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Mapping the expansion and distribution of willow plantations for bioenergy in Sweden: Lessons to be learned about the spread of energy crops

Blas Mola-Yudego^{a,*}, José Ramón González-Olabarria^b

^a University of Joensuu, Faculty of Forest Sciences, PO Box 111, FI 80101 Joensuu, Finland

^b Centre Tecnològic Forestal de Catalunya, Pujada del Seminari, s/n. 25280 Solsona (Lleida), Spain

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ABSTRACT

Where and when farmers will adopt new energy crops is a key issue for the proper development of a country's energy strategy on renewables based in bioenergy. This paper analyses the spread of willow cultivation for bioenergy in Sweden, during the period 1986–2005, linked to the changes in the policies of promotion of wood-energy crops and to the local economic framework. To perform the study, a geostatistic method based on kernel analysis is applied, in order to identify the spatial grouping patterns of growers and plantations, and the areas where cultivation was successful. The analysis of the resulting figures shows that the development of an infrastructure and a market for willow chips are essential pre-conditions for the development of short rotation coppice for bioenergy. The results of this study confirm that probably the most important factor in the location of willow plantations is the existence of consumers that can guarantee a long-term demand for willow chips. The tools and methods presented, and its analysis, can provide a better understanding of the interactions between the biomass producers, the energy consumers and the different local and national actors.

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1. Introduction

Sweden is considered as an example of the successful development and use of energy plantations for bioenergy [26]. In the years prior to 1990, the use of biofuels by the district heating sector was already well established, and increased during the decade, providing a market and infrastructure for the use of the harvested willow chips [11]. In addition, several policy measures were implemented in order to promote willow plantations and enlarge the area planted. As a consequence, during the 1990s, the area of willow plantations for

bioenergy expanded significantly, reaching a total of 16,000 ha planted [13].

According to the application of the policy measures and their effects, the spread and expansion of commercial willow cultivation can be divided into three periods. The initial period, or *early adopters*, started in the late 1980s. The first commercial plantations were established in 1986, with the number of farmers establishing willow plantations growing slowly until 1990 [15]. In 1991 there was an important change in the agricultural policy in Sweden, since a set of incentives were introduced in order to promote willow plantations,

* Corresponding author. Tel.: +358 132514408; fax: +358 132514422.

E-mail address: blas.mola@joensuu.fi (B. Mola-Yudego).

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which lead to a significant expansion of the surface planted. During the period 1991–1996, a specific subsidy for willow plantations of 10 000 SEK¹ ha^{−1} was available for willow plantations [11]. Parallel to these measures, taxes on sulphur and CO₂ for the use of fossil fuels in heat production were introduced, and were progressively increased in subsequent years to different levels: 0.25 SEK/kg CO₂ in 1991, 0.32 SEK/kg CO₂ in 1993, and 0.36 SEK/kg CO₂ in 1996 [11,7]. Since biofuels were exempt from these taxes, they became more competitive against fossil fuels. As a result of all these changes, the planted area during this period increased almost exponentially [16].

The year 1996 was a turning point in the expansion of willow. As a result of the inclusion of Sweden in the EU, the planting subsidy was reduced to 3300 SEK ha^{−1} (about a third of its previous amount), and the number of new plantations dropped significantly. During this period, the taxes on CO₂ increased again, to 0.52 SEK/kg CO₂ in 2001, while energy taxes were reduced [11]. In 1999 the subsidy for the establishment of willow was raised to 5000 SEK ha^{−1} (50% of the pre-1996 value), and new willow plantations were established. However, this did not result in an increase in the total area planted due to the fact that many plantations that were poorly established in the 1990s were removed at the same rate than new plantations were established [16].

In general, it was considered that the central-eastern parts of Sweden would enclose those areas with higher concentration of willow plantations. One of the reasons given for this pattern of distribution is that the agricultural land in these areas is mostly of medium productivity for grain, which makes willow cultivation slightly more profitable [9]. Another reason is the proximity of the population centres in the south of Sweden to the coast, which provides good conditions for transporting biomass [18,11]. Additionally, local and regional variation of the geographic pattern of willow cultivation has been attributed to different levels of interest among local agricultural cooperatives and advisers [11].

The spread of willow cultivation has an evident geographical component. However, very few models of wood bioenergy production systems, including willow cultivation, have been addressed specifically to take into account the geographical distribution and characteristics of such systems. In Sweden, Roos et al. [18] studied the geographic pattern of the wood fuel availability, combining different aggregation levels of supply and demand figures. Regarding the supply of energy crops specifically, the adoption of willow plantations by local farmers in Sweden was studied using five geographical divisions [19] and at a municipality level [15]. Additionally, Rosenqvist et al. [20] presented a descriptive analysis of the distribution of areas planted in 1995, at a county level. In general, one of the reasons for this low amount of studies in the field is the limited access to empirical data: in the EU, only the Swedish plantations provide extensive commercial experience for a sufficient interval of time to analyse changes in the distribution patterns of the willow plantations. Another limitation of the previous studies is the lack of a statistical method specifically addressed to their geographical distribution.

A possible methodology that fulfils this limitation is the kernel analysis [21]. In this approach, given a set of locations (i.e. plantations of energy crops), it is possible to estimate the spatial distribution of probabilities of occurrence, which permits showing the relative likelihood that further plantations will be established in various parts of the studied region, based upon the location of the previous plantations. This technique is distribution free, since instead of being based on distributional assumptions it attempts to estimate these from the data available [1]. By this means, we can map the probability distribution of energy crops in a given area, and analyse the areas where the highest concentration of energy plantations are located. The study of the geographical component of willow cultivation can therefore reveal where willow adoption has been successful, and can provide basis for further analysis about the factors encouraging or restricting the expansion of energy crops.

In the near future, it is anticipated that there will be an important enlargement of the area cultivated with energy crops in Europe, with the achievement of the goals set by the European Commission, expressed in the Biomass Action Plan [2], the Energy Policy for Europe [3] and the objectives of the directive on the promotion of the use of energy from renewable sources [4]. The development of methods to study the expansion and adoption of new energy crops by farmers will then play a key role in the successful development of the energy plans. In this study we present a methodology to examine the spread and distribution of the willow cultivation in Sweden, during the period 1986–2005, based on empirical data and geostatistical analyses. The overall aim is to identify areas with high concentrations of willow plantations, and to analyse the possible factors in creating the conditions for a successful development of willow cultivation.

2. Material and methods

2.1. Data origin

The data from the growers and their plantations were provided by Lantmännen Agroenergi AB (formerly known as Agrobränsle AB), which manages planting and administrates the harvesting of willow plantations. The records included references to the ownership as well as the year of establishment of the plantations. Data with inconsistent records or lacking information regarding the ownership of the plantations, the area planted or the location were excluded from the calculations. All plots were geo-referenced to a 1 km precision. The data included a total of 1164 growers and 13,110 ha planted in the area studied during the period 1986–2005. The location of the willow grower was assumed to be the location of the first plantation of the specific grower, and the corresponding year was considered to be the year of adoption.

The information regarding the combined heat and power (CHP) plants was extracted from Junginger et al. [12], and Evald and Witt [8]. Finally, the data regarding the distribution of agricultural land was based in the Image & Corine Land Cover 2000 (I&CLC2000) vector map for Sweden [5] using a 250 m resolution.

¹ Approximately, at 1991 exchange rates 10 SEK = 1.33 EUR.

2.2. Geostatistical methods

The analysis of the location and spread of the willow plantations in Sweden is based on geospatial kernels. This approach is a non-parametric method for the estimation of the spatial distribution of probabilities based on a pool of observed events. For a spatial region a continuous grid is first created, and the probability of occurrence of a specific event for all the points of the grid is calculated. This calculation is made according to the observed events, creating a density function according to the frequency of the plantations. The function of density is subsequently calculated for all the points on the grid, which results in a continuous distribution of the density of frequency for all the territory studied.

The kernel function used in this study is based on a normal bi-variate distribution curve, where the variables analysed are the Universal Transverse Mercator (UTM) coordinates of the willow plantations and the willow growers, following the equation:

$$K(x, y) = \frac{1}{2\pi nh^2} \sum_{i=1}^n \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2h^2}\right) \quad (1)$$

where $K(x, y)$ is the estimated density function for the point (x, y) , h is the bandwidth or smoothing parameter, which affects the dispersion of the density function, x and y are the coordinates of a point inside the studied area, and x_i and y_i are the coordinates of the n observed willow plantations.

The smoothing factor (h) will determine the level of aggregation of the data in the density function, and significantly affects the final outcome [21,25]. Although there is not a broadly accepted methodology to determine the optimal smoothing factor [21,1], a common method is an *ad hoc* choice, referring h to a parameter [25]. In this study, the parameter of reference was calculated according to the following equation [24]:

$$h_{ref} = n^{-1/6} \sqrt{\frac{var_x + var_y}{2}} \quad (2)$$

where h_{ref} is the reference value used to calibrate h , n is the number of plantations and var_x and var_y are the estimated standardised variances of the x and y coordinates, respectively. The final calculations are based on variable kernels, where the smoothing parameter is not fixed along the locations, being lower in areas with low concentration of plantations. By this means, the plantations in bordering areas are not over-represented.

The values of reference were calculated for several time intervals. Different values of h were applied and compared, with the final version being based on a smoothing parameter of 40% of the reference value h_{ref} (Eq (2)). The kernel estimations were based on the HRE (Home Range Extension) package in ArcGis v 9.0 developed by the Centre for Northern Forest Ecosystem Research (CNFER) [17].

To analyse the resulting kernel estimations, raster maps with standardised isopleths were created. The isopleths were based on percent volume contours (PVC), in order to compare areas with high density of plantations in the different periods of study. The PVC define the volumes under the utilisation distribution, and represent a defined percentage of

plantations in the smallest possible area. For instance, the isopleths containing the 10th percentile area shows the areas with the highest density of plantations, since it represents the smallest possible area to contain 10% of all the plantations established (the core area). On the other hand, the 90th percentile area represents the lowest density, since it contains almost the total number of plantations. The resulting maps were presented using a 150×150 grid cells resolution.

In order to study possible variables that may explain the distribution pattern of the plantations, the resulting values of volume and density were calculated for areas with different agricultural productivity, which was estimated by using the average yield of oats for the period 2003–2005 by districts, as calculated by the Swedish National Board of Agriculture [22]. In addition, the volume and density averages were calculated for areas within 10, 20 and 30 km from the location of all the CHP plants analysed. In order to simplify calculating the average values and preserving the highest level of detail possible, the resulting PVC were first converted into a new grid of points defined by $2 \text{ km} \times 2 \text{ km}$. Since willow plantations are located on agricultural land, in this grid points falling inside agricultural areas were only included, or within a radius of 2 km, as defined by the Corine land uses map (EEA 2000). The average values for the areas were therefore calculated using the resulting values of the points in the grid.

3. Results

The resulting contours for growers and plantations showed a similar pattern. In order to facilitate the visual interpretation of the distribution of plantations and willow growers, the values are grouped in three levels: 30%, 60% and 90%, representing high, medium and low densities, respectively (Fig. 1).

The proposed division into three periods is shown in Fig. 2. The willow plantations in the initial period (1986–1990) were concentrated mainly around the area of Örebro, in central Sweden. A less prominent concentration of plantations was identified in the northernmost area of distribution of the willow plantations. Plantations established in the subsequent period (1991–1996), were concentrated around the areas of Örebro, Enköping and Kristianstad, in central, east-central and southern parts of the country, respectively. This distribution was similar during the final period studied (1997–2005).

The shares of plantations established during the three periods defined were 13%, 70%, 17% of the total number, respectively (Table 1), which resulted in significantly lower values of the h_{ref} during the period 1991–1996. Therefore, due to the presence of a larger number of plantations, the predictions of the areas representing high concentrations of willow plantations are more accurate during this period.

Due to the different shares of the number of plantations between the periods, the relationship between the absolute values of density of plantations and the PVC used in the study (Fig. 3) was different in the second period. However, the relative values between the periods are equivalent when using the PVC.

During the initial period (1986–1990), the average agricultural productivity of the areas with high concentration of plantations was appreciably lower than during the middle period (1991–1996). Following these trends, during the last

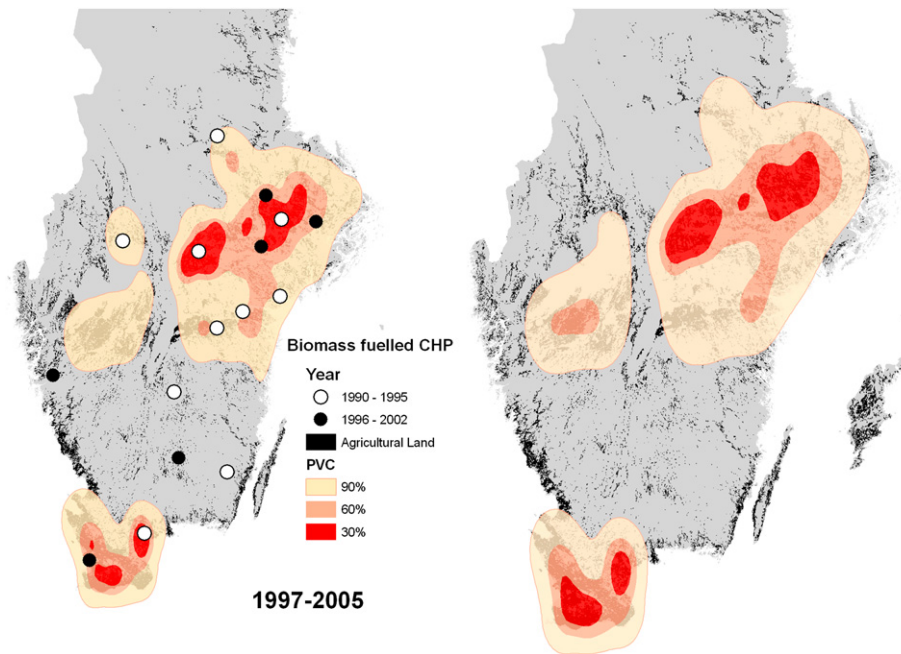


Fig. 1 – Areas with high, middle and low concentrations of plantations (left) and willow growers (right) according to the percent volume contours (PVCs) resulting from the calculations, during 1986–2005. The wood-fuelled central heating plants (CHP) are included on the left map, according to the year they started using biomass as fuel.

period studied (1996–2005) the plantations were concentrated in areas of higher agricultural productivity (Fig. 4).

The analysis of the presence of plantations around the CHP plants (Fig. 5), shows significant concentrations during the period 1991–1996 around the CHP plants of Örebro, Enköping and Kristianstad. In these three cases, the level of concentration (plantation density) is increasing with the proximity to

the CHP plants. During the period 1997–2005, there are observed concentrations around the CHP plants of Örebro, Enköping and Lomma. In these three cases, the concentration of plantations is also increasing with the proximity, and moderate concentrations around the CHP plants of the municipalities of Eskilstuna and Sala. In this period there is no clear concentration around the plant of Kristianstad.

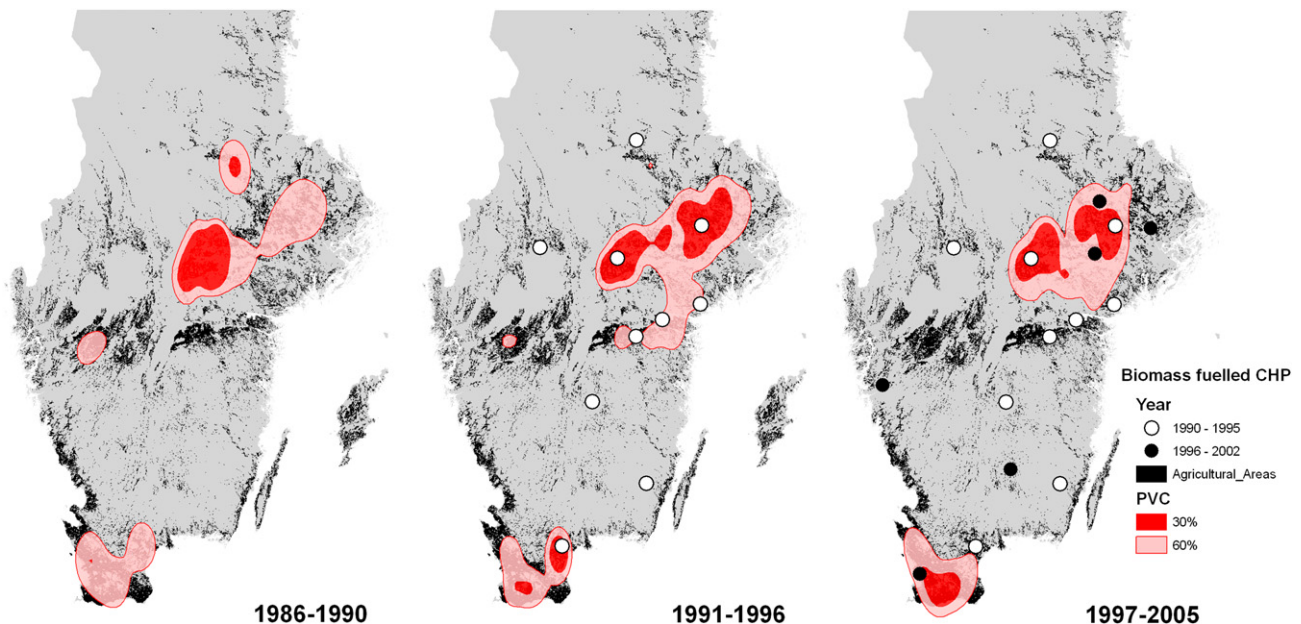


Fig. 2 – Evolution of the areas with high concentration of willow plantations for the three periods defined, resulting from the calculated percent volume contours (PVCs). For each period, previous plantations are excluded from the analyses. The maps include the location of the central heating plants (CHP) by the year when started using biomass as fuel.

Table 1 – Number of willow growers and plantations included in the analysis, variances, and calculated smoothing parameter of reference, according to the Eq (1).

	Growers	Plantations	1986–1990	1991–1996	1997–2005
	1986–2005	1986–2005			
N	1164	3450	442	2427	579
Var(x)	9412	8745	8048	8926	8142
1000 km					
Var(y)	30322	27904	26673	27132	31411
1000 km					
h_{ref}	0.308	0.247	0.362	0.273	0.346
N: Number of growers/plantations included.					
Var: Variance.					
h_{ref} : Smoothing parameter of reference (Eq (2)).					

4. Discussion

The calculations used in this study are based on empirical data about willow cultivation in Sweden for the period 1986–2005. The data available included extensive information about a high proportion of all the areas planted in Sweden during the period studied, including their location, the year of the establishment of the plantations and the ownership. Although it did not include the absolute total number of willow plantations, since some records lacked the geographical location or the specific year of establishment, it included, however, more than the 80% of the total estimated area planted with willow in Sweden during the studied time-frame.

The statistical methods performed to analyse the concentration of probabilities based on kernel distributions provide several advantages to describe the distribution of willow plantations in Sweden, and the spread throughout the country during the last 20 years. The method does not assume a defined distribution, and it is rather flexible and easy to apply, allowing the definition of the ranges where willow is spread, and the identification of the areas where there is a high concentration of plantations.

However, one of the most important parameters when defining the density distribution is the smoothing factor [21,25]. A high smoothing factor tends to find general trends, with the loss of an important part of the information. A low smoothing factor can reveal more detailed changes, although it can also identify as aggregation points randomly distributed. It is generally accepted that a smoothing factor must be defined according to the nature of the study, and different methodologies have been proposed [24], although no general rules have been broadly adopted [21]. In the case studied, several reasons point to a medium level of smoothness. The location of the plantations is determined at a 1 km definition, which could present features of uniform distribution if the data is treated with high detail. In addition, the willow plantations are located on agricultural land, which it is not evenly distributed in the area, and locations with a patched distribution of agricultural land can also be revealed as kernel aggregations due to an edge effect. In both cases, these features could be compensated by a middle level of smoothing

factor that would reduce the effect of such factors of noise. It is possible that the study of the willow plantations in a homogeneous area (i.e. a region, county, case study) could allow lower levels of smoothing factor, in order to find more precise aggregations.

The analysis of the distribution of plantations, during the different pre-defined periods considered, revealed important effects of the policy incentives applied to willow plantations. During the initial period, prior to the introduction of the establishment subsidy in 1991, the willow plantations seemed to concentrate around the area of Örebro, with an additional secondary centre, of smaller size, around the municipality of Hedemora, in the north-east region of the willow planted area. In that period, the region of Örebro already had a well established district heating system based on wood biomass. The municipality's consumption of wood fuels, by the district heating systems, was as high as 395 GWh in 1992, which reveals a previous infrastructure that could be used for willow chips. The area was also a pioneer in the commercial plantation of willow for bioenergy, and it is the headquarters of Aggrobränsle (now known as Lantmännen Agroenergi), which was particularly involved in the promotion, planting and marketing of willow varieties for biomass plantations, as well as the development and management of the sector. In previous research has been pointed out the important relation of the interest of advisers and cooperatives on local adoption of willow [11,15]. The fact that this area provides the higher concentration of plantations, not only during the initial, but in the whole period studied, underlines the important effects that active promotion can have for the diffusion and adoption of willow coppice, together with marketing campaigns and transfer of knowledge to the local farmers [23].

During the expansion period 1991–1996, when the establishment subsidy was introduced, two additional concentration areas were identified, in the municipalities of Enköping and Kristianstad. In both cases, a new wood biomass fuelled CHP plant was established during that period. In Enköping, the main central energy plant was completed in 1994, with a capacity of 55 MW of heat and 24 MW of electricity, in addition to a wood powder-fired boiler (22 MW) and two oil-fired boilers (combined power of 75 MW). Regarding the fuel, between 10% and 20% of the biofuels consumed by the power plant came from willow plantations [14]; [6]. In Kristianstad, a new CHP fuelled with biomass was also built in 1994, with a heat capacity of 35 Wh [12]. The overall consumption of wood fuel grew significantly in both municipalities. In Enköping, the capacity increased from 102 GWh in 1992, to 250 GWh in 1996. In Kristianstad, in 1992, there was no use of wood fuel in the district heating systems, with it reaching 177 GWh in 1996.

The wood-fuelled CHP plants have played a central role in the rapid expansion of bioenergy in Sweden [11], and in general terms, the demand of wood fuels has been considered as a driving factor behind the development of the bioenergy sector and the spread of willow cultivations in Sweden [9]. During the 1990s, new wood-fuelled CHP systems were established in Sweden or former oil-fuelled systems were converted to use wood fuels [12], mainly due to the taxation system. This resulted in increments of the demand for wood fuels [11] and the development of a chain to supply forest

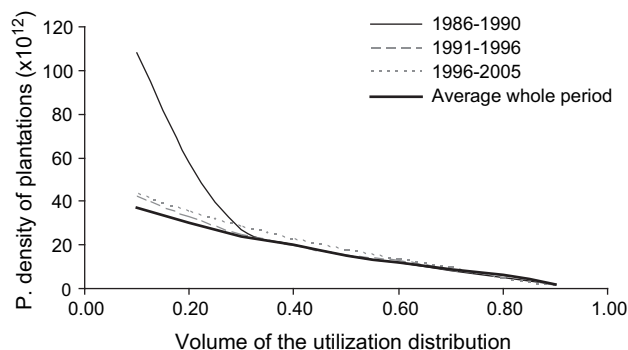


Fig. 3 – Relation of the probability density of willow plantations according to the disaggregated volume of the utilisation distribution, for the studied periods. In general, high values of volume suggest a low concentration of willow plantations, whereas low values suggest a high concentration.

biomass, which also contributed to the development of the logistics associated with the economy of the willow chips. Furthermore, the existence of a wood fuel energy plant with increasing demand for wood fuel provides guarantees to local farmers about a future market for their chips, and therefore increases their confidence and reduces the uncertainties and risks associated with willow cultivation [20]. The reduction of risks is very important in what is perceived as a significant investment due to the high establishment costs of willow plantations, and the time expected to make it profitable, as compared to annual agricultural crops. The assurance of a market for willow chips is then acting as a pulling factor in the development of the willow cultivation in the area.

Research by Helby et al. [10] found that the reasons that motivated farmers to start a plantation were identified as: changing the workload on the farm, the subsidies and expected policies, good income from sale of the crop, and site conditions more suitable for willow cultivation than for cereals. In this line, previous studies have shown slight economic advantages for food production versus willow in good soils, where crop production is high [9]. According to this

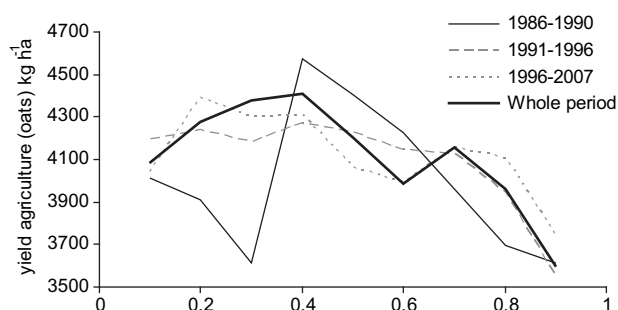


Fig. 4 – Agricultural productivity for different willow densities during the periods studied, according to the methodology proposed. Values close to 1 of the volume of the utilisation distribution suggest a low concentration of willow plantations, whereas low values suggest a high concentration.

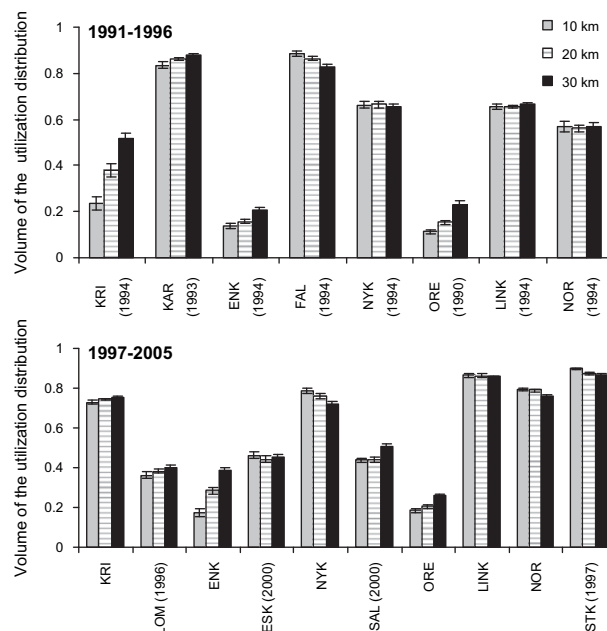


Fig. 5 – Average values of the volume of the utilisation distribution calculated around the main wood-fuelled CHP plants. High values suggest a low concentration of willow plantations, whereas low values suggest a high concentration. The values are calculated for buffer areas of 10, 20 and 30 km around the plants, for the periods 1991–1996 (above) and 1996–2007 (below). The abbreviation stands for the municipality and in brackets there is the year of establishment/conversion to wood-fuelled plant. KRI: Kristianstad; KAR: Karlstad; ENK: Enköping; FAL: Falun; NYK: Nyköping; ORE: Örebro; LINK: Linköping; NOR: Norrköping; LOM: Lomma; ESK: Eskilstuna; SAL: Sala; STK: Stockholm.

economic model, willow cultivation would be more likely to be grown on inferior soils, and would therefore be expected in agricultural areas of medium productivity. Although this point seems to stand, with most of the willow plantations concentrated in the central parts of Sweden, the observed trend is that willow cultivation is progressively spreading towards agricultural areas with higher productivity.

Although the regional productivity can play an important role, the results of this study point out that the most important factor in the location of willow plantations is the existence of consumers that can guarantee a long-term demand for willow chips. Willow is planted in areas where the local actors have a collaborative position towards the willow cultivation, which helps the establishment of long-term contractual relationships between the farmers and the district heating plants. This point, however, would have to be confirmed by further research.

5. Conclusions

This is the first study to the authors' knowledge that analyses the distribution and spread of willow plantations in Sweden,

based on a geostatistical method. The methodology proposed helps to identify areas where willow cultivation was successful, and the analyses performed revealed the importance of the development of a market and a demand on the spread of the willow cultivation, as well as active promotion among the local farmers and positive attitudes from the local actors. Further analysis of the distribution patterns of the energy plantations can help the implementation of energy programmes in countries initiating or expanding their areas dedicated to energy crops, and can aid policy makers in achieving their goals. The method proposed, complemented by additional variables, can also be used in future research in order to study, in more detail, the spread and distribution of energy crops, and even future predictive applications, to define optimal or expected locations, could be derived.

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