change: issues of scale, resolution and interpretability. Ecological Indicators 2(1-2): 3-15. https://doi.org/10.1016/S1470-160X(02)00053-5.

Lewis D (2015) Kernel density estimation and percent volume contours. Geocomputation; Brunsdon C, Singleton A (eds) SAGE Publications. Inc.: London, UK, pp 169-184.

Lindegaard KN, Adams PW, Holley M, Lamley A, Henriksson A, Larsson S, von Engelbrechten H-G, Lopez GE, Pisarek, M (2016) Short rotation plantations policy history in Europe: Lessons from the past and recommendations for the future. Food and energy security 5(3): 125-152. https://doi.org/10.1002/fes3.86.

Lindvall E (2012) Nutrient Supply to Reed Canary Grass as a Bioenergy Crop. Licentiate Thesis, Swedish University of Agricultural Sciences, Umeå. https://pub.epsilon.slu.se/8592/1/Lindvall_E_120220.pdf. Accessed 18 April 2021

Lindvall E, Gustavsson AM, Palmborg C (2012) Establishment of reed canary grass with perennial legumes or barley and different fertilization treatments: Effects on yield, botanical composition and nitrogen fixation. GCB Bioenergy 4: 661–670. https://doi.org/10.1111/j.1757-1707.2012.01178.x.

Lindvall E, Gustavsson AM, Samuelsson R, Magnusson T, Palmborg C (2015) Ash as a phosphorus fertilizer to reed canary grass: effects of nutrient and heavy metal composition on plant and soil. Gcb Bioenergy 7(3): 553-564. https://doi.org/10.1111/gcbb.12161.

Lombardo U (2014) Quantitative morphometric analysis of lakes using GIS: rectangularity R, ellipticity E, orientation O, and the rectangularity vs. ellipticity index, REi. Cartography and geographic information science 41(4): 340-347. https://doi.org/10.1080/15230406.2014.919540.

LUKE (2021) Natural Resources Institute Finland, Statistical Databases, Crop Production Statistics, Luke_Maa_Sato_0. www.statdb.luke.fi. Accessed 6 April 2021

MacLean MG, Congalton RG (2013). PolyFrag: a vector-based program for computing landscape metrics. GIScience & Remote Sensing 50(6): 591-603. https://doi.org/10.1080/15481603.2013.856537.

Magazzino C, Mele M, Schneider N, Shahbaz M (2021). Can biomass energy curtail environmental pollution? A quantum model approach to Germany. Journal of Environmental Management 287: 112293. https://doi.org/10.1016/j.jenvman.2021.112293.

Mahapatra K, Gustavsson L, Madlener R (2007) Bioenergy innovations: the case of wood pellet systems in Sweden. Technology Analysis & Strategic Management 19(1): 99-125. https://doi.org/10.1080/09537320601065423.

Mander Ü, Järveoja J, Maddison M, Soosaar K, Aavola R, Ostonen I, Salm JO (2012) Reed canary grass cultivation mitigates greenhouse gas emissions from abandoned peat extraction areas. Gcb Bioenergy 4(4): 462-474. https://doi.org/10.1111/j.1757-1707.2011.01138.x.

Marquardt K, Eriksson C, Kuns B (2022) Towards a Deeper Understanding of Agricultural Production Systems in Sweden–Linking Farmer's Logics with Environmental Consequences and the Landscape. Rural Landscapes: Society, Environment, History 9(1): 1–15. http://doi.org/10.16993/rl.78.

Mc Carthy R (2016) Establishment and early management of Populus species in southern Sweden. Doctoral Thesis, Swedish University of Agricultural Sciences, Alnarp, 52, pp 1-69. https://pub.epsilon.slu.se/13317/1/mc_carthy_r_160428.pdf. Accessed 18 October 2022

Mc Carthy R, Rytter L (2015) Productivity and thinning effects in hybrid aspen root sucker stands. Forest Ecology and Management 354: 215-223. https://doi.org/10.1016/j.foreco.2015.06.015.

McCormick K, Kåberger T (2005) Exploring a pioneering bioenergy system: The case of Enköping in Sweden. Journal of Cleaner Production: 13(10-11), 1003-1014. https://doi.org/10.1016/j.jclepro.2004.12.011.

McGarigal K, Cushman SA, Ene E (2012) FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst.

Melts I, Heinsoo K, Nurk L, Pärn L (2013) Comparison of two different bioenergy production options from late harvested biomass of Estonian semi-natural grasslands. Energy 61: 6-12. https://doi.org/10.1016/j.energy.2013.06.016.

Metzger M, Rounsevell MD, Acosta-Michlik L, Leemans R, Schröter D (2006) The vulnerability of ecosystem services to land use change. Agriculture, ecosystems & environment 114(1): 69-85. https://doi.org/10.1016/j.agee.2005.11.025.

Miyake S, Renouf M, Peterson A, McAlpine C, Smith C (2012) Land-use and environmental pressures resulting from current and future bioenergy crop expansion: A review. Journal of Rural Studies 28(4): 650-658. https://doi.org/10.1016/j.jrurstud.2012.09.002.

Mola-Yudego B (2010) Regional potential yields of short rotation willow plantations on agricultural land in Northern Europe. Silva Fennica, 44(1): 63-76. http://www.metla.fi/silvafennica/full/sf44/sf441063.pdf. Accessed 18 October 2022

Mola-Yudego B (2011) Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000. Biomass and Bioenergy 35(1): 446-453. https://doi.org/10.1016/j.biombioe.2010.09.004.

Mola-Yudego B, Aronsson P (2008) Yield models for commercial willow biomass plantations in Sweden. Biomass and Bioenergy 32(9): 829-837. https://doi.org/10.1016/j.biombioe.2008.01.002.

Mola-Yudego B, Díaz-Yáñez O, Dimitriou I (2015) How much yield should we expect from fast-growing plantations for energy? Divergences between experiments and commercial willow plantations. BioEnergy research 8(4): 1769-1777. https://doi.org/10.1007/s12155-015-9630-1.

Mola-Yudego B, González-Olabarria JR (2010) Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be learned about the spread of energy crops. Biomass and Bioenergy 34(4): 442-448. https://doi.org/10.1016/j.biombioe.2009.12.008.

Mola-Yudego B, Pelkonen P (2008) The effects of policy incentives in the adoption of willow short rotation coppice for bioenergy in Sweden. Energy Policy 36(8): 3062-3068. https://doi.org/10.1016/j.enpol.2008.03.036.

Mola-Yudego B, Pelkonen P (2011) Pulling effects of district heating plants on the adoption and spread of willow plantations for biomass: The power plant in Enköping (Sweden). Biomass and Bioenergy 35(7): 2986-2992. https://doi.org/10.1016/j.biombioe.2011.03.040.

Moser D, Zechmeister HG, Plutzar C, Sauberer N, Wrbka T, Grabherr G (2002) Landscape patch shape complexity as an effective measure for plant species richness in rural landscapes. Landscape Ecology 17(7): 657-669. https://doi.org/10.1023/A:1021513729205.

Moss MR (2000) Interdisciplinarity, landscape ecology and the Transformation of Agricultural Landscapes'. Landscape Ecology 15(3): 303-311. https://doi.org/10.1023/A:1008144402408.

Nilsson D, Rosenqvist H (2018) Marginal arable fields in Sweden-areas, shapes, transport distances and time demand and costs for machine operations. njfcongress26 106-112. http://journal.njfcongress26.eu/index.php/njfcongress26/article/view/14/55. Accessed 18 October 2022

Nilsson D, Rosenqvist H (2021) Profitability of Crop Cultivation in Small Arable Fields When Taking Economic Values of Ecosystem Services into Account. Sustainability 13(23): 13354. https://doi.org/10.3390/su132313354.

Nilsson D, Rosenqvist H, Bernesson S (2015) Profitability of the production of energy grasses on marginal agricultural land in Sweden. Biomass and Bioenergy 83: 159-168. https://doi.org/10.1016/j.biombioe.2015.09.007.

Nordborg M, Berndes G, Dimitriou I, Henriksson A, Mola-Yudego B, Rosenqvist H (2018) Energy analysis of poplar production for bioenergy in Sweden. Biomass and Bioenergy 112: 110-120. https://doi.org/10.1016/j.biombioe.2018.01.021.

Official Journal of the European Union. (2008) Communication from the Commission to All Farmers Concerning Set Aside from 2009 (2008/C 324/07). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:C:2008:324:0011:0011:EN:PDF. Accessed 15 February 2022

Oksanen T (2013) Shape-describing indices for agricultural field plots and their relationship to operational efficiency. Computers and Electronics in Agriculture 98: 252-259. https://doi.org/10.1093/erae/jbab043.

Olsson J, Salomon E, Baky A, Palm O (2008) Energigrödor–en Möjlighet för Jordbruksanvändning av Slam; Svenskt Vatten Utveckling, Svenskt Vatten AB: Bromma, Sweden, 12, p 53. [In Swedish].

Owen PW, Milionis N, Papatheodorou I, Sniter K, Viegas HF, Huth J, Bortnowschi R (2016) The land parcel identification system: A useful tool to determine the eligibility of agricultural land—But its management could be further improved. Special Report 25. https://www.eca.europa.eu/Lists/News/NEWS1610_25/SR_LPIS_EN.pdf. Accessed 18 October 2019

Parikka M (2004) Use of densified biomass fuels in Sweden-the current situation and some thoughts about the future. In: Bioenergy development in Finland, Russia and Sweden. University of Joensuu, Faculty of Forestry. Finland.

Paulrud S, Laitila T (2010) Farmers' attitudes about growing energy crops: a choice experiment approach. Biomass and Bioenergy 34(12): 1770-1779. https://doi.org/10.1016/j.biombioe.2010.07.007.

Perpiña Castillo C, Lavalle C, Baranzelli C, Mubareka S (2015). Modelling the spatial allocation of second-generation feedstock (lignocellulosic crops) in Europe. International Journal of Geographical Information Science 29(10): 1807-1825. https://doi.org/10.1080/13658816.2015.1051486.

Prade T, Finell M, Svensson SE, Mattsson JE (2012) Effect of harvest date on combustion related fuel properties of industrial hemp (*Cannabis sativa* L.). Fuel 102: 592-604. https://doi.org/10.1016/j.fuel.2012.05.045.

R core Team (2020) R: A Language and Environment for Statistical Computing R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/. Accessed 2 June 2022

Rakovic J, Futter MN, Kyllmar K, Rankinen K, Stutter MI, Vermaat J, Collentine D (2020) Nordic Bioeconomy Pathways: Future narratives for assessment of water-related ecosystem services in agricultural and forest management. Ambio 49(11): 1710-1721. https://doi.org/10.1007/s13280-020-01389-7.

Roj-Rojewski S, Wysocka-Czubaszek A, Czubaszek R, Kamocki A, Banaszuk P (2019) Anaerobic digestion of wetland biomass from conservation management for biogas production. Biomass and Bioenergy 122: 126-132. https://doi.org/10.1016/j.biombioe.2019.01.038.

Roos A, Rosenqvist H, Ling E, Hektor B (2000) Farm-related factors influencing the adoption of short-rotation willow coppice production among Swedish farmers. Acta Agriculturae Scandinavica, Section B-Plant Soil Science 50(1): 28-34. https://doi.org/10.1080/090647100750014385.

Rosenqvist H, Berndes G, Börjesson P (2013) The prospects of cost reductions in willow production in Sweden. Biomass and Bioenergy 48: 139-147. https://doi.org/10.1016/j.biombioe.2012.11.013.

Rosenqvist H, Roos A, Ling E, Hektor B (2000) Willow growers in Sweden. Biomass and bioenergy 18(2): 137-145. https://doi.org/10.1016/S0961-9534(99)00081-1.

Rowe RL, Goulson D, Doncaster CP, Clarke DJ, Taylor G, Hanley ME (2013) Evaluating ecosystem processes in willow short rotation coppice bioenergy plantations. GCB Bioenergy 5(3): 257-266. https://doi.org/10.1111/gcbb.12040.

Rytter L, Johansson T, Karacic A, Weih M (2011) Orienterande Studie Om Ett Svenskt Forskningsprogram för Poppel; Skogforsk: Uppsala, Sweden. https://pub.epsilon.slu.se/5735/1/rytter_l_etal_110221.pdf. [in Swedish]. Accessed 18 October 2022

Rytter L, Stener LG (2005) Productivity and thinning effects in hybrid aspen (*Populus tremula* L.× *P. tremuloides* Michx.) stands in southern Sweden. Forestry 78(3): 285-295. https://doi.org/10.1093/forestry/cpi026.

SalixEnergi (2022) Lantmännen SW Seed Willow Varieties 2022. https://salixenergi.se/planting-material/. Accessed on 10 October 2022

Shurpali NJ, Strandman H, Kilpeläinen A, Huttunen J, Hyvönen N, Biasi C, Kellomäki S, Martikainen PJ (2010) Atmospheric impact of bioenergy based on perennial crop (reed canary grass, *Phalaris arundinaceae*, L.) cultivation on a drained boreal organic soil. Gcb Bioenergy 2(3): 130-138. https://doi.org/10.1111/j.1757-1707.2010.01048.x

Slade R, Bauen A, Gross R (2014) Global bioenergy resources. Nature Climate Change 4(2): 99-105. https://doi.org/10.1038/nclimate2097.

Spartz JT, Rickenbach M, Shaw BR (2015) Public perceptions of bioenergy and land use change: Comparing narrative frames of agriculture and forestry. Biomass and Bioenergy 75: 1-10. https://doi.org/10.1016/j.biombioe.2015.01.026.

Stanturf JA, van Oosten C (2014) Operational poplar and willow culture. In: Isebrands JG, Richardson J (eds.), Poplars and Willows: Trees for Society and the Environment, The Food and Agriculture Organization of the United Nations and CAB International, Rome, pp 200-245. http://www.poplar.ca/upload/documents/isebrands-richardson.pdf#page=233. Accessed 15 February 2022

Stolarski MJ, Szczukowski S, Tworkowski J, Krzyżaniak M, Załuski D (2019) Willow production during 12 consecutive years—The effects of harvest rotation, planting density and cultivar on biomass yield. GCB Bioenergy 11(4): 635-656. https://doi.org/10.1111/gcbb.12583.

Stolarski MJ, Warmiński K, Krzyżaniak M, Olba–Zięty E, Akincza M (2020) Bioenergy technologies and biomass potential vary in Northern European countries. Renewable and Sustainable Energy Reviews 133: 110238. https://doi.org/10.1016/j.rser.2020.110238.

Swedish Bioenergy Association (Svebio) (2020) Roadmap Bioenergy – meeting the demand for bioenergy in a fossil free Sweden. https://www.svebio.se/app/uploads/2020/03/Roadmap-Bioenergy-2020.pdf. Accessed 16 February 2022

Swedish Bioenergy Association (Svebio) (2022) Finns det mark (Is there enough land)? https://www.svebio.se/om-bioenergi/aktuella-fragor/finns-det-mark-att-odla-energigrodor-pa/. [in Swedish]. Accessed 15 February 2022

Swedish Board of Agriculture (Jordbruksverket) (2019) Kartor och Geografiska Informations System. Available online: https://nya.jordbruksverket.se/. [In Swedish]. Accessed 20 November 2019

Swedish Energy Agency (Energimyndigheten) (2022) https://www.energimyndigheten.se/en/. Accessed 6 September 2022

Swedish Official Statistics (SCB) (2017) Standard Yields for Yield Survey Districts, Counties and the Whole Country. https://www.scb.se. [In Swedish]. Accessed 23 October 2019

Ustak S, Šinko J, Munoz J (2019) Reed canary grass (*Phalaris arundinacea* L.) as a promising energy crop. Journal of Central European Agriculture 20(4): 1143-1168. https://doi.org/10.5513/JCEA01/20.4.2267.

Vallés-Planells M, Galiana F, Van Eetvelde V (2014) A classification of landscape services to support local landscape planning. Ecology and Society 19(1). https://www.jstor.org/stable/26269503. Accessed 18 October 2022

Vasile AJ, Andreea IR, Popescu GH, Elvira N, Marian Z. (2016) Implications of agricultural bioenergy crop production and prices in changing the land use paradigm—The case of Romania. Land Use Policy 50: 399-407. https://doi.org/10.1016/j.landusepol.2015.10.011.

Vejre H, Abildtrup J, Andersen E, Andersen PS, Brandt J, Busck A, Dalgaard T, Hasler B, Huusom H, Kristensen LS, Kristensen SP, Præstholm S (2007) Multifunctional agriculture and multifunctional landscapes—land use as an interface. In Multifunctional land use (pp. 93-104). Springer, Berlin, Heidelberg.

Venendaal R, Jørgensen U, Foster CA (1997) European energy crops: a synthesis. Biomass and Bioenergy 13(3): 147-185. https://doi.org/10.1016/S0961-9534(97)00029-9.

Vepsäläinen V (2010) Energy crop cultivations of reed canary grass—An inferior breeding habitat for the skylark, a characteristic farmland bird species. Biomass and bioenergy 34(7): 993-998. https://doi.org/10.1016/j.biombioe.2010.02.007.

Wang L, Wen C (2021) Traditional villages in forest areas: Exploring the spatiotemporal dynamics of land use and landscape patterns in Enshi prefecture, China. Forests 12(1): 65. https://doi.org/10.3390/f12010065.

Weih M, Karacic A, Munkert H, Verwijst T, Diekmann M (2003) Influence of young poplar stands on floristic diversity in agricultural landscapes (Sweden). Basic and applied ecology 4(2): 149-156. https://doi.org/10.1078/1439-1791-00157.

Werling BP, Dickson TL, Isaacs R, Gaines H, Gratton C, Gross KL, Liere H, Malmstrom CM, Meehan TD, Ruan L, Robertson BA (2014) Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. Proceedings of the National Academy of Sciences 111(4): 1652-1657. https://doi.org/10.1073/pnas.1309492111.

Worton BJ (1989) Kernel methods for estimating the utilization distribution in home-range studies. Ecology 70(1): 164-168. https://doi.org/10.2307/1938423.

Wright L (2006) Worldwide commercial development of bioenergy with a focus on energy crop-based projects. Biomass and Bioenergy 30(8-9): 70. https://doi.org/10.1016/j.biombioe.2005.08.008.

Zalesny Jr RS, Berndes G, Dimitriou I, Fritsche U, Miller C, Eisenbies M, Ghezehei S, Hazel D, Headlee WL, Mola-Yudego B, Negri MC, Nichols EG, Quinn J, Shifflett SD, Therasme O, Volk T, Zumpf CR (2019) Positive water linkages of producing short rotation poplars and willows for bioenergy and phytotechnologies. Wiley Interdisciplinary Reviews: Energy and Environment 8(5): e345. https://doi.org/10.1002/wene.345.

Zscheischler J, Gaasch N, Manning DB, Weith T (2016) Land use competition related to woody biomass production on arable land in Germany. In Land Use Competition, Springer, Cham, pp 193-213. https://doi.org/10.1007/978-3-319-33628-2_12.