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Where and when are plantations established? Land-use replacement patterns of fast-growing plantations on agricultural land

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ABSTRACT

The location of fast-growing plantations for energy reveals valuable information concerning farmers' preferences and land use change patterns, necessary to have adequate environmental and economic assessments. The present study analyses the last decades' data concerning the establishment of willow, poplar and hybrid aspen plantations in Sweden. The analysis includes extension planted, a geo-statistical analysis of core location patterns, and the type of land being replaced or replacing plantations, for the period 1986–2017. The results show a steady decrease of willow plantations in recent years, which can be explained by changes in the policy framework (after 1996) and the increase in cereal prices (after 2007). The decline is partially offset by the establishment of new poplar and hybrid aspen plantations. New plantations tend to spread in southern areas; willow tends to be planted on higher productivity agricultural areas, and poplar on less productive land. There is a trend towards preferring smaller plantations (<1 ha) versus large ones (>10 ha). Although many willow plantations have been established on previous cereal land (particularly on spring barley and winter wheat), this pattern changed after 2007, preferring grasses and fallow land. The latter is the most common land use replaced by poplar plantations. These shares may have important applications in economic and environmental assessments; the general spatial patterns of the main fast-growing species for biomass can provide a valid reference for the future implementation of bioenergy production systems.

1. Introduction

During the 2000s there was a growing interest in Europe on the establishment of woody fast-growing plantations, particularly willow (*Salix* sp.) and poplar (*Populus* sp.), as they were regarded as an effective way to reduce the dependence of fossil fuels and an efficient system for the production of biomass for the forest industry. These plantations are grown on agricultural land in order to produce woody biomass in short rotations, often less than 30 years [1–3]. Comparing with other common agricultural practices, plantations are less labor intensive and offer an economic alternative to the farmers [4], which help diversify their income along seasons. In addition, fast-growing plantations have been regarded as important contributors to sustainable forestry and rural development, which in the case of planted willow and poplar represent about 6.7 million hectares globally, mainly dedicated to wood production (56%) or environmental purposes [5].

Where and when these plantations are established are key questions that reveal farmer preferences, policy framework and micro-market development, among others. One important aspect related to this spatial dimension refers to the geographical location of plantations on a region, which has economic as well as policy implications in energy planning and land use management. Those are critical factors for a successful bioenergy implementation, as was pointed out on studies in the USA, Austria or Sweden [6]. In the latter country, Mola-Yudego and Gonzalez-Olabarria [7] studied the evolution of geo-location patterns of willow plantations along several years (1997–2005), identifying areas where plantations were successful, linked to the developments of bioenergy markets and energy demand, as well as changes caused by different energy policies along time. At a lower spatial scale, it was showed that plantations were geographically associated with the location of large heating plant location and local points of high biomass demand [8].

The study of location and its spatial dimension also affects the land-use pattern, in relation, for instance, to the crops that plantations are replacing. This is fundamental information concerning land-use competition between woody biomass and food crops [9]. In addition,

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it concerns environmental assessments, as studies evaluating the environmental effects of plantations, either experimental or Life Cycle Assessment (LCA) based, require a reference cultivation (*agricultural reference system*) to make effective comparisons [10]. Furthermore, besides environmental comparisons, the use of adequate reference crops has economic consequences related to the estimation of opportunity costs (e.g. Refs. [11]).

Sweden offers a unique opportunity to study these questions thoroughly; as the pioneer in fast-growing plantations, has established plantations with various species since 1970s. Willow was the largest one in area, and has been established since 1986 [7]. Its cultivation includes 3–7 year rotations and 20–25 yeareconomic lifespan [12], mainly dedicated to energy purposes. Poplar plantations have been established in Sweden since 1980s [13]; on average, a poplar plantation has a rotation less than 20 years while lower density can lead to longer rotation years [14]. As a separate type of plantation, hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx) is currently used for pulp and bioenergy industries, which has crossbred for match industry since 1939 and commercial stands were established in the 1990s (for a review of its development in Sweden, see Ref. [15]) with 20–25 year rotation [16]. Both poplar and hybrid aspen plantations in Sweden are dedicated to fiber production for the pulp and paper industry and, to a lesser extent, energy [17].

The objective of this paper is to analyze the spatial trends of fast-growing plantations concerning land use. The analysis covers three decades of data concerning willow, poplar and hybrid aspen plantations in Sweden. The paper explores the evolution of areas planted, the location and characteristics of these areas and the strong links between agricultural trends and the establishment of plantations, by examining the type of land uses being replaced by plantations or the cultivations established after the plantations are abandoned. A working hypothesis assumes that changes in the policy framework and global agricultural markets affect their development. In addition, it is expected that the rise in cereal prices of recent years has influenced these land-use dynamics.

2. Material and methods

2.1. Data sources

An extensive database was compiled, using data from the land register, entailing the period 2001–2017. The main data were based on the IACS (Integrated Administration and Control System) databases maintained by the Swedish Board of Agriculture. These databases have cartographic information concerning all the fields in the country, location, area, and yearly agricultural land uses (scale 1:10 000). The spatial unit with crop information (*blocks* in the databases) is defined as a uniform land area that remains approximately constant from one year to the next [18], although land changes may be produced during this period (more information about the data, layers and the definitions can be found at [18], and about the methods and the land information available at [19]). Each of these spatial units can contain more than one field, but a field is always part of a *block* [18]. Land use data from 1998 to 2018 were initially included in the analysis, but the lack of records of some years restricted the effective use of the data from 2001 to 2016 in the analysis.

Data prior to that period was compiled from existing records of previous publications [7,12]. The location of plantations from 1986 (first willow plantations) to 2001 was based on the study of Mola-Yudego [20] and based largely on data provided by Agrobränsle [12]. This dataset had records up to 2004; however, some plantations were not fully recorded, and we opted to use instead data from the land registry for 2001–2004 as it was more exhaustive. Concerning poplar or hybrid aspen, there were no records available prior 2001, but the estimated area planted before that year can be considered negligible. Finally, local agricultural productivity was retrieved from the average standard yields by yield survey districts for the period 2003–2017 [21] and cereal prices along the period were retrieved from FAO databases [22].

2.2. Methods

The spatial analysis included the identification of the main fast-growing woody crops established in the country, from which willow, poplar and hybrid aspen were selected for the rest of the analysis (Fig. 1). The total cultivated area by year was also analysed, in order to have an overall idea of the relative importance of the crops. This trend was established using all existing sources of data included in the study. In addition, the average size of the plantations was analysed, estimating their distribution along time using histograms, allowing to determine whether there was any trend towards larger or smaller plantation systems. In this study, the plantation size was defined as the area of the field or parcel were the plantation is established (as defined in Ref. [18]), and a grower may have several of these parcels in their farms.

The geographic analysis of the areas planted with these species along time was based on geospatial kernels. This is a non-parametric method for the estimation of the spatial distribution of probability of occurrence based on a pool of observed events [23,24], in this case, the coordinates of the location of the plantations. The method creates a density function according to the frequency of plantations, resulting in a continuous distribution of frequency for the whole territory. The density function is based on a normal bi-variate distribution, which requires the location of the plantations as well as a bandwidth or smoothing factor, which was calculated based on the reference parameter proposed in Worton [23]. The application of the methods, reference parameter and approach were derived from the study of Mola-Yudego and González-Olabarria [7]. The kernel density estimates were then transformed in percentage volume contours, used to identify those areas with the highest concentration of planted area for a fixed percentage, in a similar way to how home range analysis is applied to define the territoriality of animal movements [25]. The core areas were defined by fixing the percent contour volume to

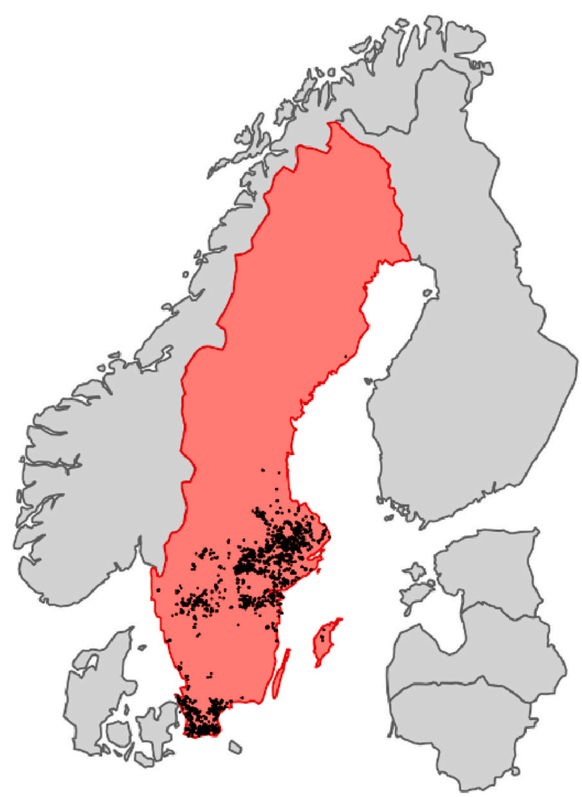

Fig. 1. Location of the studied plantations in Sweden (willow, poplar and hybrid aspen) during 1986–2017.

30% (areas with the highest concentration of plantations entailing 30% of the total planted area) and, as a reference, the larger areas entailing plantations were defined by fixing it to 60% (areas with the highest concentration of plantations entailing 60% of the total planted area). By these means, the core areas defined the areas where fast growing plantations are common, and the latter, to have an approximate area of those areas where the cultivation is in use.

The average standard yields by agricultural district were used as a proxy variable to estimate of the average land productivity where the plantations are established. The average barley yield for the period 2003–2017 was used as indicator, since it covers most of the area were plantations are established and covers enough time to reduce annual variations due to specific climatic conditions. This yield was assigned to each plantation, and the country's average was calculated by year for the three main plantation systems.

All the *blocks* including a fast-growing plantation as a single cultivation code were identified and compared to the land-use records of the previous and following year, for the same parcel. This approach provided year by year estimates of land use change. In addition, the total land use change in the period of study was made comparing two reference years, corresponding to 2001 and 2016 as the first and last years with fully documented records about land uses in the land register. By these, we aimed at identifying: a) how many plantations in 2001 were still managed in 2016; b) what were the main crops replacing plantation area (*replacing* crops); c) what were the main crops prior to the establishment of plantations (*replaced* crops).

The analysis combined the use of identifiers as well as the specific spatial locations of the fields. In some cases, the same *block* included several fields with different cultivations that could not be distinguished spatially, particularly in 2001. The potential errors were estimated by performing a GIS analysis, comparing the data from 2001 to 2016. Then, the land use change was calculated including all the cultivations recorded for the same *block*, and then only including the main cultivation in the field (the larger in area). Both results were compared, to

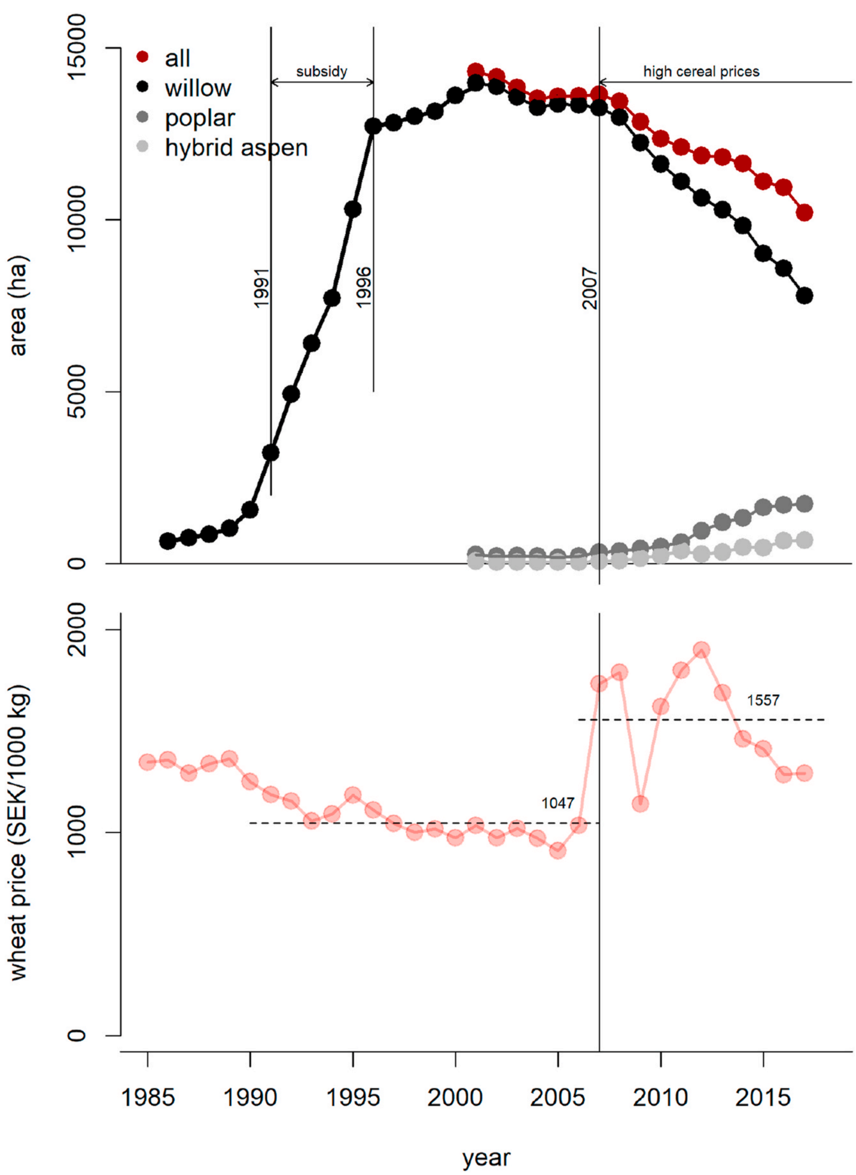

Fig. 2. Evolution of area established in Sweden with fast growing plantations (1986–2017) and wheat prices for the same period. In 1991 there was an establishment subsidy for willow plantations, that was significantly reduced after 1996. In 2007 there was a turning point in cereal prices, increasing by nearly 50% along the decade versus the previous values.

address the potential bias in the estimations. The areas were weighted based on the size of the field, and total aggregates were calculated.

Finally, the spatial trends in established area and land use changes were further examined concerning land productivity, by using the cereal standard yield as a proxy, and the changes along time were compared to the cereal prices during the studied period. The overall analysis was performed in R v4.0.2 [26], and the spatial kernels using the package *GISTools* [27].

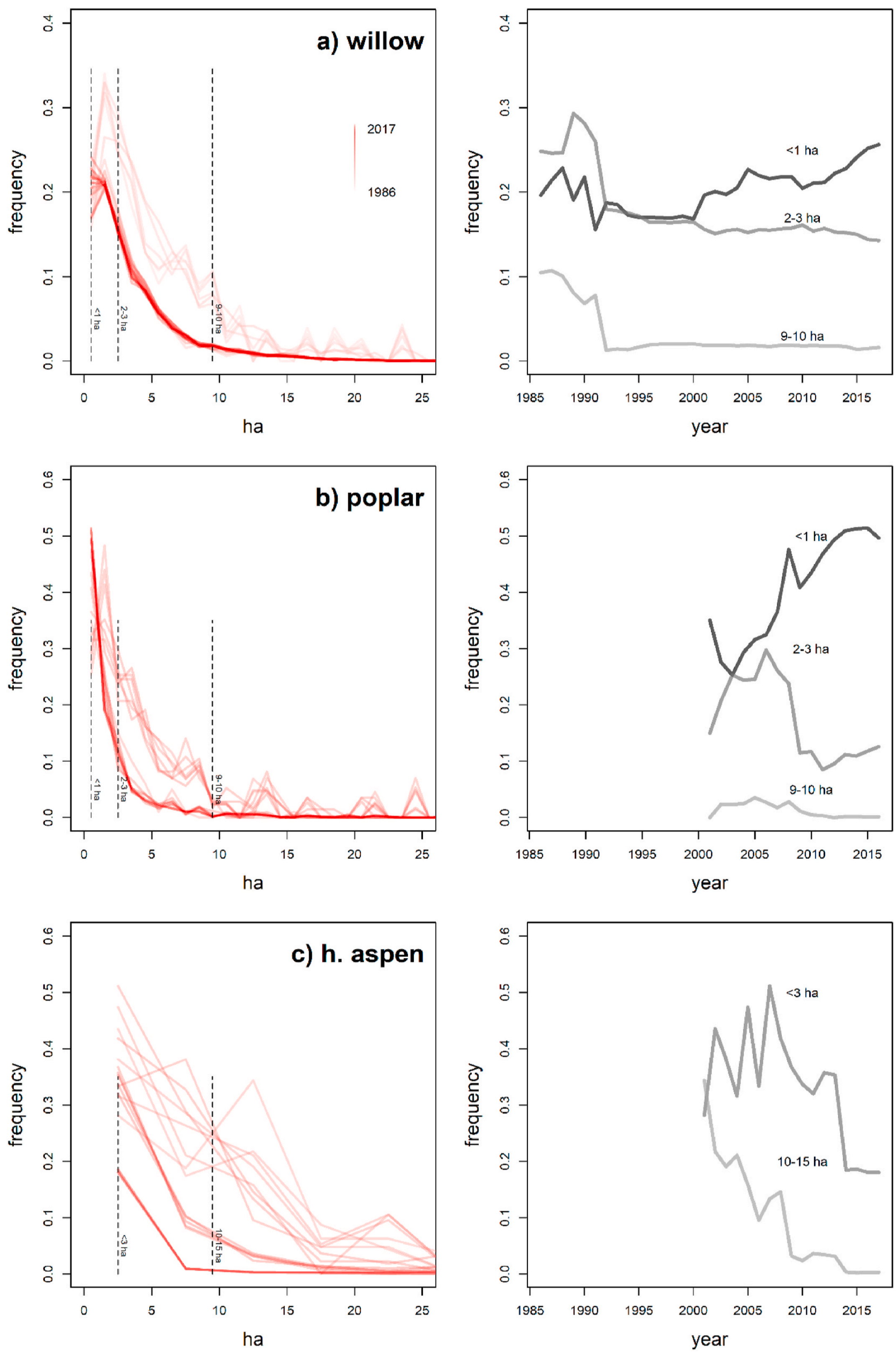

Fig. 3. Distribution of the size of the plantations along 1986–2017, for willow, poplar and hybrid aspen in Sweden.

3. Results

3.1. Plantation's area and size

The evolution of wood-based fast-growing plantations for energy in the country started in 1985, with the first willow plantations. During this period until the year 2000, willow was the main wood-based cultivation for energy purposes in the country (Fig. 2). Despite there was limited data in the land registry concerning poplar and hybrid aspen prior to the year 2000, their combined area was negligible before that year, mainly including trials and demonstration plantations [13,28]. The maximum area planted with fast-growing plantations was around the year 2000, after which started a progressive decline. After 2007, the willow area decreased fast after this year, being partially compensated by an increment of poplar and, to a lesser extent, hybrid aspen. The average cereal price after 2007 increased by 48.6%, 40.1% and 22% for wheat, barley and oats, respectively (compared to the average 1990–2006). The overall willow plantation area in Sweden decreased from a maximum around 14 000 ha (2001) to current 7785 ha (2017), whereas poplar covers 1738 ha and hybrid aspen 676 ha (2017) for a total of 10 200 ha of land established with fast growing plantations.

The size of most of the initial willow plantations was around 2–3 ha, with a significant amount (>10%) of large plantations (9–10 ha). After 1993, there was a relative increase of small plantations, and plantations smaller than 1 ha became prevalent (Fig. 3). The average plantation size has been 3.7 ha for the period 1986–2016, although in recent years has slightly increased to be closer to 4 ha, and it has remained stable since 2010.

This trend was also observed in the poplar plantations, as plantations smaller than 1 ha represented about the 50% of all plantations. In this case, the average plantation size has been 2.5 ha for many years, although in recent years there has been a steady size reduction, as the more recent plantations are ca 2 ha.

Concerning hybrid aspen, there were large plantations systems around the year 2000, however, the percentage of large plantation systems is smaller in more recent years. A clear change in the distribution of plantations' size could be observed in the last decade, although there is less data to study consistent trends. The average plantation size is about 2.2 ha although more recent plantations seem to be larger, ca 3 ha.

3.2. Plantation's location

In general, the evolution of plantation locations expanded from the east and center to the south during the periods (Fig. 4). Willow plantations initially expanded from central Sweden (*Örebro*) in the 1990s to southern areas (*Scania)*, where more of the new plantations are established in recent years. Poplar plantations are relatively more concentrated and had the core areas in the eastern coast and southern parts of the country, with no evident changes along time. Even though there is less area planted with hybrid aspen, those plantations are more dispersed along the country, often nearby poplar plantations. In this case, the trend is to establish new plantations more northwards than willow.

Concerning the agricultural productivity, willow plantations have been established in more productive agricultural districts than poplar and hybrid aspen, respectively. The average agricultural productivity of the planted areas, expressed as the standard yield of barley, was 4451 kg ha^{-1} yr^{-1}, 4063 kg ha^{-1} yr^{-1} and 3757 kg ha^{-1} yr^{-1}, for willow, poplar and hybrid aspen, respectively, for the last year studied (2017). There were important trends, as willow has been progressively established in more productive areas, whereas poplar has shown the opposite trend (Fig. 5). Prior to 1989 (willow), 2008 (poplar) and 2010 (hybrid aspen), the number of plots and cultivation area was very limited and precluded the estimation of a consistent trend.

Willow plantations in 2016 were mostly established on previous

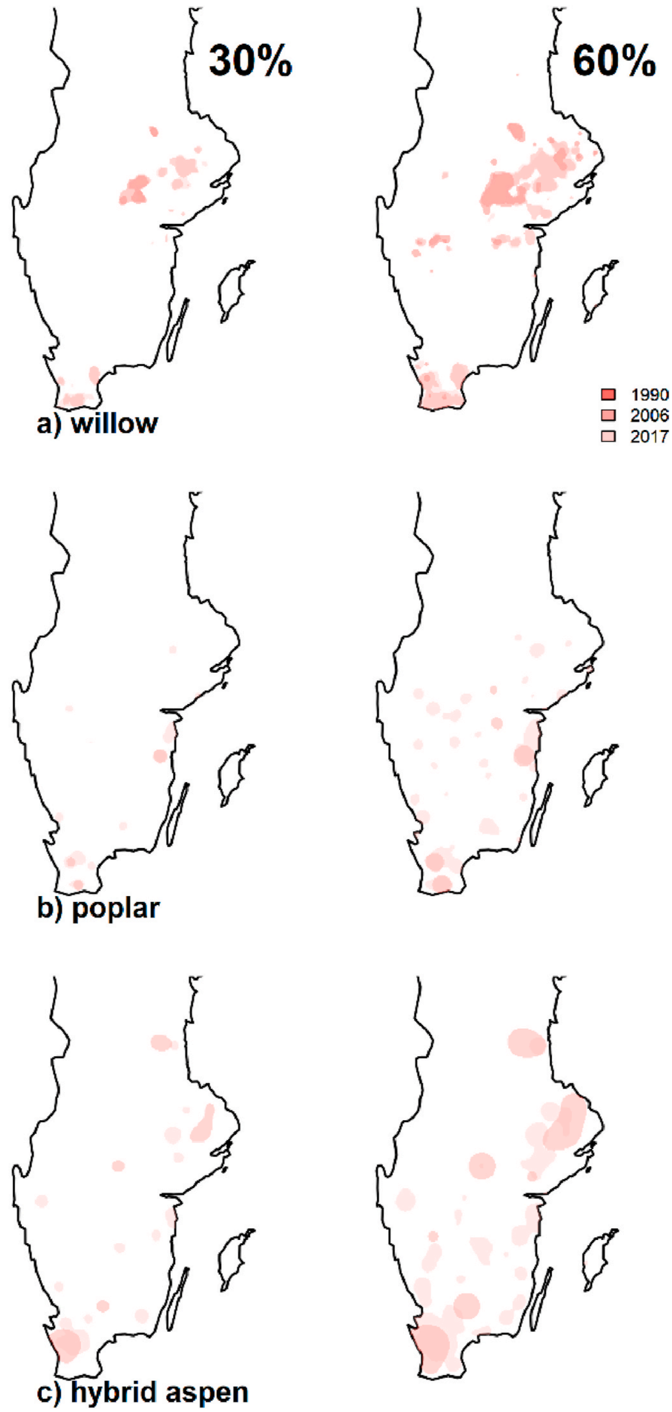

Fig. 4. Location of the main plantation areas for willow, poplar and hybrid aspen in Sweden. The percentages 30% and 60% refer to the total area included in those areas for a given period (*core areas* with the highest concentration for that given percentage).

cereal cultivation. Among those, spring barley, winter wheat and oats were the main cereals. Similarly, spring barley and winter wheat were mainly dominant for hybrid aspen plantations. In the case of poplar, non-cereal cultivation (fallow land and temporary grass) were more dominant (Table 1). About 47.2% of the area planted with willow in 2016 dates to 2001. In the case of poplar and hybrid aspen, the percentages are 7.7% and 2.2%, respectively, as most of the plantations are recently established (Table 1a). The results also showed that only about 29.4% of the willow plantations in 2001 are still being managed in 2016,

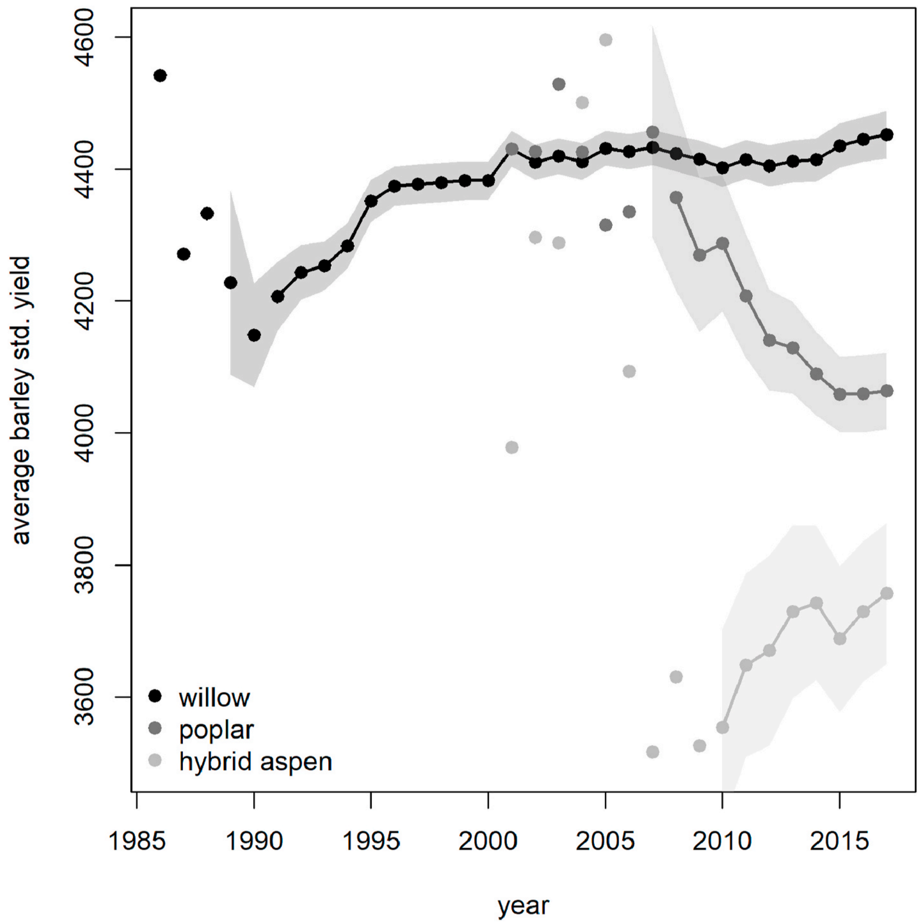

Fig. 5. Average land productivity of the plantations established in Sweden (1986–2017) for willow, poplar and hybrid aspen. The land productivity was based on the estimated standard barley yield of each yield survey district (average for the period 2003–2017). Shadow areas represent the standard error (95%) of the annual mean (only calculated when N > 100, to include representative trends).

whereas for poplar and hybrid aspen, the percentages are 62.6% and 11.0%, respectively (Table 1b). It must be noticed that in the latter, the limited amount of planted area made the data prone to errors.

During the processing of the data there were losses of information due to changes in the shape and resolution of the field areas that made the spatial overlapping difficult, especially concerning records from 2001. In total, the estimates in the land-use change resulting from the spatial overlapping of 2016 layers on the 2001 data included 12 742 ha (out of the documented 13 871 ha in 2001), 150 ha (out of 259 ha) and 108 ha (from only 76 ha documented that year) for willow, poplar and hybrid aspen. The latter figure overestimated the land use dedicated to hybrid aspen. This was due to several parcels being aggregated per *block* in the database in 2001, and the differences in the resolution of the layers, which rounded some estimates and have large effects when the total area being mapped is small (<100 ha) and dispersed). On the other hand, the spatial overlapping of layers in 2001 on the 2016 data included 8269 ha (out of 8580 ha), 1541 ha (out of 1700 ha) and 612 ha (out of 661 ha) for willow, poplar and hybrid aspen in 2016; in this case, the land database was more accurate (a detailed explanation about the methods and estimates of inaccurate spatial definition of land areas within the IACS can be found in Refs. [19]).

The sensitivity analysis applied to the estimates showed little variation in the case of willow, with the land uses changing less than 1% in almost all land uses. The largest deviations were observed in 2001 records of poplar still in use in 2016 (ranging from 48.4% to 62.6%) and for spring barley replacing earlier hybrid aspen plantations (from 38.9% to 56.7%). In both cases it is likely due to the limited amount of area of both cultivations in 2001 (<100 ha). Despite these variations, there were no large qualitative changes in the estimated percentages.

Along time, the main pattern was a consistent replacement of willow plantations by cereal after 2007 (Fig. 6). In relative terms, willow plantations were progressively established on fallow land and nearly no new plantation was established on previous cereal land after that year. There was certain dynamic pattern in land use change, with willow plantations being established and abandoned at a similar path until 2007. This pattern was not observed in poplar and hybrid aspen along the series.

4. Discussion

Even though in recent times several studies having been dealing with the development of willow plantations, particularly in Sweden, up to date there is limited information concerning the type of land those plantations replace; concerning alternative plantations systems based on poplar or hybrid aspen there are even fewer studies based on large data. The spatial analysis as well as the total estimates of land dedicated to the different crops provided in this study can be regarded as the most precise estimations up to date.

There are, however, limitations concerning the data used in the study that would affect the land use change estimates. The quality of the land use data depends on the aerial photograph used in the area and the digitizing process, as has been noticed in related studies [29], as well as on the accuracy of the reports provided by the farmer. The comparison of the data from 2001 to 2016 presented challenges: there are reported different field cultivations within the same *blocks*, and the spatial accuracy of the 2001 data was lower, presenting more aggregated fields

Table 1
Land use transition concerning fast-growing plantations for willow, poplar and hybrid aspen. a) main land uses (%) prior to the establishment of the plantations (crops in 2001 on plantation land in 2016, *replaced crops*). b) main land uses (%) on former plantations (crops in 2016 on plantation land in 2001, *replacing crops*). *: in this list, percentages considering only new plantations, must sum 100%.

a)			
	Willow (in 2016)	Poplar (in 2016)	Hybrid aspen (in 2016)
Willow (in 2001)	47.2	1.5	0.7
Poplar	0	7.7	0
Hybrid aspen	0	0	2.2
Land use in 2001*			
Spring barley	18.6	10.2	23.4
Winter wheat	17.8	12.1	27.6
Temporary grass	15.3	21.6	20.7
Fallow	14.0	23.9	7.1
Oats	13.3	6.4	3.1
Grazing land	4.0	9.1	6.2
Other	17.0	16.6	12.0

b)			
	Willow (in 2001)	Poplar (in 2001)	Hybrid aspen (in 2001)
Willow (in 2016)	29.4	4.0	0.1
Poplar	0.13	62.6	0
Hybrid aspen	0.01	0	11.0
Land use in 2016*			
Spring barley	18.0	20.4	56.7
Winter wheat	24.0	8.7	10.5
Temporary grass	16.5	28.1	0.0
Fallow	10.8	6.3	2.0
Oats	6.7	0.0	2.1
Grazing land	3.7	0.0	7.5
Other	20.4	36.5	21.1

within the same *blocks*. In addition, part of the hybrid aspen plantations could have been located on previous forest land, that had a difficult classification on the available database. Alternative land uses maps (such as the EEA CORINE Land Cover) were evaluated but did not provide the necessary detail to make effective comparisons. Despite this, the overall assessment of the results based on the sensitivity analysis showed little changes in the shares of land; there were no qualitative changes in the magnitude of the land use changes showed in the results. The large amount of data and the nearly exhaustive basis for the estimates probably compensated the limitations, especially compared to other approaches based on questionnaires or sampling methods, which may have incurred in even larger bias.

The analysis of the data relies on different methods, particularly associated to geostatistical analysis. Concerning the kernel methods, have been applied in similar cases regarding plantations [7], and have proved to be useful and versatile to estimate the frequency distributions: present no constraints, are simple, are flexible and have well-understood statistical properties [24,25]. Concerning the use of cereal productivity as a proxy, it has been shown to be an effective and simple way to assess overall area fertility, as demonstrated in previous research [12,20,30].

The results reflect the initial steps, expansion, stagnation and decline of plantations in the country. From the 1970s, research and funding prioritized the development of willow plantations, with an ambitious plan to create varieties and management regimes that would be viable in the climatic and soil conditions of the country (see Refs. [31,32]). In 1986, the were several commercial plantations, particularly in the central parts of the country, in which it has been defined as the start-up period [33], until 1991. In this period, ambitious goals were set up for the expansion of the cultivation, that lead to the implementation of subsidies for the establishment of new plantations up to 10 000 SEK ha^{-1}, (average exchange rate for 2000 was 1 SEK = 0.118 EUR = 0.109 USD [11]) in addition to other policy incentives like subsidies for transferring crop land from cereal production, fencing, taxes on sulphur

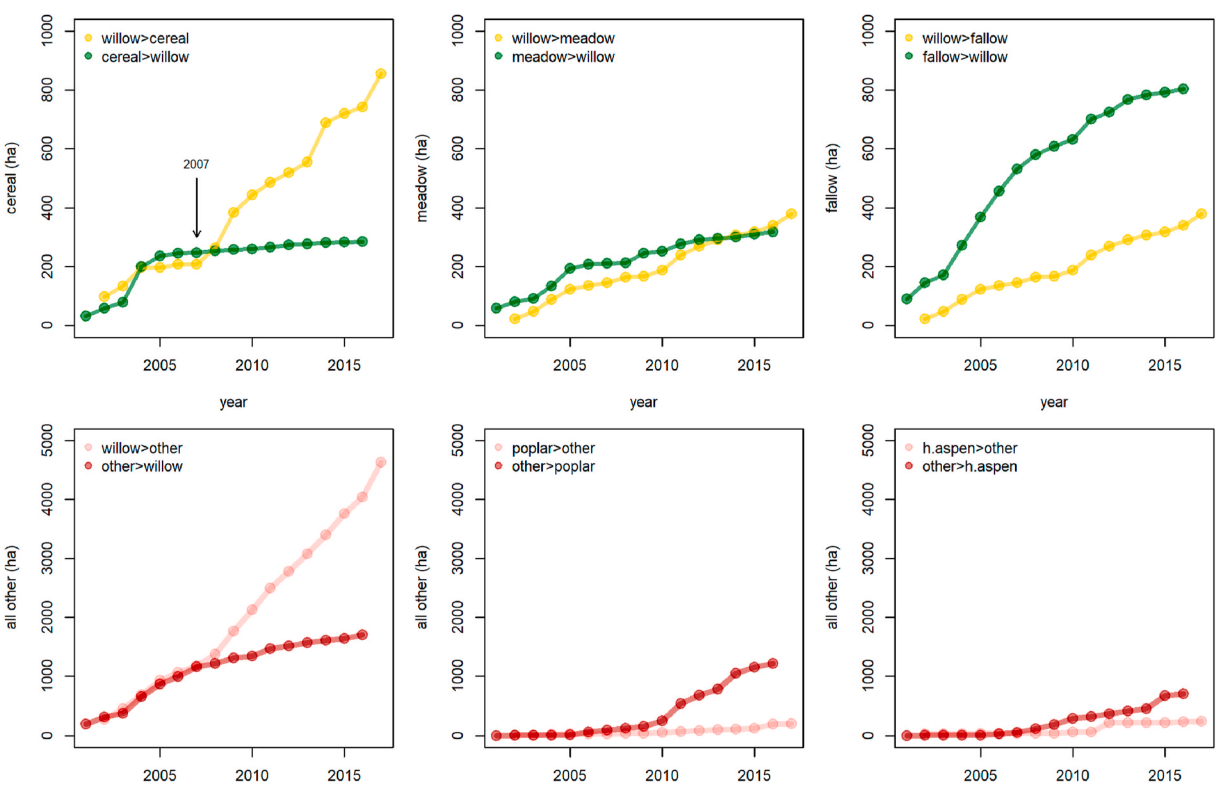

Fig. 6. Accumulated annual land-use change on fast growing plantations in Sweden (2001–2017). After 2007, a considerable amount of willow land was replaced by cereals (represented by: willow > cereal, the order being related to the chronological sequence in land uses).

and CO_2 with exemptions on biofuels, among others (see Ref. [7,34,35]). These policy incentives were drastically modified in 1996, after Sweden joined the European Union and the Common Agricultural Policy. In 1996, the establishment subsidies were reduced to 3000 SEK, and the compulsory set-aside land was reduced from 15% to 10% [35]. In addition, the performance of the plantations during the period was poorer than expected, perhaps paradoxically as a direct consequence of the type of policy incentives applied [36]. During 1996–2006, the price paid to farmers was reduced due to competition from imported biomass and increased incineration of waste [35] and as result, the new planted area annually was practically stopped and about 15 cutting producers left the market [37]. All these developments explain, to varying degrees, the observed stagnation in area planted, which has been observed in similar terms in other places, such as Germany [38], Ireland and United Kingdom [35].

However, the deeper analysis applied to the land use changes show that there was not simply a stop in the planting area, but rather many plantations were abandoned at the same path that newly ones were established on different areas. In fact, previous plantations were established on poor land, often hundreds of kilometers from heating plants [11] and were not economically viable. This rationalization of the production was perhaps a factor explaining the increases in yield during this period [20], since new plantations made use of more productive varieties and better management practices as the incentives were not driven by subsidies.

The results show a new period starting after 2007, which is dominated by a continuous decline in land area planted. Our hypothesis is that this decline was linked to the sudden demand of cereal. In 2007 cereal prices increased by ca. 50% (wheat, barley, oats), and the high price levels have been sustained for a decade. The fact that most of the new cultivations replacing willow plantations are cereals seems to be in line with this hypothesis. However, the results show that over 60% of the current willow plantations were established in the last 15 years, which shows that, despite the strong signs of decline in the figures and in previous works [36,39], there is still interest in willow among farmers. However, this must be taken with caution as less than a third of the land established with plantations before the 2000s remain currently in use.

The overall willow decline has been partly compensated by poplar and hybrid aspen plantations, which started a recent expansion. The fact that these cultivations are mainly established on fallow land or grass means are not affected by the same factors than willow. In addition, these plantations differ from willow as their biomass is not exclusively linked to energy uses, but also for pulp production [40]. The recent increase in woodchip prices may also explain the moderate expansion of these plantations.

In parallel, the cultivation patterns have also changed along the years, particularly concerning willow: there is a larger percentage of smaller plantations in recent years (less than 1 ha), also observed for poplar plantations. In general, large plantations (over 10 ha) are nowadays less frequent. Previous studies have found that smaller plantations have higher yields [41], and the reduction of the plantation size could be a sign of management intensification; in this sense it would be in line with the higher plantation yields observed in later years [20]. However, this would be rather controversial, as in some cases could also mean that farmers are no longer willing to invest in larger land, using only smaller areas on spare land. It must also be observed that the estimates in this study concern only field area and are not grouped by farmer. Rosenqvist et al. [42], estimated that the average willow farm was 11.5 ha, with most of the plantations being larger than 10 ha. Despite the differences in the consideration of *plantation* versus *farm* size, the results show that the profile of willow farmer (thoroughly studied in Refs. [35,42,43]) may have changed significantly.

Studies on farmer adoption patterns regarding plantations have shown different geographic patterns concerning the farmer's decisions related to management or plantation size (e.g. Ref. [44]). As the results show, the main areas for willow cultivation are moving south, largely increasing the share of land planted in Scania, and a simultaneous reduction of planted area in northern areas, which confirms the patters studied in Mola-Yudego and González-Olabarria [7]. The same effect can be observed in poplar plantations, with core areas in the south and eastern coast. As southern areas present a higher agricultural productivity, this could also explain the overall increments in yields in Mola-Yudego [20] and agrees with the estimates on Mola-Yudego [45] from willow, and the empirical estimates of Dimitriou and Mola-Yudego [13] for willow and poplar. In general, farmers in the south and west parts of the country tended to have smaller plantations [43], which could also explain the trends observed in plantation size. In the south (Scania) this trend seems to prevail over the effects of cereal prices. This region has a different land-use structure and farm-based culture than the rest of the country, which could explain the different patterns on plantation adoption, as observed in previous studies [34,42]. This also may reflect that other factors than price may play a role in the farmer's preferences (among others, we can mention well-established markets, higher demand of willow chips, initial success of pioneer growers). The overall results seem to contradict previous studies on farmers adoption patterns. In Greece it was observed that cereal farmers were more likely to be interested in biomass production than non-cereal farmers, and farm size was reported to have a positive effect on adoption intentions [46], which indicate that farmer preferences can also change fast when markets change.

A consequence of the analysis presented in land use change affects the baseline scenarios used for environmental assessment of plantations which has often been to consider cereal as the alternative scenario. For instance, the reference crops for willow plantations have been corn and hay in studies related to greenhouse gases and water quality in the USA [47], winter wheat and winter barley for biodiversity comparisons in the UK [48], or cereals, in general, for soil [49] and water in Sweden [50], among others. On poplar and hybrid aspen, the reference has been grasslands for greenhouse gas emissions and soil organic carbon in the UK [51] and, cereals and grasslands for soil and water quality in Sweden [13], among others. Concerning economic estimates, cereal has also been the main reference crop in Sweden [52].

The results add detail to these general assumptions; in the case of willow, around 33% of new plantations are on fallow land and grasslands, which should be included in future environmental assessments as a reference use in addition to cereal. Since cereal cultivation generally implies more intensive and demanding management, the overall assumption that short rotation plantations (e.g. less intensive management) mainly replace cereal cultivation (e.g. more intensive), disregarding grassland (e.g. less intensive) may result in under-estimating the overall environmental effects of plantations in LCA studies.

It should also be noticed that, among the cereals, some previous studies only considered barley [36], whereas the results show that wheat and oats seem to be replaced by willow and poplar plantations in similar amounts (ca 15%). As there can be differences among these cereals concerning their overall efficiency, as well as LCA profiles [53] and economics [54], the results of this study can be implemented to produce more accurate environmental and economic assessments. The percentages of land-use prior and subsequent establishment of plantations can be used to generate a portfolio of alternatives, each with a distinctive environmental and economic profile. For instance, poplar and hybrid aspen plantations showed higher aggregated carbon stocks compared with grassland, while less water eutrophication compared with cereals [13]; the use of the results of this study can weight these effects to get an overall assessment of the current situation. Similarly, this could be applied to economic calculations concerning opportunity costs (e.g. Refs. [55,56]).

5. Conclusions

The study presents updated information concerning the evolution and location of fast-growing plantations in Sweden along 30 years of data. Willow has experienced a steady decrease, possibly linked to cereal prices after 2007, only to be partially compensated by poplar and hybrid aspen plantations. Overall, the planted areas with willow are moving south and to more productive agricultural areas, with more land planted in Scania and less in the central parts of the country. In opposition, newer poplar plantations are expanding on less productive agricultural districts than the initial ones. Small plantations (<1 ha) are becoming more frequent and large plantations (>10 ha) are nowadays relatively rare. Whereas there could be signs of intensification of the biomass plantations systems, towards smaller and more productive units, it could also reflect a lack of investment by farmers, that are no longer willing to dedicate large areas for plantation systems.

Plantations are mainly replacing spring barley, winter wheat, temporary grass and fallow land, with important differences between willow, poplar and hybrid aspen. The analysis provided synthetized the existing trends in wood biomass plantations in one of the pioneer countries in Europe, and we believe the estimates are extensive and precise, which can be the basis for future studies dedicated to economic or environmental assessments of fast-growing plantations.

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References

[1] K.L. Perttu, Environmental justification for short-rotation forestry in Sweden, Biomass Bioenergy 15 (1) (1998) 1–6.
[2] D. Hoffmann, M. Weih, Limitations and improvement of the potential utilisation of woody biomass for energy derived from short rotation woody crops in Sweden and Germany, Biomass Bioenergy 28 (3) (2005) 267–279.
[3] A. Tullus, L. Rytter, T. Tullus, M. Weih, H. Tullus, Short-rotation forestry with hybrid aspen (Populus tremula L.× P. tremuloides Michx.) in Northern Europe, Scand. J. For. Res. 27 (1) (2012) 10–29.
[4] B. Hjelm, Empirical Models for Estimating Volume and Biomass of Poplars on Farmland in Sweden, Doctoral dissertation, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2015.
[5] J. Ball, J. Carle, A. Del Lungo, Contribution of poplars and willows to sustainable forestry and rural development, Unasylva 221 (56) (2005) 3–9.
[6] A. Roos, R.L. Graham, B. Hektor, C. Rakos, Critical factors to bioenergy implementation, Biomass Bioenergy 17 (2) (1999) 113–126.
[7] B. Mola-Yudego, J.R. González-Olabarria, Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: lessons to be learned about the spread of energy crops, Biomass Bioenergy 34 (4) (2010) 442–448.
[8] B. Mola-Yudego, P. Pelkonen, Pulling effects of district heating plants on the adoption and spread of willow plantations for biomass: the power plant in Enköping (Sweden), Biomass Bioenergy 35 (7) (2011) 2986–2992.
[9] J. Zscheischler, N. Gaasch, D.B. Manning, T. Weith, Land use competition related to woody biomass production on arable land in Germany, in: J. Niewöhner, et al. (Eds.), Land Use Competition, Human-Environment Interactions, 6, Springer, Cham, 2016, pp. 193–213.
[10] N.C. Jungk, G.A. Reinhardt, S.O. Gärtner, Agricultural reference systems in life cycle assessments, in: E.C. van Ierland, A.O. Lansink (Eds.), Economics of Sustainable Energy in Agriculture, Economy & Environment, 24, Kluwer Academic Publishers, Dordrecht, 2002, pp. 105–119.
[11] P. Helby, P. Börjesson, A.C. Hansen, A. Roos, H. Rosenqvist, L. Takeuchi, Market Development Problems for Sustainable Bio-Energy Systems in Sweden: (The BIOMARK Project), Environmental and Energy Systems Studies, Lund University, Sweden, 2004. Report no. 38, Revised version.
[12] B. Mola-Yudego, P. Aronsson, Yield models for commercial willow biomass plantations in Sweden, Biomass Bioenergy 32 (9) (2008) 829–837.
[13] I. Dimitriou, B. Mola-Yudego, Poplar and willow plantations on agricultural land in Sweden: area, yield, groundwater quality and soil organic carbon, For. Ecol. Manag. 383 (2017) 99–107.
[14] R.M. Carthy, Establishment and Early Management of Populus Species in Southern Sweden. Doctoral Dissertation, Swedish University of Agricultural Sciences, Alnarp, Sweden, 2006.
[15] R.M. Carthy, L. Rytter, Productivity and thinning effects in hybrid aspen root sucker stands, For. Ecol. Manag. 354 (2015) 215–223.
[16] L. Rytter, L.-G. Stener, Productivity and thinning effects in hybrid aspen (*Populus tremula* L.× *P. tremuloides* Michx.) stands in southern Sweden, Forestry 78 (3) (2005) 285–295.
[17] L.G. Stenner, L. Rytter, E. Beuker, H. Tullus, R. Lutter, Hybrid Aspen and Poplars in the Baltic Sea Region and Iceland, 41, Skogforsk, Uppsala, Sweden, 2019. ISSN 1404-305X.
[18] JBB, Swedish board of agriculture (jordbruksverket). Kartor och geografiska informations system, In Swedish. Retrieved from, https://nya.jordbruksverket.se/, 2019, 23 October, 2019.
[19] P.W. Owen, N. Milionis, I. Papatheodorou, K. Sniter, H.F. Viegas, J. Huth, R. Bortnowschi, The land parcel identification system: a useful tool to determine the eligibility of agricultural land—but its management could be further improved, Special Report (2016) 25.
[20] B. Mola-Yudego, Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000, Biomass Bioenergy 35 (1) (2011) 446–453.
[21] Swedish Official Statistics, Standard yields for yield survey districts, counties and the whole country, Several years, 2017). In Swedish. Retrieved from, https://www.scb.se, 2003, 23 October, 2019.
[22] FAOSTAT, Food and agriculture organization of the united nations, Retrieved from, http://www.fao.org/faostat/en/#data/PP, 2019, 27 May, 2020.
[23] B.J. Worton, Kernel methods for estimating the utilization distribution in home-range studies, Ecology 70 (1) (1989) 164–168.
[24] B.W. Silverman, Density Estimation for Statistics and Data Analysis, Chapman and Hall, London, 1986.
[25] W.H. Burt, Territoriality and home range concepts as applied to mammals, J. Mammal. 24 (3) (1943) 346–352.
[26] R core Team, R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, 2020. https://www.R-project.org/.
[27] C. Brunsdon, H. Chen, GISTools: some further GIS capabilities for R. https://CRAN.R-project.org/package=GISTools, 2014.
[28] A. Karačić, Production and Ecological Aspects of Short Rotation Poplars in Sweden 2005, 13, 2005, p. 42. Uppsala.
[29] J.C. Bergstrom, A. Randall, Resource Economics: an Economic Approach to Natural Resource and Environmental Policy, fourth ed., Edward Elgar Publishing Limited, Cheltenham, UK·Northampton, MA, USA, 2016.
[30] K. Ericsson, L.j. Nilsson, Assessment of the potential biomass supply in Europe using a resource-focused approach, Biomass Bioenergy 30 (1) (2006) 1–15.
[31] L. Zsuffa, Genetic improvement of willows for energy plantations, Biomass 22 (1–4) (1990) 35–47.
[32] J.G. Isebrands, J. Richardson, Poplars and Willows: Trees for Society and the Environment, The Food and Agriculture Organization of the United Nations and CABI, 2013, p. 634.
[33] B. Mola-Yudego, I. Dimitriou, S. Gonzalez-Garcia, D. Gritten, P. Aronsson, A conceptual framework for the introduction of energy crops, Renew. Energy 72 (2014) 29–38.
[34] B. Mola-Yudego, P. Pelkonen, The effects of policy incentives in the adoption of willow short rotation coppice for bioenergy in Sweden, Energy Pol. 36 (8) (2008) 3062–3068.
[35] K.N. Lindegaard, P.W.R. Adams, M. Holley, A. Lamley, A. Henriksson, S. Larsson, H.G. von Engelbrechten, G. Esteban-Lopez, M. Pisarek, Short rotation plantations policy history in Europe: lessons from the past and recommendations for the future, Food and Energy Security 5 (3) (2016) 125–152.
[36] I. Dimitriou, H. Rosenqvist, G. Berndes, Slow expansion and low yields of willow short rotation coppice in Sweden; implications for future strategies, Biomass Bioenergy 35 (11) (2011) 4613–4618.
[37] S. Larsson, K. Lindegaard, Full scale implementation of short rotation willow coppice, SRC, in: Sweden. Agrobränsle AB, Örebro, Sweden, 2003.
[38] M. Lieseba, Poplars and Other Fast Growing Tree Species in Germany: Report of the National Poplar Commission. 2016-2019, Johann Heinrich von Thünen-Institut, Braunschweig, 2020, p. 36. Thünen Working Paper 141a.
[39] H. Rosenqvist, P. Aronsson, K. Hasselgren, K. Perttu, Economics of using municipal wastewater irrigation of willow coppice crops, Biomass Bioenergy 12 (1) (1997) 1–8.
[40] L. Christersson, Poplar plantations for paper and energy in the south of Sweden, Biomass Bioenergy 32 (11) (2008) 997–1000.
[41] B. Mola-Yudego, O. Díaz-Yáñez, I. Dimitriou, How much yield should we expect from fast-growing plantations for energy? Divergences between experiments and commercial willow plantations, BioEnergy Research 8 (4) (2015) 1769–1777.
[42] H. Rosenqvist, A. Roos, E. Ling, E.B. Hektor, Willow growers in Sweden, Biomass Bioenergy 18 (2) (2000) 137–145.
[43] A. Roos, H. Rosenqvist, E. Ling, B. Hektor, 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) (2000) 28–34.
[44] G. Tate, A. Mbzibain, S. Ali, A comparison of the drivers influencing farmers' adoption of enterprises associated with renewable energy, Energy Pol. 49 (2012) 400–409.
[45] B. Mola-Yudego, Regional potential yields of short rotation willow plantations on agricultural land in Northern Europe, Silva Fenn. 44 (1) (2010) 63–76.
[46] C. Panoutsou, Bioenergy in Greece: policies, diffusion framework and stakeholder interactions, Energy Pol. 36 (10) (2008) 3674–3685.
[47] A.S. Bressler, P.G. Vidon, T.A. Volk, Impact of shrub willow (Salix spp.) as a potential bioenergy feedstock on water quality and greenhouse gas emissions, Water, Air, & Soil Pollution 228 (2017) 170.
[48] I. Vázquez-Rowe, S. Rege, A. Marvuglia, J. Thénie, A. Haurie, E. Benetto, Application of three independent consequential LCA approaches to the agricultural sector in Luxembourg, Int. J. Life Cycle Assess. 18 (8) (2013) 1593–1604.

[49] I. Dimitriou, B. Mola-Yudego, P. Aronsson, J. Eriksson, Changes in organic carbon and trace elements in the soil of willow short-rotation coppice plantations, BioEnergy Research 5 (2012) 563–572.
[50] I. Dimitriou, B. Mola-Yudego, P. Aronsson, Impact of willow short rotation coppice on water quality, BioEnergy Research 5 (3) (2012) 537–545.
[51] Z.M. Harris, R. Spake, G. Taylor, Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions, Biomass Bioenergy 82 (2015) 27–39.
[52] P. Helby, H. Rosenqvist, A. Roos, Retreat from Salix—Swedish experience with energy crops in the 1990s, Biomass Bioenergy 30 (5) (2006) 422–427.
[53] G. Brankatschk, M. Finkbeiner, Application of the Cereal Unit in a new allocation procedure for agricultural life cycle assessments, J. Clean. Prod. 73 (2014) 72–79.
[54] H. Rosenqvist, Kalkyler För Energigrödor, JBB publications ovr443, 2018, p. 98 (in Swedish).
[55] H. Rosenqvist, Salixodling - Kalkylmetoder Och Lönsamhet [Willow Cultivation - Methods of Calculation and Profitability]. För Skog-Industri-Marknad Studier, Doctoral dissertation, Sveriges Lantbruksuniveritet (SLU), Uppsala, Sweden, 1997.
[56] K. Ericsson, H. Rosenqvist, E. Ganko, M. Pisarek, L. Nilsson, An agro-economic analysis of willow cultivation in Poland, Biomass Bioenergy 30 (1) (2006) 16–27.