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Regional Potential Yields of Short Rotation Willow Plantations on Agricultural Land in Northern Europe

Blas Mola-Yudego

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The development of short rotation forestry for bioenergy requires accurate and reliable yield estimates. This paper analyses the current, expected and potential regional productivity of short rotation willow plantations for six countries in Northern Europe. The estimations for present productivity are based on empirical models, using data regarding management, and local productivity based on the regional cereal yields. The estimates of expected yield rely on the current trends of yield increase from commercial willow plantations in the region. The estimates for potential yield are based on climatic restrictions. The results show potential average yields of 9.5, 6.8, 7.9, 9.0, 9.3, and 8.0 odt ha^{-1} yr^{-1} for Denmark, Finland, Estonia, Latvia, Lithuania and Sweden, respectively. The results of the study also show that there is a wide regional variation between the different countries. In Denmark, Finland and Sweden there is a convergence between the future forecasts and the climatic potential yields in the areas of high productivity. The Baltic countries seem to present lower estimates of present productivity, reflecting possible socio-economic restrictions, although they show a high biomass potential. The methods presented in this study can be further developed in other areas where willow cultivation is considered, and can serve as a basis for future economic considerations.

Keywords short rotation forestry, willow, production models, regional biomass supply, energy planning
Addresses University of Eastern Finland, School of Forest Sciences, P.O. Box 111, FI-80101 Joensuu, Finland **E-mail** blas.mola@uef.fi
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1 Introduction

Nowadays, short rotation forest (SRF) plantations are gaining attention in many countries, especially when grown oriented towards energy production (Weih 2004). The different policies set by the EU concerning renewable energies, including the goals of the White Paper for a Community Strategy and Action Plan COM (97)599 (CEC 1997) and the Biomass Action Plan (CEC 2005), show a growing interest in expanding the current area covered by SRF in Europe. The estimations of biomass production potential made by the European Environmental Agency consider around 43 to 46 Mtoe from SRF and herbaceous crops in the EU (EEA 2006) for 2010, and up to 102–142 Mtoe 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 (Börjesson et al. 1997, Dubuisson and Sintzoff 1998). In addition, the advantages they present are wide; including efficient land use in combination with the increasing demand for renewable energy resources, increments of biodiversity, positive effects on rural economies as a result of the diversification of farm crops, and the additional possibilities for environmental control and wastewater treatments (Börjesson 1999, Aronsson and Perttu 2001, Keolian and Volk 2002, Börjesson and Berndes 2006).

Among the different fast-growing hardwoods proposed for energy uses, willow (Salix) is one of the few that has been planted commercially to a significant extent in the EU. In Northern Europe it presents the advantages of high productivity for Nordic conditions. Furthermore, it uses practices that are familiar to most farmers, presents winter harvests, thus reducing the impact on other agricultural operations, and demands low economic investments after the establishment is made (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 16000 ha of short rotation willow plantations established, which translates to about 0.5% of the total arable land in the country.

Due to the use of very short rotations, willow plantations are grown under intensive management practices. The plants are cut back after the first growing season mainly in order to promote sprouting. Whole-shoot harvest is usually conducted every 3 to 5 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 amount of fertiliser are around 70 kg N $ha^{-1}\,yr^{-1}$, during the first cutting cycle, applied especially during the third and fourth year (Nordth 2005). 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 (Nordth 2005). The plantations are established in late April to early June, using one-year old shoots (Nordth 2005). The most widely current design in Sweden is the double-row system, with distances between rows of 0.75 m and 1.5 m, and a spacing between cuttings of 0.6 m, within the rows. The densities have been reduced over time, starting from 20000 in the beginning of the 1990s, to 12000 cuttings per hectare of the recent plantations.

Apart from Sweden, in the rest of the countries of Northern Europe, there is not yet extensive commercial experience in growing willow plantations, although many studies and initiatives have shown the high potential for SRF. In Denmark, 400 ha were planted with willow during the 1990s (Venendaal et al. 1997). The Danish action Plan for Energy (1996) establishes the goal of increasing the contribution of renewable energy by 1% per year, to a total of 35% by the year 2030, and to halve the 1988 CO_2 emissions by 2030, with dedicated energy crops being expected to play an important role (IEA CADDET 1998). However, up to now the contribution of energy crops has not fulfilled these expectations (Danish Ministry of Food, Agriculture and Fisheries 2008). In Finland, extensive research and development has been performed on clone selection, and in establishing willow plantations at a commercial level (Venendaal et al. 1997, Tahvanainen 2004). Some authors have already stressed the need of finding new raw-material sources in order to fulfil the current demand of forest biomass for energy purposes (Ranta et al. 2005, 2007). In the

Baltic countries, the land suitability for willow cultivation has been estimated to be 353 000 ha in Estonia, 481 000 in Latvia and 1 332 000 ha in Lithuania, or 19%, 7.5% and 20.6% of the available agricultural land, respectively (Fischer et al. 2005).

Concerning the productivity, several models have been developed in order to assess potential productivity. For instance, Nilsson and Eckersten (1983) established a model for willow production as a function of radiation and temperature for Sweden. Also Perttu et al. (1984) presented a process model in order to simulate willow yields. More recently, Fischer et al. (2005) have presented estimations for broad areas of Europe, including the Baltic countries, based on the agro-ecological zones methodology. Also, some broad estimations have been presented for country averages (e.g. Ericsson and Nilsson 2006) or based on process models or small-plot experiments, especially in Sweden (Lindroth and Båth 1999), but also in Finland (Tahvanainen and Rytkönen 1999, Regional Energy Agency of Eastern Finland 2004), Denmark (Venendaal et al. 1997), and Estonia (Heinsoo et al. 2002).

Although these estimates can be used to set maximum potentials, one of the main disadvantages of these calculations is that they are not based on empirical data from commercial conditions, and do not take into account the effects that technology (e.g. harvesting losses) and management can have on the final calculations. In addition, these estimates often do not provide regional figures, as the productivity can vary broadly in the different areas of the same country. Estimations based on the direct extrapolation of yields from small experimental plots can also over-estimate the real productivity of the area. As shown by Hansen (1991), the yield levels derived from small-plot experiments could be up to 4–7 times higher than average yields from commercial plantations.

One of the most serious uncertainties related to biomass potential in the EU lie in the assumptions concerning the plantations yields (Ericsson and Nilsson 2006). This weakness can compromise future developments of the sector, as in general, the current profitability of willow cultivation is mostly dependent of the average annual yield. According to Rosenqvist and Nilsson (2006), for average Swedish conditions, the necessary yield to make the investment profitable in the 1990s had to be above 8 odt (oven dry tones) $ha^{-1} yr^{-1}$, when excluding land rental costs, and above 12 odt $ha^{-1} yr^{-1}$ when the land rent is included. Similar figures where calculated for Finland (Toivonen and Tahvanainen 1998). These thresholds, however, vary according to the opportunity costs and the prices of wood chips. For instance, an increase of 1% in the cereal prices can result in an increase of 1% in energy crop production cost, when included the opportunity cost in the total cost estimation (Rosenqvist and Nilsson 2006). A realistic estimation of yields is therefore a fundamental question when evaluating the profitability of future plantations and the possible development of the sector through policy promotion. Regional estimations 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.

The present paper aims at presenting yield estimates and future potentials for short rotation willow coppice for bioenergy in 6 countries of Northern Europe, that reflect the possible restrictions due to socio-economic and climatic factors. 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. Finally, the paper also analyses the possible development of willow coppice on the countries studied, and sets a methodology for future economic applications.

2 Material and Methods

2.1 Data Origin

The regional units used for the prediction of willow productivity were defined according to the provincial level classification for agricultural statistics in 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), in the case of Finland. The climatic and agronomical characteristics of these areas were defined as a basis for the modelling development.

First, a set of climatic variables were calculated based on the climate layers provided by the WorldClim database, Version 1.4 (http://www.worldclim.org). The data consists of a set of grid maps resulting from an interpolation process of averages of temperatures and precipitation during the period 1960–1990 (for details about the data and the interpolation process, see: Hijmans et al. 2005). The maps used in this study had 30 seconds spatial resolution, which provided ~1km precision. The precision of the interpolated variables was 0.1 °C for temperature and 1 mm for precipitation.

From this dataset, average daily values of mean temperatures (Tmean) were generated from the monthly average values using linear interpolation. 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 Tmean first exceeded 5.0 °C in spring until the last date that Tmean exceeded 5.0 °C in autumn. Although the calculation from interpolated daily values may result in some differences from data computed from real daily values, since the averages calculated possibly include days when temperatures were below the base value in the spring and fall periods, it is assumed that it is sufficiently accurate.

In order to simplify the calculation process, a systematic grid of 10 km × 10 km was constructed, covering all the area of study. 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 agriculture land as defined in the Corine land cover maps (EEA 2000) were excluded from the calculations.

Finally, an agro-climatic index was developed based on the estimates of cereal yields made by the official statistical services on each country studied. The index was based on averages for oats during the period 2000–2005. The sources used for the dataset were: Statistics Denmark, Statistics Estonia, Statistics Latvia, Statistics Lithuania, Statistics Sweden and the Finnish yearbook of farm statistics (2000–2005). In the dataset from Latvia, yields of oats at a municipality level were only available aggregated with other cereals. The aggregated values were used, however, to weight the national indexes of total oats production per ha, in order to get the yields of oats at provincial level.

2.2 Definition of the Scenarios and Hypotheses Addressed

For each regional unit, an estimation of maximum annual yield on the basis of water availability was defined according to the model of Lindroth and Båth (1999). This model (Eq. 1) assumes that, in conditions of optimal management (including i.e. fertilisation, weeding and control of pests and diseases), the water availability is the only limiting factor. The yield is estimated according to the formula:

$$\text{yield}_i = \tau(1 - c_l - c_r)P_i\omega \tag{1}$$

where yield is the harvestable yield of the plantation in locale i (odt ha^{-1} yr^{-1}) and P is the average precipitation aggregated during the growing season on locale i, in mm. The coefficients c_l and c_r are the fractions of total production going to leaves and roots, respectively, τ is the total water-use efficiency expressed as dry matter per unit of water transpired, and ω is the transpiration fraction of total evaporation.

In order to include the variations due to management in the estimations, a modified version of the model of Mola-Yudego (2008) was used. This model is based on empirical data from commercial willow plantations, and includes the local productivity of oats as agro-climatic index. The model reads:

$$\begin{aligned}\text{yield}_{lkj} &= \beta_0 + \beta_1 OAT_l PLA_{lkj} \\ &\quad + GRO_c PLA_{lkj} + \beta_2 EXP_{lkj}\end{aligned} \tag{2}$$

where yield is the mean annual growth of the plantations (odt ha^{-1} yr^{-1}), β_0–β_2 are parameters,

Table 1. Estimates of the parameters and variance components of the willow yield models of Eq. 1 and Eq. 2, according to Lindroth and Båth (1999) and Mola-Yudego (2008), respectively.

Eq. 1		Eq. 2	
Parameter	Estimate	Parameter	Estimate
ω	0.650	β_0	2.213
τ	6.300	β_1	0.075
c_l	0.200	β_2	–0.204
c_r	0.250	GRO_{50}	–0.129
		GRO_{25}	–0.039

OAT is the regional yield of oats used as a site index (t $ha^{-1} yr^{-1}$), *PLA* is the year of planting, using 1986 as a 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 (no experience = 1) and GRO_c is a categorical parameter for growers according to their performance (GRO_{50} for the 50% best growers, GRO_{25} for the 25% best growers). Subscripts *l*, *k*, and *j* refer to district, grower and plantation, respectively.

The coefficients used in both models are presented in Table 1. The models were the basis to define different scenarios of potential regional productivity for willow cultivation. A scenario of maximum willow productivity (Eq. 1) was defined for each region (*sMaxWL*). This scenario was used as a reference to set the ceiling potential with optimal conditions, excluding management practices as a variable, and on the basis of climatic factors (water availability during the growing period) as the only limiting factor.

Alternative scenarios to reflect the trends in productivity were set based on Eq. 2. For the productivity of established conditions, the resulting estimations for each region were calculated, using the year 2000 as the year of reference. This year is inside the range of the original dataset used to calibrate the model (Mola-Yudego 2008). For estimations on expected productivity, the projections of the model for the year 2010 were calculated. In both cases, two alternatives were presented, based on management practices. The high productivity assumption is based on the resulting estimations for the 25% best growers (*s25t2000* and *s25t2010* for the current and future conditions, respectively). The good productivity assumption is based on the resulting estimations of the 50% best growers (*s50t2000* and *s50t2010*). In both cases, some level of experience of the local farmers was assumed.

The average annual productivity for the lifespan of the plantations was simulated according to the models provided in Mola-Yudego and Aronsson (2008). The calculated yield for the first cutting cycle (Eq. 2) was used as a reference, and the cutting cycle length was fixed at 4 years. The increments of productivity during the second and third cutting cycles were based on Mola-Yudego and Aronsson (2008), also based on data from commercial willow plantations. However, there is no commercial data available for productivity from a fourth and fifth cutting cycles, from a sample broad enough. Therefore, these values were interpolated by adding the resulting estimates for the first and second cutting cycles, respectively, as it is assumed that a decline in productivity will start after the third cutting cycle (i.e. fouth cutting cycle = second; fifth cutting cycle = first). The average annual yield was then calculated by dividing the resulting accumulated production by the total number of years of the five cutting cycles, plus one, in order to include the initial year for cut back.

3 Results

There are broad differences among the countries studied regarding the cereal productivity (Fig. 1). Wheat productivity is lower in countries with colder climates. In general, barley and oats show a similar productivity in all the countries, and the differences between the countries are less extreme. In all cases, the Baltic countries show a lower agricultural productivity than Denmark, Sweden and Finland.

The willow yields calculated according to the *sMaxWL* correlate with the regional oats productivity in Denmark, Sweden, and Finland ($r = 0.678$, $F = 43.29$, p-value < 0.001). This correlation is not appreciated in the Baltic countries (p-value $= 0.158$), which indicates higher poten-

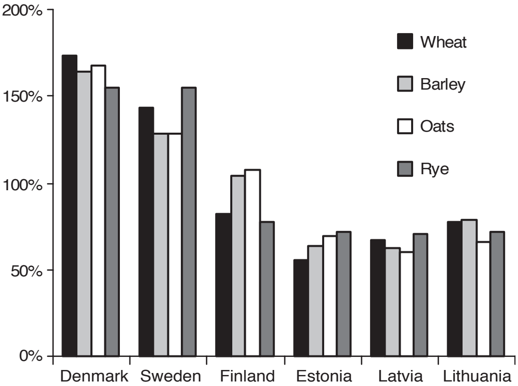


Fig. 1. Productivity of wheat, barley, oats and rye in the countries studied. The values are expressed as a percentage of the 6 countries' average, in order to allow comparisons of magnitude.

tial yields than expected according to their oat productivity (Fig. 2). There is convergence over time of the scenarios based on *s50* (*s50t2000* and *s50t2010*) and the trends of maximum productivity, especially in the areas of highest oats yields. The scenario *s25t2010* crosses the maximum productivity almost in all regions. In general, scenarios *s50t2000* and *s25t2000* run parallel to the curve of maximum productivity.

The predictions for Sweden show convergence over time with the estimated maximum productivity (Fig. 3), according to the scenarios for the *s50* and *s25*, 50% and 25% best growers, respectively. In this case the predictions reflect real data, as have been the basis to produce the models used in the scenarios. In addition, the average predictions for the *s50* follow the same trends to the experimental results from the different willow varieties released in the market during recent years, although with lower performance.

The average yields for the countries studied are presented in Table 2. In the different countries there were broad regional differences (Fig. 4). As an example, the ranges between the maximum and minimum regional yields for the 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 differences between the *sMaxWL*, and the

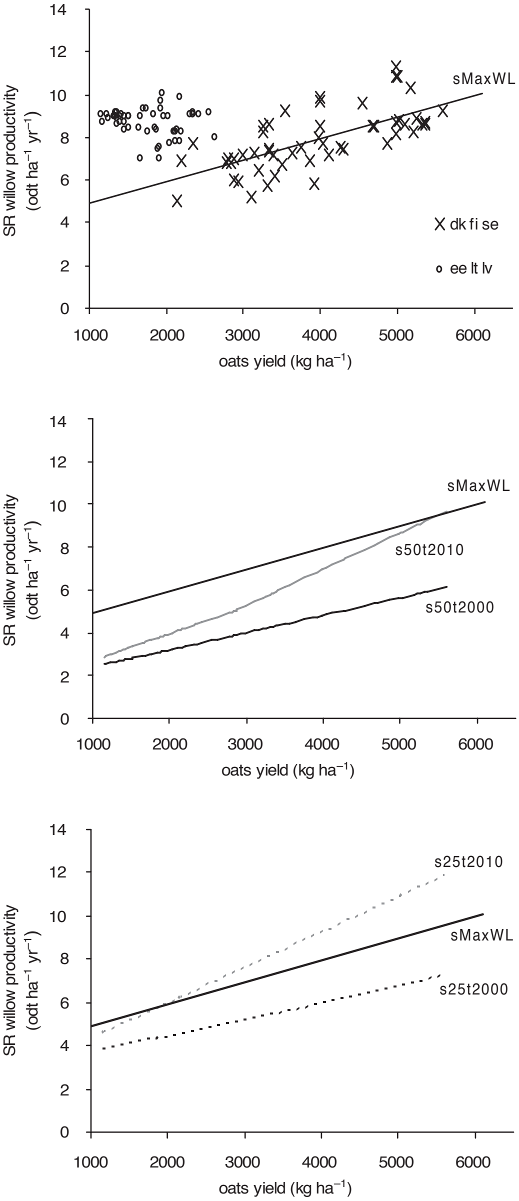


Fig. 2. Trend of the maximum productivity of willow plantations on the basis of water limitation (*sMaxWL*), according to the local cereal productivity in Finland (fi), Sweden (se) and Denmark (dk) (above). This trend is compared to the predictions of the scenarios *s50t2000* and *s50t2010* (middle) and *s25t2000* and *s25t2010* (below). The same approach for Estonia (ee), Latvia (lv) and Lithuania (lt) did not follow the same trend. SR: Short rotation.

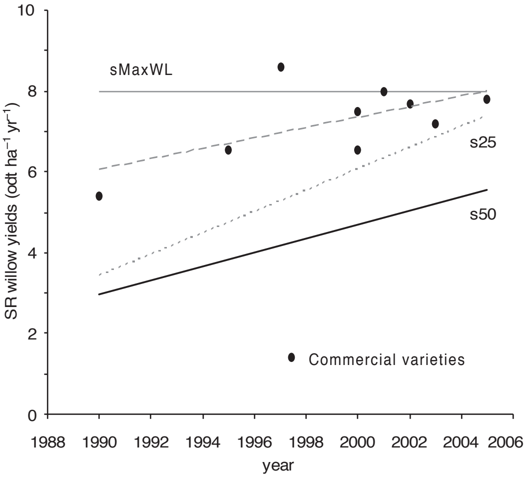


Fig. 3. Yield predictions for the first cutting cycle in central Sweden compared to the performance of the willow varieties released in the Swedish market (Larsson and Dobrzaniecki 2004). The year refers to the time when the variety was released to the market (dots), or when the commercial plantations were established (lines). The predictions refer to the maximum annual productivity on the basis of water limitation (*sMaxWL*), and for the 25% and 50% best growers (*s25* and *s50* respectively), calculated for central Sweden (Örebro county) during the period 1990–2005. A linear trend has been added to the dots (discontinuous line).

scenarios of current and forecasted productivity are in Fig. 5. The Baltic region presents the highest differences between the potential productivity versus the estimated present and future productivity. In Denmark, Finland and Sweden there is a convergence between the future forecasts and the potential yields in the areas of maximum agricultural productivity.

4 Discussion

The present paper offers regional yield estimations for different countries in Northern Europe, combining both empirical and process models, under different scenarios. In general, the estimates presented in this study are significantly lower than predictions from previous studies for potential willow productivity based on process models or experimental data. The general estimations 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 under current agricultural practices ranged around 9.05, 10.13 and 9.71 odt ha^{-1} for Estonia, Lithuania and Latvia, respectively, in very suitable conditions, and slightly below 5 odt ha^{-1} in all three countries in moderately suitable land. 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

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.

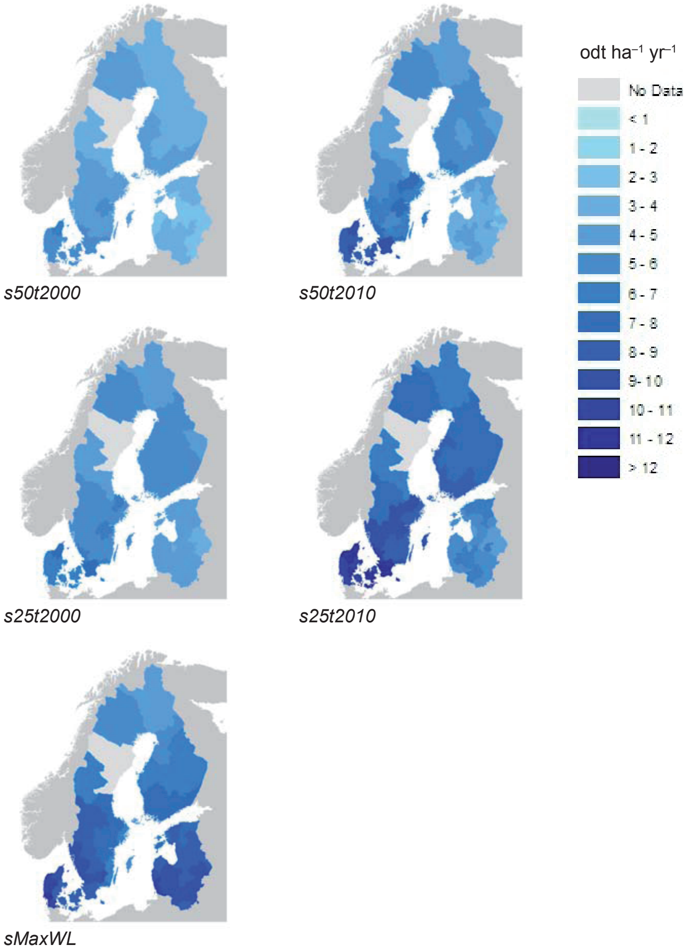
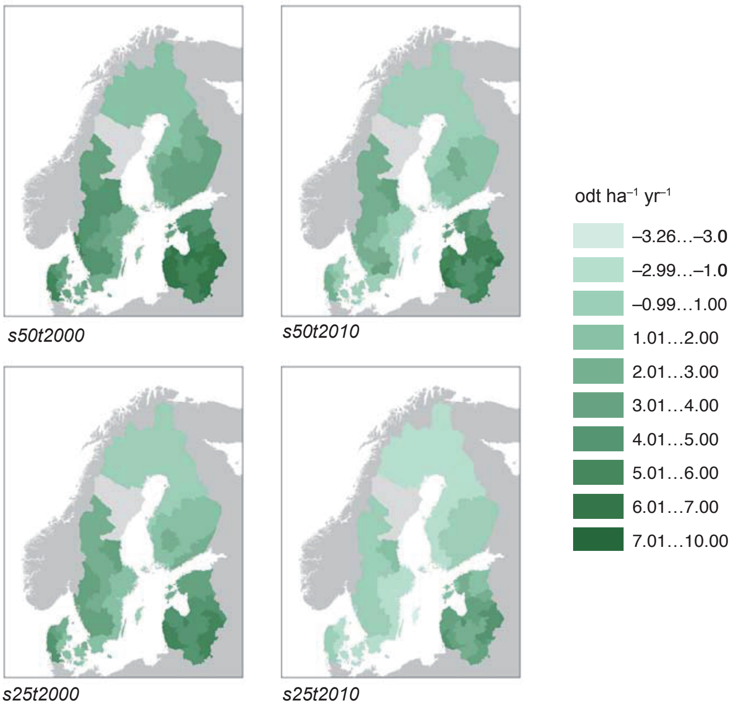


Fig. 4. Estimates of productivity from short rotation willow plantations for the different scenarios presented for Northern Europe. Scenarios *s25t2000* and *s25t2010* are based on the resulting estimations for the 25% best growers, for the years 2000 and 2010, respectively. Scenarios *s50t2000* and *s50t2010* are based on the resulting estimations for the 50% best growers, for the same years. Scenario *sMaxWL* are estimates based on potential productivity in optimal conditions.

ha^{-1} yr^{-1}, in the medium quality soils (Heinsoo et al. 2002). In Eastern Finland, the production ranges were estimated from 6 to 9 odt ha^{-1} yr^{-1} (Regional Energy Agency of Eastern Finland 2004). In Denmark, Nonhebel (2002) presented estimates ranging from 10 to 20 odt ha^{-1} yr^{-1} for intensively managed short rotation poplar plantations.

However, the estimates produced by the models in the different scenarios are similar to the averages measured in 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 harvest. This 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 reported productivity lower than 2 odt ha^{-1} yr^{-1} were 56%



s50t2000 *s50t2010*

s25t2000 *s25t2010*

Fig. 5. Differences between the estimates of yield based on the extrapolation of the Swedish plantations, and the estimated maximum yield only restricted by climatic factors, for the studied regions. Scenarios *s25t2000* and *s25t2010* are based on the resulting estimations for the 25% best growers, for the years 2000 and 2010, respectively. Scenarios *s50t2000* and *s50t2010* are based on the resulting estimations for the 50% best growers, for the same years.

and 44%, for Finland and Sweden, respectively, although the Finnish sample consisted of only 16 plantations (Tahvanainen and Rytkönen 1999, Mola-Yudego and Aronsson 2008). In Denmark, the average productivity for the first cutting cycle at commercial level has been estimated to be around 7–8 odt ha^{-1} yr^{-1} (Venendaal et al. 1997), which also is consistent with the calculations presented in this study (the calculated average estimates for the first cutting cycle by Danish regions are between 5.5–6.5 odt ha^{-1} yr^{-1} and 6.8–7.9 odt ha^{-1} yr^{-1}, for *s50* and *s25* respectively, for the year 2000). The experience of 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.

The use of agricultural productivity as a proxy in order to extrapolate existing data of willow production has already been used by the Regional Energy Agency of Eastern Finland (2004), using timothy to estimate the productivity of willow, reed canary grass, rape and straw, and by Ericsson and Nilsson (2006), using wheat yields as an indicator of the agro-climatic conditions of several European countries. The use of cereal as an indicator of productivity not only reflects the climatic and soil conditions, but also the local socio-economic conditions, and local agricultural policy. Oats is a cereal widely spread in Northern Europe that is grown on soils of less quality than wheat. Geographically, it has a range of distribution similar to willow, and can reflect the conditions where willow will be planted. In previous studies based on this approach, oats showed a better performance than wheat in order to predict the productivity of Swedish willow plantations (Mola-Yudego and Aronsson 2008).

If we assume optimal management, then the climatic restrictions will define the regional productivity. The predictions from this approach can be taken as an upper ceiling, although changes in the water efficiency of the clones or in the local availability of water can raise this limit. In the method used, the regional estimations of the maximum potential were restricted to agricultural land, where willow plantations are located. This resulted in lower estimations of regional productivity in Sweden than the estimates made by Lindroth and Båth (1999) using the same model. For instance, the highest yielding locations reported in their study, with annual averages up to 15 odt ha^{-1} corresponded to locations in the south-west of the country, where the amount of agricultural land is very small, and thus the possibilities for willow cultivation.

The predictions resulting from both modelling approaches used can be combined to give an idea of how close to the climatic potential we can expect the different areas studied to be. According to the results, the Baltic countries present the largest differences between the 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 be easily implemented in the Baltic countries, the potential increments of yields could be restricted due to imperfect techniques, the use of unskilled labour, and the lack of follow up (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 to the level of mechanisation and agricultural practices, the use and availability of fertilisers may explain the different agricultural productivity in the Baltic countries. The total consumption of active ingredient per agricultural land in 2000 was 132 kg ha^{-1}, 134 kg ha^{-1} and 86 kg ha^{-1} in Denmark, Finland and Sweden, respectively (Eurostat 2000, Statistics Finland 2000), whereas the consumption in the Baltic countries for the same year was 36 kg ha^{-1}, 20 kg ha^{-1} and 44 kg ha^{-1}, for Estonia, Latvia and Lithuania, respectively (Eurostat 2000, Statistics Estonia 2000). This lack of fertilisation can also significantly affect the productivity of short rotation forestry. It is estimated that fertilisation below the recommended levels can decrease yields 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 around 0.5–1.2% per kg N applied (Mola-Yudego and Aronsson 2008). However, increments in the prices of fertilizers can result in lower productivity rates than the predictions, as the higher productivity due to fertilization may not necessarily add profitability to the plantations.

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 south and west parts there is the lowest techno-economical forest fuel potential (Ranta et al. 2005) 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 west areas, attempts to develop proper clones with high productivity and frost tolerance were developed in the late 1980s (Lumme and Törmälä 1988), and pointed at frost tolerance during the first growing seasons as a major challenge for willow development in the area.

In addition to the present and potential estimations of productivity, the projections of the models include the expected productivity improvements during the next years. The calculations are based on linear extrapolation of the observed production trends in Sweden (Mola-Yudego 2008). Although future productivity will be dependent on various factors and must not necessarily follow a linear trend, it is very likely to expect yield improvements in the regions analysed. 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 at least 8 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, and the 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 future perspectives of willow cultivation in the boreal area are quite promising. The areas suitable for short rotation willow plantations in northern Europe 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 significant growth stimulation on properly fertilised plantations, although the magnitude of this increment will depend strongly on various and confounding factors (Weih 2004): i.e. the performance of the varieties used (Vanhatalo et al. 2003) and possible pest diseases. In addition, significant yield improvements can be expected in the next years, beyond the scope of the projections presented. On one hand, the vast genetic resources for willow in Russia offer broad possibilities for breeding (Tsarev 2005a). 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 may 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).

The development of plantations and yields in the area studied will certainly be determined by the profitability of the willow cultivation. On one hand, the development of a market for willow chips will be a key factor, and the existence of a sustained demand (Helby et al. 2004). The existence of a well established wood fuelled heating system in Sweden, Finland and Denmark (Johansson et al. 2002) and the perspectives of a similar development in the rest of the countries (Klevas et al. 2007) can contribute to the expansion of the cultivation. The reduction of costs will also be a fundamental factor for the development of the willow plantations. In this respect, during the period 1990–1995, the establishment costs have been reduced by 50% in Sweden, and the new establishment methods developed during recent years seem to decrease the costs even further (Venedaal et al. 1997). The lower establishment costs reached in Sweden were mainly due to large-scale rationalisation, and similar reductions can be expected in other countries with significant areas planted. In fact, even further cost reductions have been estimated for the countries analysed, if there are the conditions of large scale utilisation and the consistent increments of yields during the next years (Rosenqvist and Nilsson 2006). However, probably the most important factor for a rapid development of short rotation willow plantations will be socio-political, i.e. agricultural policy, energy policy, public attitudes and market development (Weih 2004).

Although there is a great level of uncertainty about the expected productivity of willow plantations, due to the general lack of data from commercial plantations, this study contributes with estimates of current, expected and potential productivity based on solid empirical data from the Swedish experience. The estimations presented can be the basis for future analysis concerning profitability of plantations, and for bio-energy policy and planning.

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