Dissertationes Forestales 84

Wood biomass production potential on agricultural lands in Northern Europe – achieving the goals of energy policy

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Academic dissertation

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ABSTRACT

Short rotation forestry for bioenergy is an important means of meeting renewable energy targets for the shift towards a more sustainable energy model. This research focuses on the production and expansion of short rotation willow coppice on agricultural land in Northern Europe, based on empirical data from a large sample of commercially managed plantations. The thesis reviews six manuscripts concerning: the current yields of willow plantations in Sweden, for first, second and third cutting cycles (Paper I), the yield trends for the first cutting cycle during the period 1986-2000 (Paper II), the use of remote sensing in order to assess productivity from willow plantations (Paper III), the geographical spread of willow cultivation in Sweden (Paper IV) and the effect of policy incentives on the expansion of willow cultivation in Sweden during the period 1986-2006 (Paper V). The final paper presents estimates of productivity potential from willow plantations on agricultural land on six EU countries in Northern Europe (Paper VI).

The results of the analysis of yield performance (Paper I) show a great variability between growers, which suggests the importance of proper management in the establishment and tending of the plantations. Although the average yields of the first established plantations were significantly lower than previous estimates, the results show a clear trend of yield improvement over time (Paper II). During the period studied, the average productivity of the plantations increased each year by 0.20 odt ha^{-1} yr^{-1}, and in the best managed plantations 0.27 odt ha^{-1} yr^{-1}, possibly due to the release of improved willow clones and management practices. In addition to regional estimates, the thesis also provides tools for the assessment of yield at plantation level using remote sensed images, with reasonable levels of accuracy (Paper III).

The research stressed the role of policy incentives as an important tool for the spread of short rotation forestry (Paper IV), which significantly affects the adoption of willow cultivation by local farmers (Paper V). The thesis offers methodological tools to analyse and measure these effects, confirming the importance of consumers that can guarantee a long-term demand for willow chips. Finally, the models performed during the study serve as a basis for yield projections for Finland, Denmark, Estonia, Latvia, Lithuania and Sweden, assuming different scenarios of productivity (Paper VI).

The final conclusions of this thesis show that the conditions for a successful development of the sector include the spread of know-how based on research, skilled growers, existence of an infrastructure and favourable policies. The yield estimates and projections not based on empirical data can significantly over-estimate the actual production of new biomass cultivations. Finally, the models and tools provided can be useful for energy management and planning, and are a starting point for further research on the topic and for management and economic considerations.

Keywords: Empirical growth and yield models, productivity trends, remote sensing, adoption models, short rotation forestry, energy policy and planning, bioenergy, renewable resources.

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Joensuu, March 2009

Blas Mola-Yudego

LIST OF ORIGINAL PAPERS

This research thesis is a review of the following papers, which will be referred in the text by Roman numerals, I – VI.

I MOLA-YUDEGO B., ARONSSON P. 2008. Yield models from commercial willow plantations in Sweden. Biomass and Bioenergy, 32: (9) 829-837. doi:10.1016/j.biombioe.2008.01.002

II MOLA-YUDEGO B. Trends and improvements of the yields from commercial willow plantations in Sweden during the period 1986-2000. Submitted manuscript.

III MOLA-YUDEGO B., SELKIMÄKI M. Estimation of yields of commercial short rotation forest plantations in Central Sweden using Landsat ETM+ imaginery. Submitted manuscript.

IV MOLA-YUDEGO B., GONZÁLEZ-OLABARRIA J. R. Mapping the expansion and distribution of willow plantations in Sweden: lessons to be learned about the spread of energy crops. Submitted manuscript

V 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. doi:10.1016/j.enpol.2008.03.036

VI MOLA-YUDEGO B. Regional potential yields of short rotation willow plantations on agricultural land in Northern Europe. Submitted Manuscript.

B. Mola-Yudego was responsible for the data preparation and analyses, compiling the results and writing all the studies. In articles I, III, IV and V, P. Aronsson, M. Selkimäki, J. R. González-Olabarría and P. Pelkonen, when they were co-authors, participated in the planning of the study and discussion of the results. Papers I and V are reprinted with kind permission of the journals concerned.

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ACRONYMS, ABBREVIATIONS AND UNITS

CEC	Commission of the European Communities
CHP	Combined Heat and Power
EEA	European Environmental Agency
EU	European Union
EUR	Euro (currency)
FAO	Food and Agriculture Organisation of the United Nations
GWR	Geographically Weighted Regression
NDMI	Normalised Moisture Vegetation Index
NDVI	Normalised Difference Vegetation Index
PVC	Percent Volume Contours
RMSE	Root Mean Squared Error
SEK	Swedish Krona (currency)
SRF	Short Rotation Forestry

toe	ton of oil equivalent
odt	oven dry ton
Wh	Watt hour

k =Kilo =10^3
M =Mega, Million =10^6
G =Giga =10^9
T =Tera =10^{12}
P =Peta =10^{15}
E =Ekta =10^{18}

Conversion coefficients

	toe	MWh	GJ
toe	1	11.630	41.868
MWh	0.08598	1	3.6
GJ	0.02388	0.2778	1

1 INTRODUCTION

1.1 Policy aims for Short Rotation Forestry

All issues concerning energy supplies are of capital importance in the present international context, especially since the European Union (EU) energy supply is mainly based on oil, the price of which reached historical levels in 2008 (EIA 2008). The EU energy policy sets the security of energy supply, the competitiveness and the importance of sustainable, environmentally friendly sources of energies as its main goals (CEC 2002). Additionally, climate change has become a major international issue, due to the concern regarding the potential impact of increasing CO_2 levels on the climate. In this context, the research presented is an attempt to provide technical tools for achieving the political goals and the demands of both society and industry.

The European Commission expects the EU to increase its bioenergy production up to 1570 TWh (around 135 Mtoe) by 2010; an ambitious objective that translates to nearly four times more the linear projection of the trends of recent years (Helby *et al*. 2004). According to the European Commission's White Paper for a Community Strategy and Action Plan COM (97) 599 (CEC 1997), the overall aim was to double the share of renewable energy in the EU's total energy consumption from 6 to 12% by 2010, and according to the more recent directive for a promotion of the use of energy from renewable sources COM (2008) 19 (CEC 2008), to increase this share to 20% by 2020, with a significant part of this energy coming from woody biomass. In fact, biomass fulfils, in many respects, the goals set out in the energy policy. It is a renewable source of primary energy, with no CO_2 emissions if managed sustainably, and contributes to achieving the objectives of the Framework Convention on Climate Change (FCCC). Moreover, it is important from an energy security and self-dependency perspective. As pointed out in the Second Assessment Report of the Intergovernmental Panel on Climatic Change (IPCC) published in 1996, bioenergy is considered the most important energy resource in the future.

These objectives are confirmed and further developed by the Biomass Action Plan (CEC 2005) which aims at raising the production of bioenergy from biomass and waste from 67 Mtoe in 2003 to 143 Mtoe by 2010. However, according to Röser *et al*. (2008), the volume of technically available forest fuels in the EU25 is 140 Mm^3, which comprises 72 Mm^3 felling residues from current fellings and 68 Mm^3 roundwood and felling residues from unutilised increment or roundwood balance. This means that forest biomass can only account for about a third of the increment targeted by the policy makers.

Biomass from short rotation plantations is an important way of meeting the requirements for renewable energy, in the expected shift towards a more sustainable energy supply infrastructure. To accomplish the goals targeted in the energy policy, at least 8 million hectares will need to be dedicated to short rotation forestry (SRF) in the EU, assuming yields around 10 odt ha^{-1} yr^{-1} and, according to Kuiper (1998), an additional area of 11 million ha of agricultural land will be needed, in order to fill the gap between the future demand and supply of wood by the traditional actors and the growing bioenergy sector. The estimates of the European Environmental Agency (EEA, 2006) show that most of the potential biomass production in the EU during the next few years will rely on energy crops on agricultural land, which can account for more than half of the total biomass potential in 2030.

The important role that the development of SRF can play in the reduction of the CO_2 emissions to the atmosphere through the production of biomass for fossil substitution and CO_2 storage in vegetation and soil has been stressed (e.g. Börjesson *et al.* 1997, Dubuisson and Sintzoff 1998, Cannell 2003). In addition, the advantages they present are wide ranging, for example, efficient land use in combination with the increasing demand for renewable energy resources, increasing biodiversity when planted in open spaces, the positive effects on rural economies as the result of the diversification of farm crops, and the additional possibilities for environmental control and wastewater treatments (Börjesson 1999a, Aronsson and Perttu 2001, Keolian and Volk 2002, Börjesson and Berndes 2006).

1.2 Willow cultivation in Sweden

Among the different fast-growing hardwoods on agricultural lands proposed for energy uses, willow (*Salix*) is amongst the few planted commercially to a significant extent in the EU. In fact, willow presents several characteristics that favour its use for energy production. It is a high-yielding species, providing large amounts of lignocelluloses in a short interval after establishment, it has a broad genetic base which allows potential for improved and adapted varieties, it has a short breeding cycle, it is easy to expand through vegetative propagation, it has the ability of re-growth after multiple harvests, and it demands low economic investments after its establishment (Ledin and Willebrand 1996, Makeschin 1999, Nordh 2005).

In Northern Europe, the cultivation of willow presents additional advantages: good yield performance even in cold conditions, its management generally requires practices that are already familiar to most farmers, and it provides with winter harvests, thus reducing the impact on other agricultural operations and minimising soil compaction resulting from the use of heavy machinery, as the ground is frozen during the harvesting period (Abrahamson *et al.* 1998, Helby *et al.* 2004).

Currently, Sweden is the leader in SRF for bioenergy purposes in Europe (Wright 2006), with more than 16 000 ha of willow plantations established in the country, which translates to about 0.5% of the total nation's total arable land. Some projections estimate the plantation area to reach 30 000 ha by 2010, and over 200 000 ha in the near decades (Larsson and Lindegaard, 2003), although there can be serious doubts about the practical realisation of these estimates, observing the recent trends (Helby *et al.* 2004).

Due to the use of short rotations, willow plantations are grown under intensive management practices compared to conventional forestry. The plants are cut back after the first growing season mainly in order to promote sprouting. Whole-shoot harvesting is usually conducted every three to five years, but the harvest interval is often longer if the growth is poor as the fixed costs related to harvesting operations are high (Helby *et al.* 2004). After the establishment, the recommended amounts of fertiliser are around 70 kg N ha^{-1} yr^{-1}, during the first cutting cycle, applied especially during the third and fourth year (Ledin *et al.* 1994, Ledin and Willebrand 1996). This amount varies between 60 to 80 kg N ha^{-1} yr^{-1} during the subsequent cutting cycles. These recommendations roughly correspond to the amount of nitrogen removed after harvesting (Nordh 2005). The plantations are established between late April to early June, using one-year old shoots (Nordh 2005). The most widely used current design in Sweden is the double-row system, with distances between rows of 0.75 m and 1.5 m, and spacing between cuttings , within the rows, of 0.6

m. The densities have been reduced over time, starting from 20 000 at the beginning of the 1990s, to 12 000 cuttings per hectare of the most recent plantations.

The introduction of willow cultivation in Sweden was stimulated by the government of the time through the implementation of different measures and policy incentives. According to the application and effects of these measures, 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, and the number of farmers establishing willow plantations grew slowly until 1990.

In 1991 there was an important change in the agricultural policy in Sweden, and a set of incentives was introduced in order to promote the establishment of willow plantations, which lead to a significant expansion. During the period 1991-1996, a specific subsidy for willow plantations of 10 000 SEK ha^{-1} was available for willow plantations (at 1991 exchange rates, approximately 10 SEK=1.33 EUR), plus in some cases additional amounts for fencing (Rosenqvist *et al.* 2000). In parallel to these measures, taxes on sulphur and CO_2 for fossil fuels in heat production were introduced, and were progressively increased in subsequent years: 0.25 SEK/kg CO_2 in 1991, 0.32 SEK/kg CO_2 in 1993, and 0.36 SEK/kg CO_2 in 1996 (Johansson *et al.* 2002, Ericsson *et al.* 2004). Since biofuels were exempted from these taxes, they became more competitive versus fossil fuels. As a result of all these changes, the planted area during this period increased almost exponentially (Nordh 2005).

However, 1996 signalled 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 a third of its previous amount, and the number of new plantations dropped significantly (Helby *et al.* 2004). After that year, the subsidy for the establishment of willow plantations was raised again in 1999 to 5000 SEK ha^{-1} (slightly over 50% of the pre-1996 value), and new willow plantations were again established. During this period, the taxes on CO_2 increased again, to 0.52 SEK/kg CO_2 in 2001, while energy taxes were reduced (Johansson 2002). But despite these conditions, the total area planted in Sweden was more or less constant around 16 000 ha, due to the fact that many plantations that were poorly established in the 1990s were removed at the same rate that new plantations were established (Nordh 2005).

Nowadays, Sweden is the only country in Europe that has sufficient experience regarding the introduction at a commercial level of a new woody crop on agricultural land for bioenergy purposes, both in years and extension of area planted. Therefore, the performance and expansion of the Swedish willow plantations is an invaluable precedent and source of information for analysis.

If the ambitious targets set by the energy policies of the EU are to be fulfilled, there is an urgent need to develop tools and methods to study the development of the sector in Sweden during recent years and the application of this experience to other areas of the EU. Among others, it is necessary to analyse the yield performance of the current commercial plantations established, and the changes and trends of the productivity during the last few years. Additionally, tools for fast and reliable estimations of productivity from established plantations must be developed for local energy planning. In addition, the role of the policy incentives applied in Sweden and the different actors involved in the development of the sector must be carefully analysed. Finally reliable and accurate yield projections based on this commercial experience must be provided, in order to implement regional energy and policy plans.

1.3 Aims of the study

The study of the potential development of short rotation plantations on agricultural land must address several aspects. First, realistic estimates of yields from commercially managed plantations are fundamental when evaluating the possible development of the sector. In addition, accurate local yield estimates at a farm level are also necessary for the efficient energy planning of the local district heating plants, in order to know the amounts of wood supply that could be available from nearby areas. Finally, there are certain conditions, such as the policy framework and the local market forces that can determine the successful expansion of the energy plantations schemes.

This thesis aims to present the potentials for short rotation willow coppice for bioenergy in six EU countries (Denmark, Estonia, Finland, Latvia, Lithuania and Sweden), addressing the above mentioned aspects. The estimates rely on models based on empirical data from commercial plantations in Sweden, and different approaches are taken in order to evaluate the potentials considering proper management practices and climatic conditions.

The research can be divided into the following stages:

i. estimate the current commercial yields from short rotation willow plantations, and develop tools and methodologies to assess the current and future productivity.

ii. study the expansion of short rotation plantations in Sweden, and provide adequate tools for its analysis, based on empirical data

iii. analyse the effects that policy incentives have in the development of the SRF sector, based on the Swedish precedents.

iv. study the potential productivity of short rotation plantations on agricultural land in Northern Europe, and set different short-term scenarios.

The results of this research will have applications in policy making, as well as in economic and management related fields.

2 MATERIAL AND METHODS

2.1 General framework for the thesis

The general framework of the thesis is presented in Figure 1. The main assumptions are that yields from commercial plantations can be defined as a combination of local climatic and soil factors and restrictions, biotic impacts, management practices, and the effects of the economies of scale on research and development, as well as innovations. Local climatic and soil factors would define the site potential. Management would include the selection of site and clone, establishment of the plantations, the tending, fertilisation, weed management, rotation length and harvesting operation. The resulting levels of productivity of the plantations consequently affect their profitability and thus the willingness of local farmers to adopt willow as a crop, and thus expand the planted area. In addition, the existence of a local demand and market for willow chips, the local perception of the cultivation and the total costs of the plantations significantly affect the adoption and expansion of the cultivation. At the same time, the amount of area planted with willow will determine the scale of the economy of the sector, which potentially can reduce costs, produce higher yielding varieties, and contribute to a better understanding of the willow management, which will also result in higher yields.

The role of the policies implemented to develop the sector directly affects adoption, e.g. through subsidies. In addition, policy influences the market forces, through taxation of alternatives, subsidies on wood-fuelled district heating plants, and promoting a framework for long-term contracts between the farmers and the wood-fuel consumers. Finally, the policies can also affect the yield performance positively, e.g. through investments in research of new varieties and better management practices, but also negatively, e.g. the existence of subsidy levels not linked to the productivity of the plantations, which can lead to poorly established plantations.

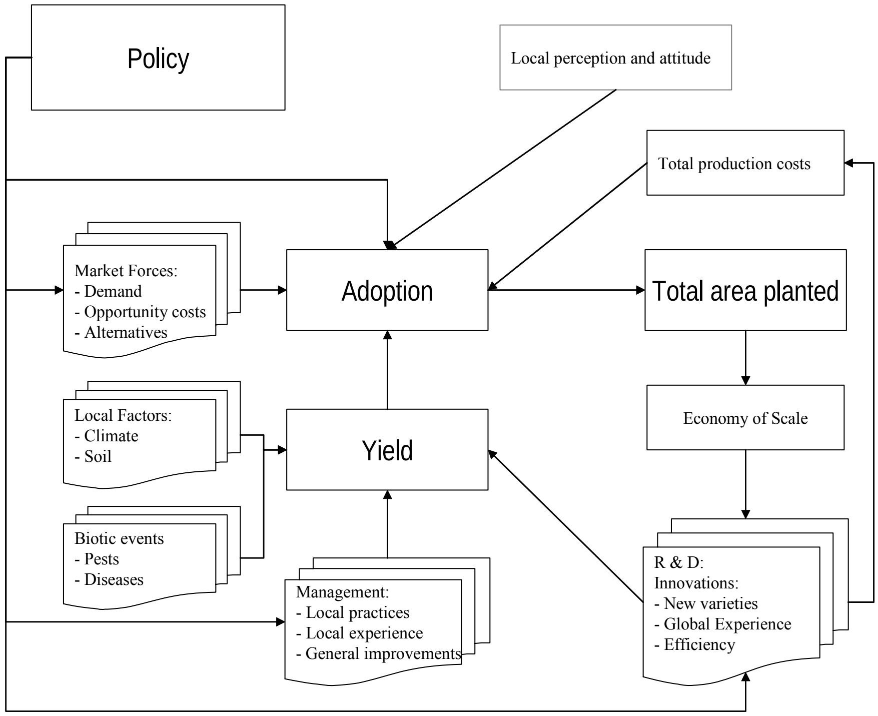


Figure 1. A simplified model for the production of willow plantations for biomass as a result of interactions between the policy framework, the yield levels and the adoption of the cultivation by the local farmers (*R & D*: Research and development).

This thesis focuses on the different interactions presented in Figure 1. Paper I analyses the current productivity of Swedish commercial plantations based on extensive empirical data. It uses a mixed model approach, considering between-farmer and between-plantation-random factors. The variability explained by the between-farmer factor is attributed to the different management practices. Paper II analyses the productivity trends for the first cutting cycle experienced in Sweden during the period 1986-2000, after the release in the market of improved willow varieties, as well as the general improvements of willow management. This paper also explores the effects of the grower's experience on the plantation's performance. Paper III provides tools to estimate the willow yields through remote sensing images, and thus the possibilities of assessing the plantation's performance. It uses a mixed model and geographically weighted regression (GWR) approach to calibrate the resulting models. Paper IV studies the expansion of the cultivation in Sweden, based on a non-parametric kernel methodology, providing tools for the analysis of the location of the plantations and the interactions with the combined heat and power (CHP) plants. Paper V analyses the adoption of willow by the Swedish farmers, and the different effects that policy incentives have had on the adoption by the local farmers, based on sigmoid adoption curves. Finally, Paper VI offers different regional productivity estimates for areas of Northern Europe, where the Swedish knowledge, technology and experience can potentially be extrapolated.

2.2 Data origin

A database of information from commercial plantations was constructed to serve the basis for the different areas of this research. The dataset was provided by Lantmännen Agroenergi AB (formerly known as Agrobränsle AB), which manages planting and administrates the harvesting of commercial willow plantations. The data included, among others, the harvest records from a first, second and third cutting cycle, as well as data concerning the ownership of the plantations, the area planted, and the establishment and harvesting dates, during the period 1986-2005. Some human errors were detected resulting in inconsistent records, and were excluded. In other cases, some information was missing, regarding the ownership, harvesting dates, total area planted or the location of the plantation, resulting in their exclusion from the calculations according to the needs of the studies where they were used.

All plantations were geo-referenced to a 1 km precision, covering the area from 55º 20' N to 61º 29' N and from 11º 33' E to 18º 56' E. The biomass production of the willow plantations was calculated by dividing the total harvested biomass of the cutting cycle by the planted area. The yield (mean annual growth) was calculated by dividing the biomass production by the rotation length of the cutting cycle (the number of years since the previous harvest or cut back). The cut back was a general practice in the management of the plantations, almost in all cases at the end of the first growing season.

In Paper I, 2082 plantations representing 9048 ha during the period 1986-2005 were included in the calculations. Most of the plantations had been harvested several times, although records from the first harvest were not always available. In Paper II, only the first cutting cycle was analysed, which means that 1515 plantations representing 6779 ha during the period 1986-2000 were used. In this study, plantations with rotation lengths longer than 9 years were excluded from the calculations, in order to avoid over-estimating the change in productivity from the early plantations.

In Paper III, 95 plantations from Central Sweden covering 445 ha falling inside a Landsat image were used to perform the analyses, including harvests from all of the cutting cycles. In Papers IV and V, the records with full information, except the harvested biomass, were also included resulting in the studying of 1164 growers and 13 110 ha planted during the period 1986-2005. In these studies, the location of the willow grower was assumed to be the location of the first plantation of the specific owner, and the corresponding establishment year was considered to be the year when the owner planted willow for first time.

A productivity index, based on local agricultural productivity was defined, using cereal yields from the different regions studied, estimated by their respective national statistics. In Papers I-V, the cereal yields were aggregated according to agricultural districts defined by the Swedish Board of Agriculture (2005). Paper I also used the averages at a county level. In Paper VI, the level of aggregation was the EU NUTS-2 level (Nomenclature of Territorial Units for Statistics), based on the COM (2004) 592 final (CEC 2004) classification for Denmark, Sweden, Estonia, Latvia and Lithuania, and according to the employment and economic development centres (former rural business districts) as defined in the Finnish yearbook of farm statistics (2005), for Finland.

In Paper III, the exact boundaries of the willow plantations were obtained from the Swedish land register, in order to increase the accuracy of the data. The remote sensing data was based on a orthorectified Landsat 7 ETM+ image, taken 12th September 2002, path 194, row 19, with 28.5 m pixel resolution (NASA 2002). In Paper IV the information concerning the location and establishment of the CHP plants was extracted from Junginger *et al.* (2006), and Evald and Witt (2006). In Paper V, the data regarding wood-fuel consumption by the district heating systems was provided by Svensk Fjärrvärme AB.

In Papers V and VI, the data concerning the distribution of agricultural land was based on the Image & Corine Land Cover 2000 (I&CLC2000) vector map for the different countries studied (EEA 2000) using a 250 m resolution. The climatic variables were calculated based on the climate layers provided by the WorldClim database, Version 1.4 (http://www.worldclim.org). The data consisted of a set of grid maps resulting from an interpolation process of averages of temperatures and precipitation during the period 1960-1990. The maps used in this study had a 30 second spatial resolution, which provided ~1km precision. The precision of the interpolated variables was 0.1° C for temperature and 1 mm for precipitation.

2.3 Modelling approaches

2.3.1. Models for yield and productivity trends (Papers I, II)

For the yield models (Papers I and II), the harvesting records were grouped according to the plantation owner, in order to include the different management practices carried out by the different farmers. Due to the hierarchical structure of the data, a mixed model approach was used in both studies.

In Paper I, the different cutting cycles were considered as repeated measures of the same plantation and grower. In both papers, the residual variation was divided into between-grower and between-plantation components, which were calculated using the Maximum Likelihood (ML) criterion.

In Paper II, the between-grower random factor was the basis for the classification of the willow growers into four classes of equal number of farmers. This factor shows the differences of yield with respect the district average due to the grower effect, and it is assumed to reflect management practices (including clone and site decisions by the farmers, as well as establishment, fertilisation and weeding operations).

2.3.2. Model for yield assessment using remote sensing images (Paper III)

Band ratios and vegetation indices were calculated for all pixels corresponding to the plantations. Correlations for yield and biomass production were first calculated, using the indices NDVI (Normalised Difference Vegetation Index), NDMI (Normalised Difference Moisture Index), and NDVI130s (as defined in Paper III: Eq 1, Eq 2 and Eq 3, respectively), as well as the bands values. The possible edge effects of nearby agricultural areas were also analysed, defining buffer areas from 10 to 50 m from the boundaries of the plantations. The results were compared, in order to fix a threshold performing least distortion for the rest of the calculations.

Two modelling approaches were used and compared to predict the plantations' yield from the satellite images, aiming at including the effects of region-specific factors in the modelling process. The first approach was based on a linear mixed-effects model, using the agricultural districts as a grouping factor, and calculated using the maximum likelihood (ML) criterion. The second approach was based on a GWR model, using an adaptative kernel method in order to locally calibrate the predictors of the model defined by the general equation:

$$y_i = \beta_0(u_i, v_i) + \beta_1(u_i, v_i) \cdot x_{1,i} + \ldots + \beta_j(u_i, v_i) \cdot x_{j,i} + e_i \qquad \text{Eq 1}$$

where β_i are parameters to be estimated, allowed to vary in the space defined by the location of the plantations, x_i are the predictors, u and v are the coordinates of the plantation studied and e is the error term. The resulting parameters where mapped in order to examine local variations in the parameter estimates. The bandwidth was determined by minimising the Akaike Information Criterion (Fotheringham *et al.* 2002). A Monte Carlo approach was used to test the stationarity of the parameters.

The models used logarithmic transformations in order to simplify the computation of the coefficients. The predictions were converted to the arithmetic scale by using an empirical ratio estimator for bias correction proposed by Snowdon (1991). In all cases the models were evaluated quantitatively by examining the magnitude and distribution of the residuals for all possible combinations of variables, aiming at detecting obvious dependencies or patterns that indicate systematic discrepancies. In order to determine the accuracy of the predictions, absolute and relative biases and root mean square errors (RMSEs) were calculated for all the models.

2.3.3 Mapping willow cultivation (Paper IV)

The analysis of the location and spread of the willow plantations in Sweden was based on a non-parametric method for the estimation of the spatial distribution of probabilities based on a pool of observed events (kernel functions). For a spatial region a continuous grid was first created, where the probability of occurrence of a specific event for all the points of the grid was calculated. This calculation was made according to the observed events, creating a density function according to the frequency of the plantations. The function of density was subsequently calculated for all the points of the grid, which results in a continuous distribution of the density of frequency for all the territory studied. The kernel function used was based on a normal bi-variate distribution curve, where the variables analysed are the UTM coordinates of the willow plantations and the willow growers (following the equation in Paper IV: Eq 1).

In this case, the bandwidth or smoothing factor (h), referred to a parameter based on Worton (1989), according to the formula:

$$h_{ref} = n^{-1/6} \sqrt{\frac{\mathrm{var}_x + \mathrm{var}_y}{2}} \qquad \text{Eq 2}$$

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 values of reference were calculated for several time intervals. Different values of h were applied and compared, and the final version presented used a smoothing parameter of 40% of the reference value h_{ref}. The kernel estimations were based on the HRE (Home Range Extension) developed by the Centre for Northern Forest Ecosystem Research (CNREF) (Rodgers and Carr 1998).

To analyse the resulting kernel estimations, raster maps with standardised isopleths were created. The isopleths were based on percent volume contour (PVC), in order to compare areas with high density of plantations in the different periods of study. The PVCs define the volumes under the utilisation distribution, and represent a defined percentage of plantations in the smallest possible area. For instance, the isopleth 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 all the plantations. The maps were presented using a 150 x 150 grid resolution. In order to study possible variables that 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 using the average yield of oats for the period 2003-2005 by agronomic district, as calculated by the Swedish Board of Agriculture (2005). In addition, the volume and density averages were calculated for areas within 10, 20 and 30 km from all the CHP plants analysed. In order to simplify the calculation of the average values and preserve the highest level of detail possible, the resulting PVC were first converted into a new grid of points defined by 2 x 2 km. Since willow plantations are located on agricultural land, in this grid only points falling inside agricultural areas, or within a 2 km radius, as defined by the Corine land use map (EEA 2000), were included. The average values for the areas were therefore calculated using the resulting values of the points in the grid.

2.3.4 Model for adoption (Paper V)

A model for the adoption of willow cultivation by the Swedish farmers was performed in Paper V. The number of adopters (willow growers establishing plantations for the first time), was grouped by municipalities and counties. A mixed non-linear model including fixed and random effects was estimated using the ML procedure of the nonlinear mixed model statistical package in R-software (Pinheiro *et al*. 2007). The model was based on a sigmoidal curve, defined by three parameters and three grouping factors: between-municipality, between-county and between-years (Paper V: Eq 1). The fixed parameters of the curve were furthermore defined by equation including location, socio-economical and policy variables (Paper V: Eq 2, Eq 3 and Eq 4).

2.3.5 Mapping regional willow productivity (Paper VI)

Regional yield estimates for Northern Europe were calculated in Paper VI. In order to define the climatic and agronomical variables of the regional units, as a basis for the modelling development, average daily values of maximum and minimum temperatures were generated using linear interpolation from the climatic layers, based on monthly average values. In the case of precipitation, the daily values were generated assuming a uniform distribution of the monthly values by the number of days in the month. The precipitation during the growing season was computed by summing the average daily precipitation from the time when T_{mean} first exceeded 5.0°C in spring until the last date that T_{mean} exceeded 5.0°C in autumn.

To simplify the calculation process, a systematic grid of 10 x 10 km was constructed, covering all the area studied. The potential willow productivity was calculated for each point of the grid, and the resulting values were grouped in the spatial units defined, in order to get average regional values comparable to the estimates for present and future conditions. The points of the grid not falling on agricultural land, as defined in the Corine land cover maps (EEA 2000), were excluded from the calculations.

The resulting variables were used to calculate the potential willow productivity on the basis of climatic restrictions (*sMaxWL*). The model used was based on Lindroth and Båth (1999). This model assumes that, in conditions of optimal management (including e.g. fertilisation, weeding and complete control of pests and diseases), water availability is the only limiting factor.

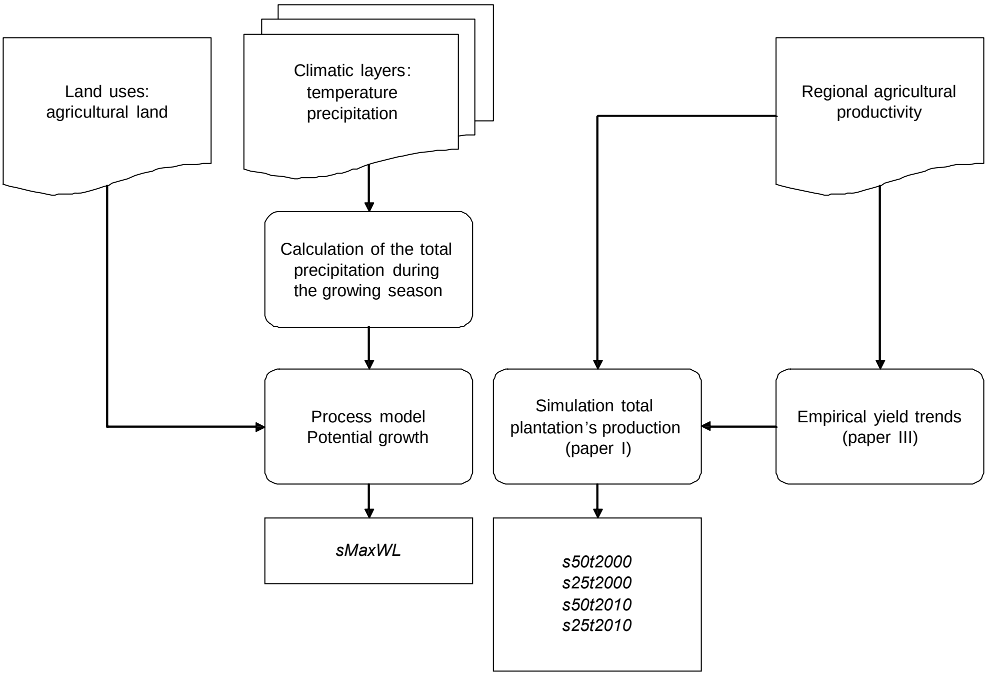


Figure 2. Flow chart of the estimates of regional productivity for Northern Europe, according to different scenarios (Paper VI). *sMaxWL*: based on projections only restricted by climatic factors, and excluding any effect of management. *s25t2000* and *s25t2010*: High productivity scenarios based on performance of 25% of the best farmers, for years 2000 and 2010, respectively. Analogously, *s50t2000* and *s50t2010*: good productivity scenarios based on 50% of the best farmers.

Alternatively, in order to include the variations due to management in the scenarios of current and expected productivity a modified version of the model resulting from Paper III was used. The modelling process is defined in Figure 2. For the productivity based on current conditions, the resulting estimations for each region were calculated, using the year 2000 as the year of reference. This year was inside the range of the original dataset used to calibrate the model in Paper III, and therefore relies on a solid empirical basis. For estimating expected productivity, which aims at including the effects of genetic and management improvements of the last years, the projections of the model for the year 2010 were calculated. In both cases, two alternatives were presented, on the basis of the performance of the growers. The high productivity assumption was based on the resulting estimations for the 25% best growers (*s25t2000* and *s25t2010* for the current and expected conditions, respectively). The good productivity assumption is based on the resulting estimations for the 50% best growers (*s50t2000* and *s50t2010*). In both cases, some level of experience of the local farmers was assumed and included in the predictions.

The average annual productivity for the whole lifespan of the plantations was simulated according to the models provided in Paper I. The calculated yield for the first cutting cycle was used as a reference, and the rotation length was fixed at 4 years in all the cutting cycles. Since no empirical data from a broad enough sample is available for a fourth and fifth cutting cycle, these were interpolated by using the calculated figures for the second and first cutting cycles, respectively. The average annual yield was then calculated by dividing the resulting accumulated production by the total number of years of five cutting cycles, plus one additional year, in order to include the initial year when the cut back was performed. The standard lifespan of a plantation was therefore fixed at 21 years.

3 RESULTS

3.1 Yield performance of commercial willow plantations (Papers I, II)

According to the data analysed, the annual average yield of the studied commercial willow plantations during the period 1986-2005 for the first to third cutting cycles were 2.63, 4.19 and 4.47 odt ha^{-1} yr^{-1}, respectively. The corresponding average lengths of the cutting cycles were 6.0, 4.5 and 4.2 years (the year previous to the cut back excluded in the first cutting cycle). Among the various cereals tested as site index, both oats (*Avena*) and barley (*Hordeum*) offered good performance. The standard yields of oats by agronomic district were finally selected for the final version of the model.

The analyses of the commercial yields and rotation lengths resulted in the following models:

$$yield_{lkjt} = 1.54 + 2.90 \cdot \frac{oat_l}{rl_{lkjt}} - 1.075 \cdot CUT_1 - 0.197 \cdot CUT_2 + \mu_{kt} + e_{lkjt} \qquad \text{Eq 3}$$

$$RL_{lkjt} = 4.23 + 1.95 \cdot CUT_1 + 0.31 \cdot CUT_2 + \mu_{kt} + e_{lkjt} \qquad \text{Eq 4}$$

where *yield* is the mean annual growth of the plantations (odt ha^{-1} yr^{-1}), *oat* is the yield of oats by districts used as productivity index (1000 kg ha^{-1} yr^{-1}), *rl* is the length of the cutting cycle (yr). Subscripts *l*, *k*, *j* and *t* refer to district, grower, plantation and cutting cycle, respectively. μ_{lk}, is the between-grower random factor for each cutting cycle, independent and identically distributed with mean equal to 0 and constant variances equal to $\sigma^2_{grower,t}$. Finally, e_{lkjt} is the between-plantation random factor for yield of cutting cycle *t*, on plantation *j*, managed by grower *k* in the district *l*, with mean equal to 0 and constant variance equal to σ^2_{pl}.

The coefficients of determination (R^2) for the fixed part of the model were 0.27 and 0.30 using yields on a county and district level, respectively. It should be taken into account that part of the residual variation of the fixed part was explained by the random grower factor. The model showed similar yields for the second and third cutting cycle, both significantly higher than the yields during the first cutting cycle. The estimated variances for the random part of the models were similar among the alternative agro-climatic indices. In all cases, the variance due to the grower was similar during the first and second cutting cycles, and was higher during the third cycle.

According to the predictions of the model, the estimated willow yield during the first cutting cycle varied from 2.4 – 3.5 odt ha^{-1} yr^{-1}, with a rotation length of 6 years, using the minimum and maximum yields of oats by district, respectively. For the second harvest, the corresponding yields varied from 4.3 - 5.9 odt ha^{-1} yr^{-1} for a rotation length of 4 years using the minimum and maximum yields of oats by district, respectively. Including between-grower differences from the random part of the model and using the same parameters, results for the 25% best growers vary from 3.6 – 4.8 odt ha^{-1} yr^{-1} during the first cutting cycle and from 5.5 - 7.1 odt ha^{-1} yr^{-1} for the second cycle.

The same predictor for agro-climatic index based on yields of oats (Paper II, Eq 1) was not significant in order to explain the length of the cutting cycle. The parameter estimates, excluding site index, indicate shorter rotation lengths of the second and third cutting cycles as compared with the first. As in the yield model, a significant part of the variability was explained by the between-grower variation included in the random part of the model.

The productivity of the plantations was also modelled along time, for the period 1986-2000. The resulting model was as follows:

$$\begin{aligned} yield_{lkj} &= 2.213 + 0.075 \cdot oat_l \cdot pla_{lkj} - 0.375 \cdot GRO_I \cdot pla_{lkj} - 0.298 \cdot GRO_{II} \cdot pla_{lkj} \\ &- 0.219 \cdot GRO_{III} \cdot pla_{lkj} - 0.039 \cdot GRO_{IV} \cdot pla_{lkj} - 0.204 \cdot EXP_{lkj} + e_{lkj} \end{aligned} \qquad \text{Eq 5}$$

where yield is the mean annual growth of the plantations (odt ha^{-1} yr^{-1}), *oat* is the yield of oats by districts used as a site index (1000 kg ha^{-1} yr^{-1}), *pla* is the year of planting, using 1986 as starting point, *EXP* is a dummy variable that refers to the experience of the farmer growing willow for bioenergy for at least two years before planting (having no experience, EXP=1) and GRO_c is a categorical parameter for each class of growers (*I, II, III, IV*) according to the performance of plantations managed by the same farmer, being GRO_I the lowest and GRO_{IV} the highest. Subscripts *l*, *k*, and *j* refer to district, grower and plantation, respectively. Finally, e_{lkj} is the between-plantation random factor for yield of plantation *j*, managed by grower *k* in the district *l*, with mean equal to 0 and variance equal to σ^2_{pl}.

The parameter estimates of the yield model were significant, except the dummy for the best grower category (GRO_{IV}). The coefficient of determination of Eq 5 was 0.57. In general, growers of class I were managing more plantations than the other classes, and the variability of the performance of the plantations managed by the same grower was similar for classes GRO_{II} and GRO_{III}, and significantly higher in class GRO_{IV}, formed by the growers that attained the highest yields. In general, growers with at least 2 years experience of growing willow achieved higher yields, with an absolute average of 0.34 odt ha^{-1} yr^{-1} higher than the inexperienced growers. However, the classes of growers used in Eq 5 partially included this increment since the percentage of plantations managed with previous experience increases in the groups with higher yields (Paper II: Table 4).

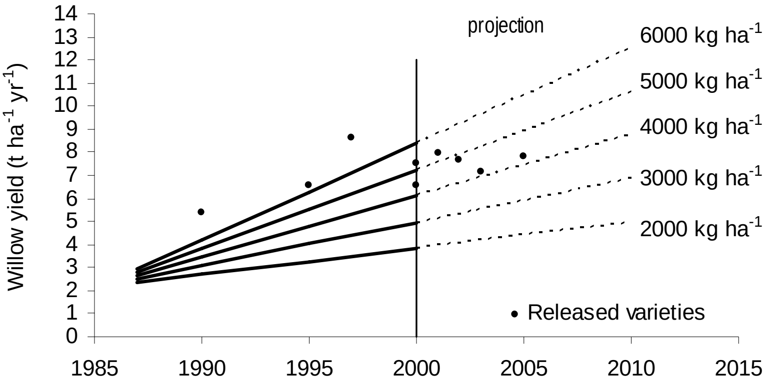


Figure 3. Trend projections for different productivity areas, expressed as oat yields (kg ha^{-1}), for the 25% best growers analysed. The trends are compared to the yields from the first cutting cycle of commercial willow varieties on different trials by year of release into the market, according to Larsson and Dobrzeniecki (2004).

In the areas of low productivity (using the minimum yields of oats by district), the estimated willow yield at the first cutting cycle during 1986-2000 increased from 1.0 to 2.5 odt ha^{-1} yr^{-1}, and in the areas of high productivity from 1.3 to 5.4 odt ha^{-1} yr^{-1}. In fact, the yields increased an annual average of 0.206 odt ha^{-1} yr^{-1}. Concerning the possible effects of management, the best growers group (GRO_{IV}) showed an annual average increment of 0.275 odt ha^{-1} yr^{-1}, and the latest plantings reached a mean productivity for this group of 6 odt ha^{-1} yr^{-1} (Figure 3). In the areas of high productivity, the yields of the latest plantings for this group were around 8.37 odt ha^{-1} yr^{-1}.

3.2 Yield estimates from commercial plantations based on satellite images (III)

The first analysis of the satellite images used to predict the yield performance of the plantations showed that the band values of the pixels falling inside the first 10 m within the boundary of the plantation were significantly different than the average values of the rest of the pixels in the plantation limits. These differences tended to disappear after the first 20 m. The use of a buffer longer than 40 m reduced the number of samples (from 95 to 72), as many plantations were not wide enough to apply this threshold. The threshold of 20 m was therefore used in the rest of the calculations.

The NDMI showed the best correlations both for predicting total production and yield, followed by the NDVI130s and the NDVI (Paper III: Table 2). There were no significant differences between plantations harvested during the season 2002-2003 and all the plantations included. In general, the relationship of total harvested biomass versus the vegetation indices was similar, no matter whether the plantations were harvested within months or during the next few years after the image was taken. The indices used to assess biomass production (NDVI, NDVI130s and NDMI) seemed to be efficient estimators in classifying the plantations according to their final yields (Paper III: Figure 3). NDVI and NDMI performed similarly, whereas NDVI130s seemed to be successful only for identifying the plantations with low productivity.

Table 1. Estimates, standard error (S.E.) and significance level of the parameters and variance components of the yield mixed model, and summary of the local parameters estimates of the GWR. Below, absolute and relative bias and RMSEs, and coefficient of determination (R^2) of the original models (no back-transformation applied).

Parameter Mixed Model	**Estimate**	**S.E.**	**df**	**t**	**p-value**
β_0	-5.884	(0.832)	61.107	-7.076	0.000
β_1 *OAT*	0.439	(0.123)	16.711	3.583	0.002
β_2 *NDMI*	0.611	(0.124)	88.913	4.909	0.000
β_3 *CC*	0.039	(0.008)	92.867	5.015	0.000
$\sigma^2_{pl,1}$	0.123	(0.019)			0.000
$\sigma^2_{loc,1}$	0.015	(0.016)			0.329

Parameter GWR	**Median**	**Minimum**	**Lower Quartile**	**Upper Quartile**	**Maximum**	**Non-stationarity**
β_0	-5.713	-7.061	-6.176	-5.515	-2.447	0.120
β_1 *OAT*	0.000	0.000	0.000	0.001	0.001	0.120
β_2 *NDMI*	0.492	0.273	0.394	0.727	0.915	0.000
β_3 *CC*	0.043	0.001	0.037	0.046	0.055	0.110

	N	Bias (odt ha^{-1} yr^{-1})	% Bias	RMSE (odt ha^{-1} yr^{-1})	%RMSE	R^2
Mixed model	93	-0.001	-0.12%	0.37	33.5%	0.65
GWR	93	-0.003	-0.30%	0.29	26.7%	0.78

N: number of plantations. S.E.: Standard Error of the estimations. df: degrees of freedom. OAT: Average oat productivity of the district, NDMI: Average NDMI of the plantation excluding the first 20 m from the inner side of the boundaries, CC: Dummy variable for the cutting cycle, being 1 in the first cutting cycle, and 0 in the rest. β_0, β_1, β_2, β_3 are parameters, σ^2_{pl} and σ^2_{loc} are the estimated variances of the random effects terms μ_l and $\varepsilon_{i,l}$, referring to between-districts and between-plantations respectively. Non-stationarity refers to the significance of the spatial variation in the local parameter estimates derived from a Monte Carlo test.

The accuracy of the predictions was improved in the final versions of the models proposed (Table 1). In the mixed-model, the coefficient of determination for the fixed part was 0.65. The parameter estimates for the fixed part of the model were all significant. The variance explained by the random factor was 0.111 for the model using NDMI as a single predictor, and 0.057 for the final version of the model (p-values of 0.087 and 0.329, respectively). An alternative random factor for the slope of the NDMI was not significant in either case, and was removed from the model. The use of the GWR model improved the results of the mixed model (F=2.54, p=0.003). For the GWR model, the overall coefficient of determination was 0.78.

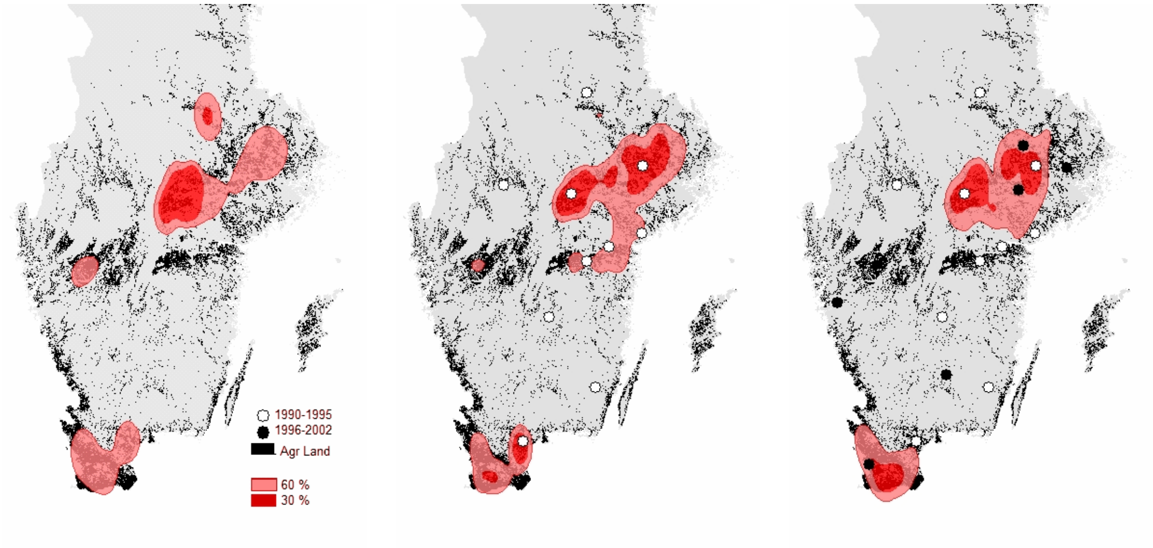
The bias of both yield models was examined by plotting the residuals as a function of the predictors of the model. No obvious dependencies or patterns that indicate systematic trends among the residuals and the independent variables were found. Results of the Moran’s I statistic indicated a lower overall spatial autocorrelation in the residues of the GWR models (I=0.141 and I=0.016, for the mixed model and the GWR model, respectively). The Snowdon (1991) correction ratio was 1.062, and 1.046 for the mixed model and the GWR model, respectively. In both cases the correction factor was applied in order to correct the bias in the back-transformed predictions. The coefficients of determination for the back-transformed data were 0.48 and 0.64 for the mixed model and GWR model, respectively.

3.3 Spread and adoption of commercial willow plantations (IV, V)

The geographical distribution of the willow plantations resulting from the application of the method is presented in Figure 4, for the three periods proposed. In order to facilitate the visual interpretation of the distribution of plantations and willow growers, the values of the PVC are grouped in two levels: 30% and 60%, representing high and medium densities, respectively.

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, which resulted in significantly lower values of the h_{ref} values 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 was different in the second period. However, the relative values between the periods are comparable when using the PVCs.



1986-1990 1991-1996 1997-2005

Figure 4: Evolution of the areas with high density of willow plantations for the three periods defined. The values represent percentage volume contours (PVCs), for 30% and 60% of the plantations. In each period, previous plantations are excluded from the calculations. The maps include the location of the combined heat and power plants by period when started using wood biomass as main fuel: 1990-1996 white dots, 1996-2002, black dots.

During the initial period (1986-1990), the average agricultural productivity of the areas of high concentration of plantations was appreciably lower than during the middle period (1991-1996). Following these trends, during the last period studied (1996-2005) the plantations were concentrated in areas of higher agricultural productivity (Paper IV: Figure 4).

The analysis of the concentration of plantations around the CHP plants showed hotspots around the CHP plants of Örebro, Enköping and Kristianstad, during the period 1991-1996. In these three cases, the level of concentration (density of plantations) was increasing with the geographical proximity to the CHP plants. During the period 1997-2005, concentrations around the CHP plants of Örebro, Enköping and Lomma were also observed. In these cases, the concentration of plantations was also increasing with the proximity, and moderate concentrations around the CHP plants of the municipalities of Eskilstuna and Sala were identified. In this period there was no clear concentration around the plant of Kristianstad (Paper IV: Figure 5).

The adoption of willow by the local farmers during the timeframe studied was modelled according to Eq 6. All the parameters were significant at the 0.05 level. The coefficient of determination of the adoption model was 0.83 for the fixed part of the model, and 0.98 when the between-municipalities random factor was included.

$$N_{lkt} = \frac{a + \mu_l + \mu_k}{1 + e^{b\cdot(t-c)}} + \varepsilon_{lkt} \qquad \text{Eq 6}$$

where parameter *a* is the maximum adoption ceiling, defined as:

$$\begin{aligned} a = {} & 13.552 \cdot \frac{agr_l^{\,2}}{1000} + 0.886 \cdot ORE \cdot agr_l + 0.029 \cdot SUB \cdot agr_l + 0.155 \cdot iwf_k \cdot agr_l + \\ & + 0.148 \cdot \frac{tax \cdot agr_l}{10000} + NOR \cdot (-2.415 \cdot grass_l + 7.330 \cdot bar_l - 1.470 \cdot bar_l^{\,2}) \end{aligned} \qquad \text{Eq 7}$$

and parameters *b* and *c* are defined as:

$$b = 0.977 - 0.156 \cdot Z2 \qquad \text{Eq 8}$$

$$c = 5.064 + 1.638 \cdot Z2 + 2.854 \cdot SOU \qquad \text{Eq 9}$$

where N_{lkt} is the accumulated number of growers planting willow for the first time until year *t*, in municipality *l* in region *k*, *agr* is the agricultural land of municipality *l* (in 1000 ha) as estimated in 1995 (Statistics Sweden 1995), *ORE* is a dummy variable for the region of Örebro, *SUB* is a dummy variable for the period of subsidies for willow plantations of 10 000 SEK ha^{-1} (1991-1996), *iwf* is the increment in the use of wood fuel by the district heating plants compared to 1991 in region *k* and year *t* (TWh)*, tax* is the amount of revenues from energy taxes in SEK for the period 1990-1996, based on Johansson *et al.* (2002), *NOR* and *SOU* are dummy variables that refer to the municipalities of the central-north and southern part (Kristianstad and Malmöhus regions) of the country, respectively, *grass* is the grassland area in ha of municipality *l* as estimated in 1995 (Statistics Sweden 1995), *bar* is the average yield of barley for the period 2003-2005 by municipality as extracted from the agricultural districts (Swedish National Board of Agriculture 2005), in t ha^{-1} yr^{-1}, *Z2* is a dummy variable that refers to the regions with total increments of biofuel consumption by the district heating systems above 100 GWh during the period 1994-1996. Subscripts l, k, and t refer to municipality, region and time, respectively. $\mu_{l,}$ is the between-municipality random factor, independent and identically distributed with mean=0 and constant variance (σ^2_{mun}). Finally, ε_{lkj} is the between-years random factor for year t, municipality l, and region k, with mean equal to 0 and variance equal to σ^2_t. Initially both random parameters, municipality and region, were included in the model. However, the between-region parameter ($\mu_{k,}$) was not significant and was therefore excluded from the final version of the model.

The parameter estimates included in the model were all significant at the 0.05 level. As expected, the effect of available agricultural land was positive, as well as the effect of subsidies and consumption of wood fuel by the district heating systems. Additionally, the cereal productivity measured by the barley yields showed a positive effect. However, its marginal influence decreased in the areas of high yields resulting in a negative coefficient of the squared barley yield. The grassland area showed a negative correlation in the areas of the centre and north of the country. Finally, the region of Örebro showed higher adoption than the rest of the country.

For the fixed part of the model, the absolute and relative bias were 0.032 and 0.55%, respectively; and the absolute and relative RMSE were 3.84 and 65.5%, respectively. In addition, the mean bias of the fixed part of the model was examined by plotting the residuals as a function of the predictors of the model. A slight trend was observed in the available agriculture land, but no overall obvious dependencies or patterns that indicated systematic trends were observed in the rest of the variables analysed. The predictions of the model reasonably reproduced the variations in the screened number of growers that adopted willow in the whole of Sweden during 1986-1996. The results of the model allowed different simulations to perform scenarios without incentives. The version when the incentives were removed showed a reduction in the total number of adopters by 70% for the period 1991-1996 (Figure 5).

In the southern and central-eastern areas of the country, the inclusion of the incentives meant a higher increment, in absolute and relative terms, as compared to the predictions without incentives, whereas the increment was much smaller in the central and western areas of the country. This was parallel to the actual demand for wood fuels by the district heating systems, which increased proportionally in the south and central-eastern areas of the country compared to the central-western areas, during the period studied (Paper V: Figure 4).

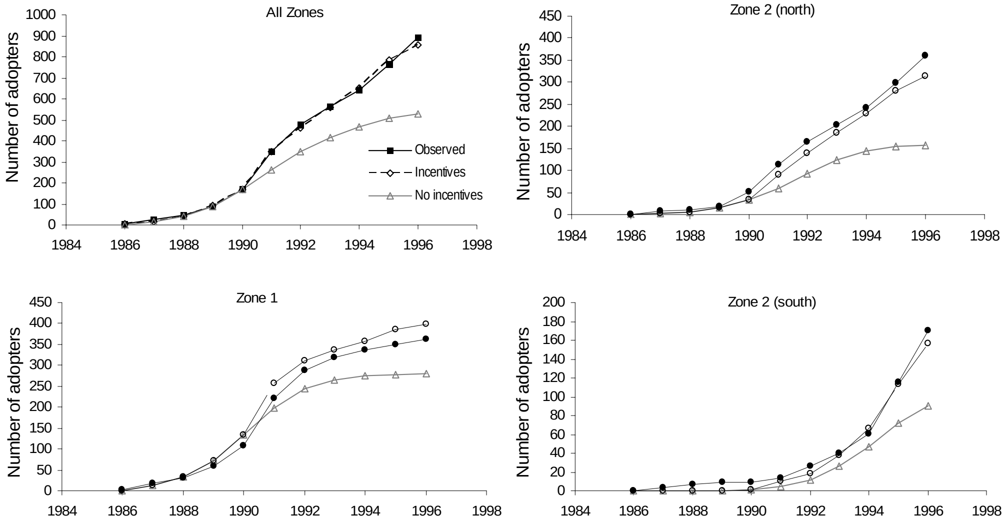


Figure 5. Results of the observed and predicted values by municipalities, aggregated by zones. For the no-incentives predictions, the tax parameter is fixed to 1990 levels, no subsidies assumed and no increment of wood fuel consumption by the central heating systems. Zone 1 includes the areas of central-western Sweden, Zone 2 (north) includes the counties of Uppsala, Stockholm, Södermanland and Östergötland and Zone 2 (south) is specifically referred to Skåne (comprising the regions of Kristianstad and Malmöhus).

3.4 Scenarios of SRW on agricultural land in Northern Europe (VI)

The willow yields calculated according to the *sMaxWL* correlated with the regional oats productivity in Denmark, Sweden, and Finland (r=0.678, F=43.29, p-value=0.000). This correlation was not observed in the Baltic countries (*p*-value=0.158), which indicated higher potential yields than expected according to their oat productivity (Paper VI: Figure 2). There was convergence over time of the scenarios based on s50 (i.e. *s50t2000* and *s50t2010*) and the trends of maximum productivity, especially in the areas of highest oats yields. The scenario *s25t2010* crossed the maximum productivity almost in all regions. In general, scenarios *s50t2000* and *s50t2010* run parallel to the curve of estimated maximum productivity.

The predictions for Sweden showed convergence over time with the estimated maximum productivity (Paper VI: Figure 3), according to the scenarios for the s50 and s25, 50% and 25% best growers, respectively. It must be taken into account that the estimated maximum is a fixed estimation provided by a process model, whereas s50 and s25 reflect direct measures of the yield performance of a large sample of growers over time. In addition, the average predictions for the s50 followed the same trends as the experimental results from the different willow varieties released in the market during the last few years, although with overall lower yields.

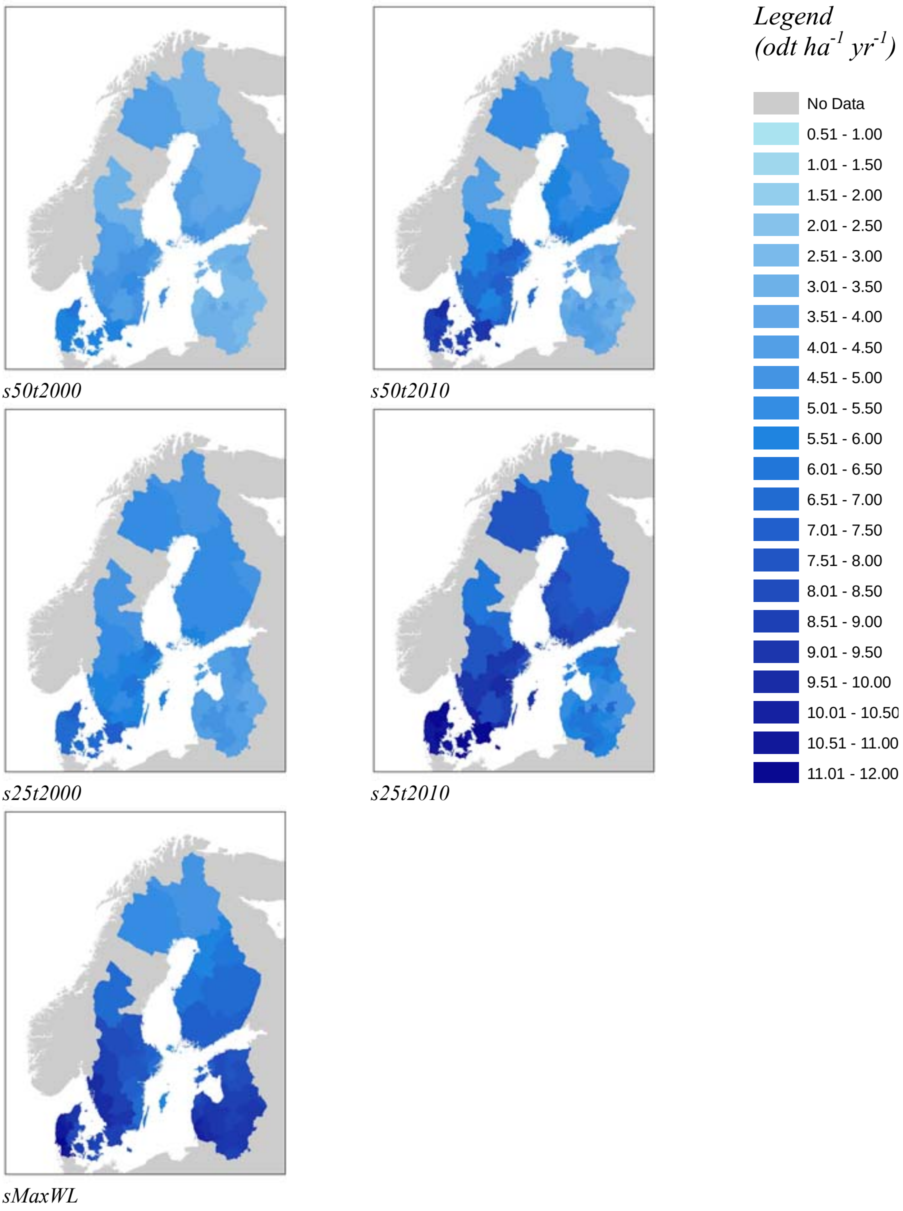
Table 2. Average yield estimates (odt ha^{-1} yr^{-1}) for the countries studied, according to the different scenarios proposed.

	s50t2000	*s50t2010*	*s25t2000*	*s25t2010*	*sMaxWL*
Estonia	3.14	3.44	4.85	6.29	7.9
Latvia	2.82	2.87	4.58	5.79	9.0
Lithuania	3.10	3.37	4.81	6.22	9.3
Sweden	5.29	7.20	6.83	9.77	8.0
Finland	4.48	5.80	6.06	8.44	6.8
Denmark	6.44	9.16	7.93	11.65	9.5

s25t2000 and *s25t2010*: High productivity scenarios based on the performance of 25% of the best farmers, for years 2000 and 2010, respectively. Analogously, *s50t2000* and *s50t2010*: good productivity scenarios based on 50% of the best farmers. sMaxWL: projections only defined by water limitation, excluding the effect of management.

The average yields for the countries studied are presented in Table 2. However, in the different countries there were broad regional differences, mapped in Figure 6 for the different scenarios considered. As an example, the ranges for the regional predictions according to *s50t2000* were 3.5, 1.69 and 1.01 odt ha^{-1} yr^{-1} in Sweden, Finland and Denmark, respectively, and 1.64, 1.08 and 0.6 odt ha^{-1} yr^{-1} in Latvia, Lithuania and Estonia, respectively.

The Baltic region presented the largest differences between the potential productivity versus the estimated current and expected productivity. In Denmark, Finland and Sweden there was a convergence between the future forecasts and the potential yields in the areas of maximum agricultural productivity.



s50t2000

s50t2010

s25t2000

s25t2010

sMaxWL

Figure 6: Estimates of productivity from short rotation willow plantations for the different scenarios proposed for Northern Europe. High productivity scenarios use projections of the 25% best growers: *s25t2000* and *s25t2010* for current and future conditions, respectively. The good productivity scenario use projections for the 50% best growers: *s50t2000* and *s50t2010*. The scenario *sMaxWL* is based on projections only restricted by climatic factors, and excludes any effect of management.

4 DISCUSSION AND CONCLUSIONS

4.1 Yields from commercial plantations

The framework presented in Figure 1 and developed throughout this thesis reflects the complexities of the introduction of a new cultivation for energy purposes. The results of this thesis provide analyses and methodological tools in order to contribute to a better understanding of the current situation of short rotation forestry in Europe and the future development of the sector.

Although there is already extensive literature concerning the productivity of short rotation forestry under different management regimes, there is a lack of studies based on commercial management on a large scale. This thesis is mostly based on empirical data from commercial willow plantations in Sweden for the period 1986-2005. The dataset available for the analyses provides extensive information, covering a large share of the total area planted with willow in Sweden. However, it must be taken into account that the purpose of the records was not specifically designed to develop yield models. A disadvantage of the data used is the lack of information concerning the growth during each of the individual years of the cutting cycle. In addition, many factors related to the management and care of the plantations were unknown. Furthermore, some human errors or missing values were detected in the original dataset and had to be excluded from the calculations. However, these deficiencies are compensated for by the large amount of data available, which provides a more realistic approach of productivity in large scale commercial plantations than previous studies.

In general, the estimates presented are significantly lower than predictions from previous research for potential willow productivity based on process models or data from field or laboratory experiments. For instance, in the 1980s in Sweden, predictions of yields above 10 odt ha^{-1} yr^{-1} were expected on several studies based on process models (Nilsson and Eckersten 1983, Perttu *et al.* 1984). More recently, the estimates of Lindroth and Båth (1999) showed production potentials ranging from 8-9 odt ha^{-1} yr^{-1} in the north-east of Sweden, to 16-17 odt ha^{-1} yr^{-1} along the west coast. Ericsson and Nilsson (2006) presented average yields ranging from 9.0 to 11.7 odt ha^{-1} yr^{-1} as a national average. In the other countries studied, Nonhebel (2002) reviewed estimates for Denmark, ranging from 10 to 20 odt ha^{-1} yr^{-1} for short rotation poplar plantations intensively managed. Other studies for Denmark estimated annual yields from 10.9 to 14.1, and for Finland from 4.5 to 5.9 (Ericsson and Nilsson, 2006). In eastern Finland, the production ranges were estimated from 6 to 9 odt ha^{-1} yr^{-1} (Regional Energy Agency of Eastern Finland 2004).

Yield estimates for the Baltic countries and Eastern Europe in Fischer *et al.* (2005) were in the range of 13.8 to 18.1 odt ha^{-1} in the most suitable conditions, and from 7.3-8.4 odt ha^{-1} in the moderately suitable conditions. In Dam *et al.* (2008), the predictions for Estonia, Latvia and Lithuania under current agricultural practices were around 9.0, 9.7 and 10.1 odt ha^{-1}, respectively, in very suitable conditions, and slightly below 5 odt ha^{-1}, in all three countries, in moderately suitable land. In Ericsson and Nilsson (2006) the annual yield estimations for the Baltic countries ranged around 2.9 to 7.5 odt ha^{-1} for Estonia, 4.7 to 12.2 odt ha^{-1} for Lithuania and 3.9 to 10.1 odt ha^{-1}, for Latvia. In Estonia, results from experimental plantations yielded up to 10 odt ha^{-1} yr^{-1}, in the high quality soils, when there was proper management practices, and 6 odt ha^{-1} yr^{-1}, in the medium quality soils (Heinsoo *et al.* 2002).

However, one of the main limitations of the previous studies was the difficulty to predict the many and various factors that can affect productivity, other than site conditions and climate, possibly due to the lack of reliable statistics of yields from commercial plantations. The resulting estimates produced by the empirical models presented in this thesis are closer to the averages measured in other samples of commercially managed plantations. For instance, the measured productivity from plantations managed by local farmers in Finland ranged from 0.37 to 8.35 odt ha^{-1} yr^{-1} (Tahvanainen and Rytkönen 1999) for the first cutting cycle. In fact, the measured yield distribution of commercial plantations in the first cutting cycle was rather similar in Finland and Sweden: in total, the percentages of plantations with a reported productivity lower than 2 odt ha^{-1} yr^{-1} were 56% and 44%, for Finland (Tahvanainen and Rytkönen 1999) and Sweden (Paper I), respectively, although the Finnish sample consisted of only 16 plantations. In Denmark, the average productivity for the first cutting cycle in commercial plantations was estimated to be 7-8 odt ha^{-1} yr^{-1} (Venendaal *et al.* 1997), which is consistent with the calculations presented in this study.

The overall experience from the studies based on empirical data, reveals that management has a fundamental influence on the performance and success of the plantations. The selection of the site and clone to be used, sufficient weed control, proper fertilisation and water availability are variables difficult to model, but that must be considered in the estimations of productivity in order to have reliable data. As was found in Tahvanainen and Rytkönen (1999), the general attitude and skills of the farmer is another variable that greatly affects the final outcome of the plantation. Among the factors that could affect this attitude, it should be noted that the subsidies to plantations given during the period 1991 to 1996 had an important effect on the farmer’s motivation to plant willow.

This support scheme led to the planting of large low-productive areas rather than smaller high productivity areas, among other effects (Helby *et al.* 2004). The reduction of the subsidies in 1997 to one third of the previous level implied that farmers had to invest a significant amount of their own money, and thus would have encouraged better management, in order to increase the productivity and success of their own plantations (Helby *et al.* 2004). In addition, there are technological limitations that result in additional reductions of the harvested biomass from the predicted biomass potential. For instance the losses carried out during the harvesting operations are estimated to be around 5%-10% of the standing biomass by the time of the harvest (Graham *et al.* 1992).

The figures provided in this study and the expectations in previous studies show the differences between the potential and the current level of productivity. However, it must be taken into account that short rotation willow is a fairly new cropping system when compared with the experience and development of most other agricultural crops. The results of this study also show that the production of the willow plantations in Sweden has increased during the last years at a good rate, starting with very poor results from the plantations established in the middle 1980s, but achieving significantly higher production levels in the recently established plantations.

Management would explain the increment of yields on two levels: on a general level, the various studies carried out during the last years (e.g. Ledin and Willebrand 1996) would contribute to a better understanding of the proper practices and cultivation treatments, and the spread of these practices would improve the productivity of the plantations; on the individual farmer level, the grower’s attitude and experience in growing willow (learning-by-doing) contributes to an improvement of the yields. Experienced farmers account for a significant part of the group of growers with high yields, and the model shows an average increment of 0.34 odt ha^{-1} yr^{-1}, for all farmers. The importance of breeding programmes together with training for growers is stressed, as well as mechanisms to encourage best practices in order to reduce the gap between actual and potential yield in commercial willow plantations.

For most of the tree species, typical gains for first and second generation breeding programmes are around 10-20% and 20-30%, respectively (Mead 2005). For instance, the early clones used in the Swedish commercial plantations were mostly dominated by old, non-bred willow varieties and particularly affected by infections and frost damage (Larsson 1998). However, the more recent plantings included new varieties more vigorous than the older clones, which resulted in shorter rotations, greater resistance to pests and diseases, and higher productivity. In the period 1995-2005 several new willow varieties have been released in the Swedish market, increasing the relative yields by 60% compared to the levels reached in the early 1990s. Furthermore, leaf rust (*Melampsora*) has been almost completely reduced (Larsson and Dobrzeniecki 2004). Willow has easy vegetative propagation and the genus *Salix* is one of the largest among the tree genera; therefore rapid yield improvements through breeding programmes can be expected, if there is the necessary investment.

The analyses of the trends presented, however, are limited to the first cutting cycle. One of the reasons is that there is still limited information from further harvest records to define a clear trend, as most of the recent plantations were not yet harvested for the second or third time. It can be assumed that the yield trends of the first cutting cycle will also be manifested in the second and further cycles. The experimental data in Larsson and Dobrzeniecki (2004) shows productivity increments during the second cutting cycle for two-year rotations of the varieties 78183 (released in 1990), Jorr (released in 1995) and Tora (released in 1997), of 60%, 60% and 80% respectively. From the same dataset, it is possible to calculate averages assuming cycles of four-year rotations, which are closer to the practices observed in commercial plantations. In that case, the respective increments for the three varieties would be 30%, 50% and 70%. That could indicate that there are additional trends of productivity increase affecting the second cutting cycle as well, since the increments are not directly proportional. The magnitude of these yield improvements during the different cutting cycles will have to be further analysed, although there is ground for optimistic results.

In general terms, from the models developed in Papers I and II, it is easier to understand the high variability of yields from plantations, resulting from differences in farmer practices, and possibly attitude, towards the cultivations. In this respect, the genetic improvements of breed varieties during recent years would only show their full potential in properly established and managed plantations, whose owner is willing to adopt them. Therefore management, together with genetic improvements, are determinant factors in the success of commercial plantations, and it is expected that more experience among the farmers, better advisory service as well as improvements of the varieties will result in a significant increase in the mean yields during the next few years.

4.2 Methods for yield assessment

The development of willow cultivation will require accurate estimates of productivity on more detailed scale, rather than regional averages, in order to develop specific strategies of energy supply. The use of remote sensing indices to estimate willow biomass can provide the necessary level of accuracy on both a plantation and district level. Remote sensing has been extensively applied to estimate above-ground biomass in the forest (see e.g. Meng *et al*. 2007), in forest inventory (e.g. Tomppo and Katila 1991) and in agronomy (e.g. for modelling regional wheat yields, Moriondo *et al*. 2007).

However, willow plantations differ significantly in their characteristics (e.g. management of the stands, the use of short rotations, agricultural practices, small areas planted, discontinuous distribution) from both traditional forestry and conventional agricultural crops. Currently, only aerial pictures have been applied to a limited extent in short rotation plantations (Larsson and Nilsson 2005), possibly due to the lack of extensive data regarding biomass plantations. The results from the preliminary correlations with conventional vegetation indices presented in Paper III are consistent with other research (Trotter *et al*. 1997, Meng *et al*. 2007), although generally they present low accuracy. One of the reasons for the low correlations is the small range of standing biomass from willow plantations, estimated between 2 and 40 odt ha^{-1}, with respect to other forest areas. For instance, the range to define the relationship used in Zheng *et al*. (2004) between above ground biomass and NDVI (corrected with mid-infrared) in a pine forest was from 4 to more than 100 t ha^{-1}. In addition, the estimations are based on wood harvested and not on total growing biomass, and the losses due to the harvesting methods and the biomass from weeds are not accounted for in the models, although they would affect the NDVI measurements. In fact, results from plot experiments show that the total weed biomass in a plantation can be up to 2.5 odt ha^{-1} if no herbicide treatment is applied (Turnbull 2000).

The final predictions presented in Paper III resulting from the application of a model based on GWR significantly improves the accuracy of the predictions, and presents a methodology more adapted to the requirements of SRF. The use of locally calibrated methods in yield modelling offers interesting applications that can be used, among others, to monitor carbon stocks. In addition to the method used, the accuracy of the predictions can also be improved using satellite images with higher resolution, and annual growth data from the plantations to calibrate the models. It is quite possible that future research in areas with higher density of willow plantations would provide enough data to test these possible improvements. Regarding the source of remote sensing measurements, alternatives to the Landsat images would include the use of aerial photography or small format cameras adapted for use with remote controlled planes, which would increase both spatial resolution and frequent repeat coverage at the expense of the size of the area covered. These methods have been applied in agriculture for precision crop management (Moran *et al*. 1997), and its application in willow monitoring seems to be promising.

4.3 Expansion of willow cultivations

The expansion and future development of willow plantations will surely be determined by their profitability, and yield is a key factor, as it significantly affects the final profitability. However, there are other variables that must be analysed. For instance, during the period 1990-1995, the establishment costs were reduced by 50% in Sweden, and the new establishment methods developed during recent years, seem to decrease the costs even further. The lower establishment costs reached were mainly due to large-scale rationalisation, and a similar reduction can be expected in other countries with significant areas planted (Venedaal *et al*. 1997). Further cost reductions have been estimated for the countries analysed (Rosenqvist and Nilsson 2006) if there are the conditions for large scale utilisation and consistent increments of yields during the next few years. However, the cost reductions due to a scaling of the economy are subject to the development of the sector. Some authors have shown the difficulties and needs of policy incentives during the early stages of development, before a critical mass is reached and the sector develops its own momentum (e.g. Roos *et al*. 1999).

These policy incentives can be implemented through different actions. For instance, one approach is introducing an establishment subsidy for willow plantations. The establishment costs are estimated to be around 20% of the total investment during the lifespan of the plantations. Since the first cutting cycle means lower yields and lower incomes, an establishment subsidy can help to reduce the initial investments, reducing the risks taken by the farmer (Johansson *et al*. 2002), and making the option of planting willow more appealing.

The use of establishment subsidies was one of the options taken in Sweden. The analyses of the distribution of willow plantations and growers performed in Paper IV show that it clearly helped the promotion of willow after its introduction in 1991, and the reduction of the subsidy in 1996 had drastic effects in the sector. However, the results of this thesis also reveal the fundamental role of the demand of wood-fuel as a driving force to spread willow cultivation. In this respect, no policies other than taxation on fossil fuels were specifically implemented in order to ensure a demand for energy crops in Sweden (Helby *et al*. 2004).

In general, the demand for willow chips was left to market forces. Nevertheless, during the 1990s oil and electricity prices were quite low to increase significantly the demand for willow chips, and as in many other biomass sources, the willow plantations were not competitive against fossil fuels (Helby *et al*. 2004). This was despite the fact that the biomass prices were declining in real terms over most of the decade (Johansson *et al*. 2002). In addition, the use of fixed establishment subsidies (i.e. not linked to the plantation's productivity) as a main tool to promote willow cultivation affected the motivation and commitment of the farmers, which lead to lower yields, and did not necessarily promoted proper management practices. Subsidies were a very important tool for rapidly increasing the areas, but it many cases it led to plantations with low productivity, established in remote fields, far from the end users.

Among the proposed measures that also can promote the expansion of willow, there is the establishment of long-term contracts between district-heating companies and farmers, with the state as facilitator and sponsor (Helby *et al*. 2004). That would contribute to the reduction of the risks taken by the farmer and therefore would promote adoption. This has been one of the characteristics of the model followed in Enköping, in central Sweden, based on agreements between the main actors involved in the biomass supply and demand (Börjesson and Berndes 2006). The mutual agreements include the obligation of the CHP plant to buy the harvested willow at the current market price, and the farmer is expected to sell their willow chips to the plant. In addition, the CHP is encouraged to recycle the wood ash back to the plantation, and there are some other rather informal agreements working between the CHP and the sewage plant operators. Another approach could include a long-term stable EU agricultural policy, which promotes cultivation systems with environmental benefits. This could be a very important factor in encouraging the expansion of perennial energy crop cultivation.

Concerning other factors that can affect the expansion and location of willow plantations, the results of Paper V shows better adoption rates by farmers in regions with less area covered by grasslands. As found in previous studies (Roos *et al*. 2000, Rosenqvist *et al*. 2000), the area for pastures had a negative relationship with the number of adopters in a municipality, and the same effect was found when the model included variables related to animal production (such as number of cows, and horses, etc.). This can be explained as a conflict in land use between willow coppice and animal husbandry, since farmers with cattle may prefer to keep larger areas set-aside to feed their animals (Roos *et al*. 2000).

Regarding other possible conflicting uses, previous studies on profitability calculations for plantations showed that willow is less competitive in regions with high yielding cereal or in areas with lower productivity where they can conflict with other uses (like fodder or cattle production). However, it is more appealing in areas of medium productivity (Helby *et al*. 2004). Although this was in general observed in Paper V in central Sweden, it must be taken into account that a significant amount of plantations where established in the south (Skåne area) after 1994, where cereal productivity is considerably higher than in the rest of the country. This can be explained, among others, by the increasing demand for wood by the district heating systems in the area that increased the consumption of wood fuels from 160 GWh in 1992, to 650 GWh in 1996.

In general, the use of wood for heating can be considered a pre-requisite for the expansion of short rotation plantations, as it develops the infrastructure and network for the process and distribution of wood fuels to the district heating plants that can serve for the willow biomass (Johansson *et al*. 2002). This also implies additional pressure on the wood stocks that can provide impetus for the search of new raw material sources (Ranta *et al*. 2007) that can include willow plantations. Therefore, the establishment of plantations in Denmark and Finland can theoretically be easily implemented, since the wood fuelled district heating already plays a very important role, as it covers around 60% and 50% of the market share, respectively (Nordvärme 2004).

For Denmark and in the southernmost cultivation zone in Finland, the results of the Swedish research and development in willow varieties can be directly applied, if there are the conditions of technology transfer. In Finland, in the southern and western parts there is the lowest forest fuel potential (Ranta *et al*. 2007) and a very high demand for energy, which makes willow an interesting alternative, since the productivity of these areas would be higher. However, the main part of the Finnish area will need to develop its own biomass research on willow varieties according to its special needs (Pohjonen, 1991). For the north-western areas, attempts to develop proper clones with high productivity and frost tolerance were developed in the late 1980s (Lumme and Törmälä 1988), and highlighted frost tolerance during the first growing seasons as a major challenge to the willow development in the area.

In the Baltic countries the situation might differ: for instance, Lithuania inherited a developed but inefficient oiled-based district heating network, which can serve as a basis for a future modernised wood-based infrastructure. Although currently wood fuels are being introduced in Lithuania, increasing from 0.17 Mtoe in 1990 to 0.70 Mtoe in 2002 (Štreimikiene 2007) they still account for a limited share, as compared to Sweden, Finland or Denmark (Abaravicius 2002). One of the reasons for the slow development of wood biomass in Lithuania is the regulated costs for domestic fuel (Štreimikiene 2007). However, some studies show that boiler-house based on wood can be the most cost efficient technological solution in Lithuanian conditions (Dzenajaviciene 2006). Also, the Austrian experience shows that a fast development of district heating systems based on wood-fuels is possible (Madlener 2007), which can be done in parallel to the establishment of short rotation plantations. In addition, short rotation forestry can be oriented towards the production of biomass for international trade, as has also been speculated in the case of Lithuania and Latvia (Ericsson and Nilsson 2006).

Concerning the productivity in this region the Baltic countries present the largest differences between the estimated maximum potential and the commercial expected productivity. In general, the current agricultural practices in the Baltic countries are older and more labour intensive than in Western Europe (Hoek *et al.* 1996), which is observed in the current agricultural productivity. Although the clones and the experience obtained in Sweden could easily be implemented in the Baltic countries, the potential increments of yields produced by better varieties and improved knowledge of the optimal management could be restricted due to imperfect techniques, the use of unskilled labour, and the lack of monitoring of the management of the plantations by qualified advisors (Mead 2005). According to Mead (2005) the median differences in commercial productivity generally associated with low skilled workforces can be up to 20% due to different establishment practices, 25% in the application of fertiliser, and 20% in spacing. In addition, the use and availability of fertilisers may explain the different agricultural productivity in the Baltic countries. Any possible lack of fertilisation can also significantly affect the productivity of short rotation forestry, as it is estimated that fertilisation below recommended levels can decrease yield by at least 20% (Venendaal *et al.* 1997). In two Swedish fertilisation trials, the yield increase relative to that of unfertilised plots was found to be 0.5 to 1.2% per kg N applied (processed data from Ledin *et al.* 1994 and Nordh 2005).

4.4 Future perspectives and research needs

Sirén (1983) listed, as pre-requisites for the successful development of short rotation cultivation schemes, the spread of know-how based on research, skilled growers, existence of an infrastructure and favourable policies. The overall results analysed in this thesis are largely confirming these conditions as being fundamental for the expansion and development of the sector. The papers presented provide with tools and methods to define and understand the present situation of SRF from a commercial experience, but there are several points that must be addressed in the future.

Future analyses concerning present yields and trends must take into account more detailed variables concerning the actual management and clones used in the plantations. This is an important limitation of the study, as detailed information on the management practices used by the farmers was not available. The new plantations schemes, such as the case of Poland, where 140-170 000 ha are expected to be planted with energy crops, including willow, by 2010, and up to 250-300 000 ha in the following years (Kunikowski *et al.* 2005), must consider the needs for monitoring the performance of the plantations, and to conduct extensive research concerning specific management practices and their effects on the productivity, based on large samples. This can create the possibility of developing more accurate models.

The inclusion of the climatic variability during the years studied can also help to increase the accuracy of the predictions, and to explain part of the variability not caused by management practices. The effect of extreme events, such as early frost in autumn and dry periods can play an important rolw on the success of the plantations, especially in the immediate years after establishment, as was observed by Tahvanainen and Rytkönen (1996). These studies can also help to quantify, with more detail, the yield improvements due to the experience of the farmers, as some effects possibly attributable to climatic variations were observed (Paper II).

The methods and estimates of commercial yields (Papers I, II and VI) can serve as a basis for future economic studies focussing on the profitability of willow cultivation. However, these estimations must be developed at a regional or local scale, also considering the regional trends in wood demand and supply, and the role of the local district heating systems. In addition, the positive externalities provided by willow plantations must be taken into account in the future development of the areas planted. There are many positive effects derived from the willow cultivation, as the plantations can also be used as vegetation filters to purify municipal and industrial wastewaters, municipal sludge and landfill leachate (Aronsson and Perttu 2001, Dimitriou and Aronsson 2003). Furthermore, willow cultivation has positive effects on the soil structure (Ledin 1996), and can be used as shelter belts in order to prevent soil erosion (Börjesson 1999a), and to provide space for fauna diversity and hunting opportunities (Helby *et al*. 2004). In general, there are mostly positive effects from an environmental point of view, especially if the alternatives are most of the other conventional farm crops (Ledin 1998). Börjesson (1999b) estimated that up to 19 TWh of perennial crops could be produced in Sweden at 50% lower costs when all the multi-functional potential of the cultivations are fully utilised. However, future research should focus on developing economic systems where willow cultivation can take full advantage of these externalities in a way that make its expansion more appealing to the farmers.

In addition, future developments of the sector will require cost-efficient and fast methods to predict accurate yields and potentials based on small samples of plantations. The experience of this research (Paper III) reveals the problems and the possible methodologies that can be used to overcome them. The use of satellite, as well as aerial photos, have promising applications for forecasting yields from plantations, when combined with non-parametric methods in order to interpolate the data. The use of GWR and non-parametric *k-nn* based methods can provide the necessary level of accuracy for locally calibrated models of biomass supply.

Although currently there is already a high understanding of the management requirements of willow cultivation, and the crop is technically developed to a large extent, the farmers' perception of the crop is a major barrier to the expansion of the cultivation (Venendaal *et al*. 1997) that must be considered and analysed. This requires a deeper understanding of the motivations and attitudes of the farmers towards the cultivation (e.g. Rosenqvist *et al*. 2000, Roos *et al*. 2000, Helby *et al*. 2006), including marketing and sociological studies at regional and national levels. The geo-statistical methods performed can help to map and understand the combination of factors that produce a successful establishment of a SRF scheme. Based on this methodology, future research can be aimed at developing predictive models for those areas where the establishment of willow plantations is considered. Also, there is great need to develop less human dependent methods of cultivation that reduce the learning curve and can be used in scarcely populated areas.

As many previous studies have concluded, there are no significant climatic, technical or environmental constraints for the rapid development of short rotation plantations for energy in Northern Europe, but the main barriers for large plantations schemes are socio-political, including agricultural and energy policies, market developments and public perceptions and attitudes (Alker *et al*. 2001, Weih 2004). The Swedish development during the last years provides an invaluable experience to make this expansion a reality, and shows the possible contradictions in policy applications. One of the main conclusions is that stable policies and long term contracts between the different actors can reduce the uncertainties associated with the cultivation, and increase the potential number of farmers willing to plant willow (Helby *et al.* 2004). The signs perceived by Johansson (2001) concerning significant future changes in the Swedish bioenergy oriented policies can have important effects on the development of the sector. In this respect, the development of new financial models, oriented to reduce the risks taken by the farmers and to encourage the adoption of short rotation forestry, require further exploration.

From the productivity point of view, the future perspectives of willow cultivation in Northern Europe are promising. The areas suitable for short rotation willow plantations can be significantly enlarged based on scenarios of climate warming (Tuck *et al.* 2006). In addition, the predicted rise in the temperature and CO_2 levels can lead to stimulation of significant growth stimulation on properly fertilised plantations, although the magnitude of this increment will depend strongly on various and confounding factors (Weih 2004): e.g. the performance of the varieties used (Vanhatalo 2003) and possible diseases. In addition, significant yield improvements can be expected in the next years, beyond the scope of the projections presented in this study. For instance, the vast genetic resources for willow in Russia, where there are 2.85 million ha of natural willow according to the International Poplar Commission (IPC, 2004), offer broad possibilities for breeding (Tsarev 2005a), which results in great expectations, given the limited degree of domestication of willow as a crop (Keolian and Volk, 2002). In fact, yields reported from experiments of plant breeding in Russia are well above 20 odt ha^{-1} yr^{-1} (Tsarev 2005b). Another source of yield improvement can come from genetically modified germoplasm, as already has been speculated in Dam *et al.* (2008), which also can contribute to an increasing digestibility of the lignocellulosic crops as a source of biofuel (Gressel 2008).

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