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Yield models for commercial willow biomass plantations in Sweden

Blas Mola-Yudego[a,*], *Pär Aronsson*[b]

[a]*Faculty of Forestry, University of Joensuu, P.O. Box 111, FI-801 01 Joensuu, Finland*
[b]*Department of Crop Production Ecology, Swedish University of Agricultural Sciences (SLU), P.O. Box 7016, S-750 07 Uppsala, Sweden*

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ABSTRACT

A yield model for willow plantations for bioenergy production in Sweden was developed based on recorded production of 2082 commercial plantations during the period 1989–2005. The model predicts yield for the first, second and third harvest using oats (*avena*) production as agro-climatic index. The mean annual yields were 2.6, 4.2 and 4.5 oven dry tonnes (odt) per hectare during the first, second and third cutting cycles, respectively. The yield correlated inversely with the length of the cutting cycle. The results of the study show significant differences between growers, which suggest the importance of proper management in the establishment and tending of the plantations. Model estimates for 25% of the best growers vary from 4.0 to 6.3 odt ha^{-1} yr^{-1} in 5-year-rotation plantations during the first cutting cycle, and from 5.4 to 7.1 odt ha^{-1} yr^{-1} in 4-year-rotations for the second cutting cycle. The proposed model can be applied in policy making and for management planning.
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1. Short rotation willow plantations in Sweden

Short rotation plantations have been regarded as one of the main alternatives in the shift towards a more sustainable energy supply, to substitute fossil fuels, in Europe [1]. In order to cover the demand by both traditional uses and the renewable energy sector, a substantial increase in the area of short rotation plantations will be required during the next few years [2]. In fact, to accomplish the goals of the EU White Paper [3] for 2010, about 230 Mm^3 of roundwood equivalents are required from short rotation forestry production systems, which entails (at the current annual biomass production rates) the establishment of approximately 11 million ha of additional short rotation plantations [4].

Willow (*Salix*) has been cultivated as an agricultural crop for bioenergy purposes in Sweden for the last 20 years and is regarded as an important crop for the production of wood fuel for the Swedish energy sector [5]. Grown and processed in a sustainable way, wood fuels from willows represent an energy source with low net CO_2 emissions when substituted for fossil fuels [6]. During the last two decades, more than 16,000 ha of short rotation willow plantations have been established in Sweden, i.e. about 0.5% of the total arable land in Sweden [7], making Sweden the leader in commercial plantations of short rotation willow in Europe. After harvest, the shoots are usually converted into wood chips and used as fuel in district heating plants, in Sweden contributing about 1% of the wood fuel requirement of the energy sector [7].

Willow cultivation fits well with current farm operations, because it uses agricultural practices that are familiar to farmers, and after establishment, it is a relatively low input crop with winter harvests and limited impact on other farming operations [8]. Willows constitute alternative non-food cash crops for farmers in several countries across Europe. In Sweden commercial willow plantations are established using a double-row system, currently with 1.5/0.75 m spacing between the rows, and approximately 0.75 m between

*Corresponding author. Tel.: +358 132514408; fax: +358 132514422.
E-mail address: blas.mola@joensuu.fi (B. Mola-Yudego).
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plants within the rows. In the early 1990s, the planting density was about 20,000 cuttings per hectare, but today it is around 12,000 cuttings per hectare. The plants are cut back after the first growing season mainly in order to promote sprouting. Whole-shoot harvest is usually conducted every 3–5 years, but the harvest interval is often longer if the growth is poor as the fixed costs related to harvesting operations are high.

It is generally believed that the economic lifespan of a willow plantation is less than 25 years, although the biological lifespan can be longer [1,9]. Since the early 1990s, the market for willow cuttings has been dominated by varieties bred for short rotation willow plantations, mainly crossings and hybrids of *Salix viminalis*, *Salix dasyclados* and *Salix schwerinii*, which have been tested for productivity, pest resistance, frost hardiness and shoot straightness [10].

Numerous studies have shown the high production potential of short rotation willow. An average annual growth of 10–20 oven dry tonnes (odt) per hectare has been observed in many experiments [11] and even higher growth rates (i.e. above 30 odt $ha^{-1} yr^{-1}$) have been recorded in intensively irrigated and fertilized research plots of *S. dasyclados* in southern Sweden [12]. Such findings may have contributed to over-optimistic predictions of the yield in commercial willow plantations. Furthermore, extrapolation of yields from small experimental plots is troublesome. As shown by Hansen [13], production levels derived from small-plot experiments could be four to seven times higher than average yields from plantations. However, annual average yields over 10 odt ha^{-1} are possible in commercial plantations fertilized and properly weeded [7].

Lindroth and Båth [14] developed a model for estimating the potential yield of willows in Sweden based on water availability, i.e. precipitation during the growing season divided by the water use efficiency. Their model predicted the annual maximum yield to be 8–9 odt ha^{-1} for north-eastern, 9–10 odt ha^{-1} for eastern and 11–17 odt ha^{-1} for southern and south-western Sweden. However, there is no empirical yield model derived from commercial short rotation willow plantations in Sweden or elsewhere, simply due to the lack of yield data [15].

This study aims to develop a yield model to estimate the yield in short rotation willow plantations in southern and central Sweden based on recorded yields of 2082 commercial short rotation willow plantations. The model includes yield predictions for the first, second and third cutting cycles and explores the ranges of production in different areas by using official estimates of cereal yields as a predictor for site conditions. The influence of management and tending is studied indirectly by exploring the variability of yield between growers in the same area.

2. Material and methods

2.1. *Yield data from commercial willow plantations*

Yield data from willow plantations established on private farms in southern and central Sweden were provided by Lantmännen Agroenergi AB (formerly known as Agrobränsle AB), which manages planting and are the administrators of the harvesting of the willow plantations. Data with inconsistent records or lacking information regarding the dates of harvesting or the location were excluded from the calculations. All plots were geo-referenced with a 1 km precision. They covered the area from 55°20′N to 61°29′N and from 11°33′E to 18°56′E (Fig. 1). The models were based on a total of 2082 plantations covering 9048 ha, managed by 859 growers, during the period 1986–2005. Most of the plantations had been harvested several times during the period studied, although records of the first harvest were not always available in the database of harvests. The yield was divided by the number of years since the last harvest (i.e. rotation length, RL). All plantations studied had been cut back, in most cases after the first growing season.

2.2. *Yield model for willow plantations*

The predicted variable of the yield model was the mean annual growth per hectare, expressed as oven dry tonnes per hectare and year (odt $ha^{-1} yr^{-1}$). The predictors were chosen so as to show the influence of management and site characteristics. All predictors had to be significant at the 0.05 level, and the residuals had to indicate a non-biased model.

The harvesting records were grouped according to the plantation and grower. Therefore, due to the hierarchical structure of the data, a mixed model of repeated measures was used. The residual variation was divided into between-grower and between-plantation components. The linear models were estimated using the maximum likelihood procedure of SPSS.

An agro-climatic index was developed based on the official estimates of cereal yields (at 15% moisture content) made by the Swedish National Board of Agriculture [16,17]. The index was based on two sets of data; county averages for 1990–2005 ($n = 17$) [16] and district average standard yields for 2003–2005 ($n = 47$) [17]. The standard yields are published every year and formed by calculating the survey district mean of the yield data for the last 15 years, adjusted for an estimated yearly growth increase [17]. Yields of oats and barley could be used for all 2082 plantations analyzed on a county or district level. Yields of wheat were available for 2060 plantations on a county level and for 2031 (winter wheat) and 1685 (spring wheat) on a district level.

The yield of commercial Swedish willow plantations was modeled according to:

$$\text{yield}_{lkjt} = \alpha + \beta \times \frac{\text{CER}_l}{\text{RL}_{lkjt}} + \text{CUT}_t + \mu_{kt} + e_{lkjt}, \quad (1)$$

where yield is the mean annual growth of the plantations (odt $ha^{-1} yr^{-1}$), α and β are parameters, CER is the yield of the cereal used as agro-climatic index (t $ha^{-1} yr^{-1}$), RL is the rotation length of the cutting cycle (yr), CUT is a dummy for the cutting cycle (first, second or third). Subscripts l, k, j and t refer to county/district, grower, plantation and cutting cycle, respectively. μ_{kt} is the between-grower random factor, independent and identically distributed with diagonal covariance structure, with mean = 0 and a constant variance for every cutting cycle ($\sigma^2_{\text{grower},t}$). Finally, e_{lkjt} is the

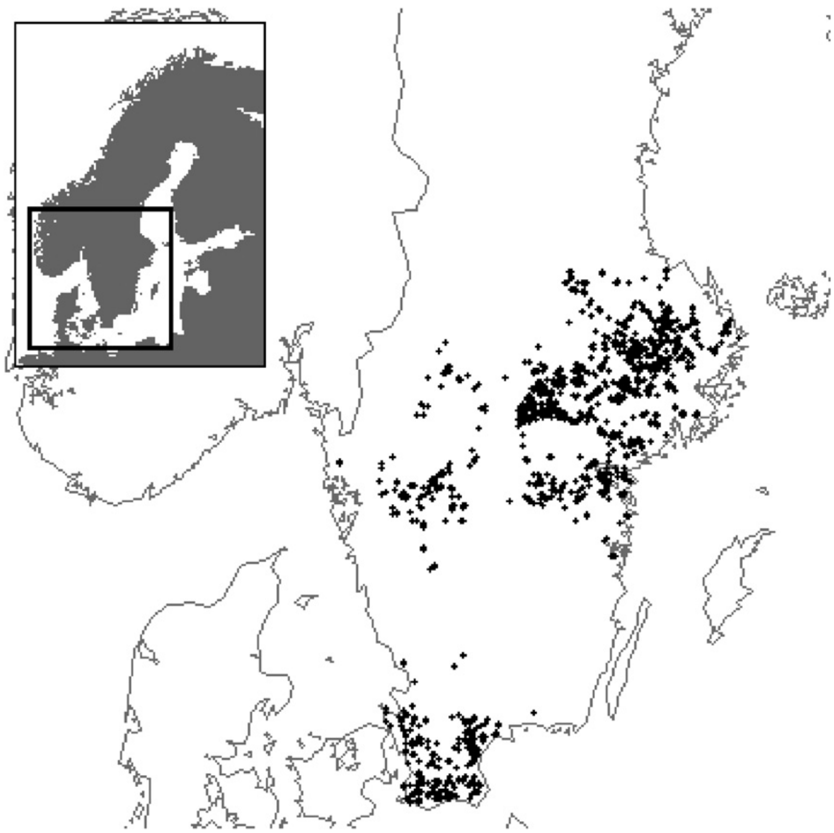

Fig. 1 – Distribution of the commercial willow plantations for bioenergy used in the model.

between-plantation random factor for yield of cutting cycle t on plantation j, managed by grower k in the county/district l, with mean = 0 and variances $\sigma^2_{\mathrm{pl},t}$.

In order to study the effect of the length of the cutting cycles, the following model was proposed using the same maximum likelihood procedure of SPSS:

$$\mathrm{RL}_{lmkt} = \alpha + \beta \times \mathrm{CER}_l + \mathrm{CUT}_t + \mu_{kt} + e_{lkjt}. \quad (2)$$

The yield model was 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 as follows:

$$\mathrm{bias} = \frac{\sum(y_i - \hat{y}_i)}{n}, \quad (3)$$

$$\mathrm{bias}\ \% = 100 \times \frac{\sum(y_i - \hat{y}_i)/n}{\sum \hat{y}_i/n}, \quad (4)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-1}}, \quad (5)$$

$$\mathrm{RMSE}\ \% = 100 \times \frac{\sqrt{\sum(y_i - \hat{y}_i)^2/(n-1)}}{\sum \hat{y}_i/n}, \quad (6)$$

where n is the number of observations, and y_i and $\hat{y}_i$ are observed and predicted values.

3. Results

The resulting yield data from the harvest records included in the model is presented in Fig. 2. The annual average yield during the first to third cutting cycles were 2.63, 4.19 and 4.47 odt ha^{-1} yr^{-1}, respectively, and the corresponding lengths of the cutting cycles were 6.0, 4.5 and 4.2 years (Table 1).

The parameter estimates of the yield model were significant (Table 2). Among the various cereals tested as agro-climatic index, oats (*Avena*) were finally selected for the final version of the model. 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.

The model showed similar yields for the second and third cutting cycles, both significantly higher than 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.

The same predictor for agro-climatic index based on yields of oats (Tables 3 and 4) was not significant in the model for the length of the cutting cycle (Eq. (2)). Parameter estimates excluding site index (Table 5) 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.

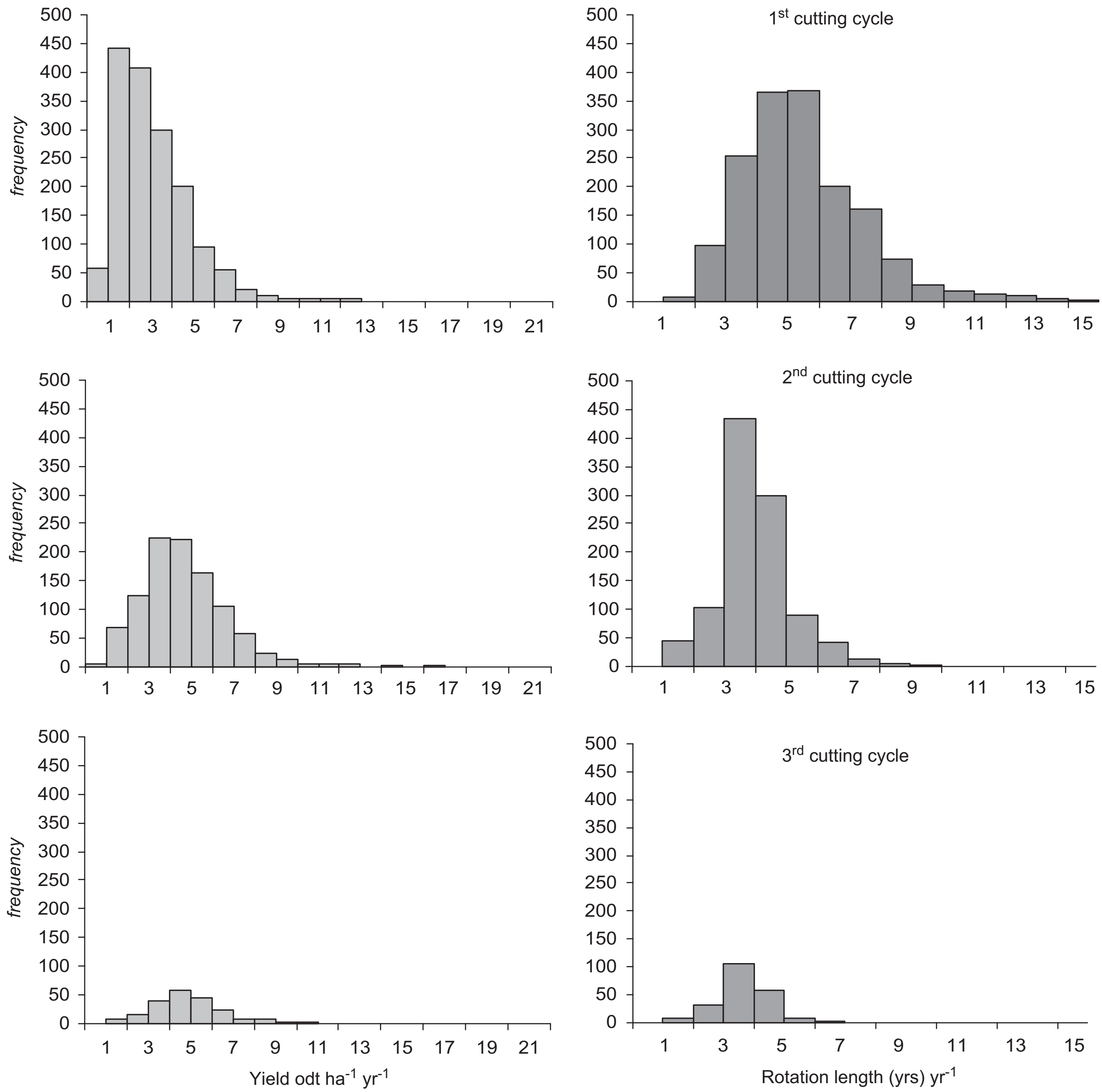

Fig. 2 – Frequencies of yields (left) and rotation length (right) of the first to third cutting cycles.

The bias of the fixed part of the yield model, using oats by survey districts, was examined by plotting the residuals as a function of the predicted variable and predictors of the model (Fig. 3). No obvious dependencies or patterns that indicate systematic trends among the residuals and the independent variables were found. It should be taken into account that part of the residual variation of the fixed part is explained by the random grower and plantation factors. Including the random parameters in the model increases the model R^2 from 0.31 to 0.69 (Fig. 4).

The estimated willow yield during the first cutting cycle varied from 2.8 to 5.1 odt ha^{-1} yr^{-1}, with a rotation length of 5 years, using the minimum and maximum yields of oats by district, respectively. For the second harvest, the corresponding yields vary from 4.3 to 5.9 odt ha^{-1} yr^{-1} for a rotation length of 4 years and the same yields of oats (Fig. 5). Including between-grower differences from the random part of the model and using the same parameters, results for the 25% best growers vary from 4.0 to 6.3 odt ha^{-1} yr^{-1} during the first cutting cycle and from 5.4 to 7.1 odt ha^{-1} yr^{-1} for the second cutting cycle. The relation of the average yields with the length of the rotation length is shown in Fig. 6.

4. Discussion and conclusions

This study presents a yield model for biomass production from willow in southern Sweden, based on harvest records

Table 1 – Mean, standard deviation (S.D.) and range of the willow yield data obtained and the variables used in modeling

Variable	Mean	N	S.D.	Maximum	Minimum
First cutting cycle					
Yield (odt $ha^{-1} yr^{-1}$)	2.63	1610	1.88	20.54	0.03
RL (yrs)	5.98	1610	2.00	15.00	2.00
Second cutting cycle					
Yield (odt $ha^{-1} yr^{-1}$)	4.19	1035	2.23	20.67	0.10
RL (yrs)	4.50	1035	1.23	11.00	2.00
Third cutting cycle					
Yield (odt $ha^{-1} yr^{-1}$)	4.47	216	2.00	15.59	0.93
RL (yrs)	4.18	216	0.98	10.00	2.00
Site indicators					
OAT_{sd} (t $ha^{-1} yr^{-1}$)	4.13	2082 (47)	0.643	6.32	2.40
OAT_c (t $ha^{-1} yr^{-1}$)	4.01	2082 (17)	0.392	4.90	2.56

Figures in parenthesis refer to the number of districts and counties included in the data.
Yield: average annual yield of willow plantations; RL: rotation length, i.e. length of the cutting cycle.
OAT_{sd}: average for 2003–2005 of standard yields of oats in agronomical districts as calculated by the Swedish Board of Agriculture [17].
OAT_c: official yield of oats using the average of county yields for 1990–2005, as published by the Official Statistics of Sweden [16]. Growers for a *t* cutting cycle.

Table 2 – Estimates, standard error (S.E.) and significance level of the parameters and variance components of the willow yield models (Eq. (1)) using oats as site index and the yield of the third cutting cycle as reference

Parameter	Using oats yield by district[a]		Using oats yield by county[b]	
	Estimate (S.E.)	*p*-Value	Estimate (S.E.)	*p*-Value
α	1.543 (0.190)	0.000	1.523 (0.201)	0.000
β	2.907 (0.114)	0.000	3.017 (0.128)	0.000
CUT_1	−1.075 (0.162)	0.000	−1.050 (0.168)	0.000
CUT_2	−0.197 (0.167)	0.239	−0.173 (0.173)	0.319
CUT_3				
$\sigma^2_{pl,1}$	1.698 (0.077)	0.000	1.713 (0.078)	0.000
$\sigma^2_{pl,2}$	2.734 (0.157)	0.000	2.729 (0.157)	0.000
$\sigma^2_{pl,3}$	2.285 (0.372)	0.003	2.292 (0.358)	0.000
$\sigma^2_{grower,1}$	1.148 (0.112)	0.000	1.270 (0.119)	0.000
$\sigma^2_{grower,2}$	1.110 (0.176)	0.000	1.216 (0.182)	0.000
$\sigma^2_{grower,3}$	1.259 (0.487)	0.001	1.461 (0.485)	0.003

S.E.: standard error of the estimations are given in parenthesis.
p-Value: significance of the estimation of the parameter.
Variance between-growers for a *t* cutting cycle.
[a] Using average standard yields for 2003–2005 by agronomical districts as calculated by the Swedish Board of Agriculture [17].
[b] Using the average of yields from 1994 to 2005 as published by the Official Statistics of Sweden [16].

from 2082 plantations for the period 1989–2005. The dataset used provides extensive information about commercial willow plantations, although it should be taken into account that the purpose of the records was not specifically designed to develop yield models. A disadvantage of these data is that the average yield is calculated from harvest records and it lacks information about the growth during individual years of the cutting cycle. Also, many factors related to the management and care of the plantations are unknown and some human errors or missing values were detected and excluded from the calculations. However, these deficiencies were compensated by the large amount of data available that allowed include in the models almost 60% of the whole area planted with willow for bioenergy in Sweden.

As any other agricultural crop, willow shows different production potentials as related to climate and soil conditions. In order to include this variation in the model, some cereals were tested as indicators of agro-climatic conditions,

Table 3 – Absolute and relative bias and RMSEs and coefficient of determination (R^2) of the yield model (Eq. (1)) using different cereals as site index

	N	Bias (odt $ha^{-1} yr^{-1}$)	% Bias	RMSE (odt $ha^{-1} yr^{-1}$)	% RMSE	R^2
BAR_{sd} (t $ha^{-1} yr^{-1}$)	2082	−0.08564	−2.4	1.87	54.7	0.263
WHE_{sd} (t $ha^{-1} yr^{-1}$)	2063	−0.08082	−2.2	1.86	54.5	0.271
OAT_{sd} (t $ha^{-1} yr^{-1}$)	2082	−0.08128	−2.3	1.86	54.4	0.273
BAR_c (t $ha^{-1} yr^{-1}$)	2082	−0.06254	−1.8	1.83	53.8	0.296
WHE_c (t $ha^{-1} yr^{-1}$)	2033	−0.0632	−1.8	1.85	54.3	0.285
OAT_c (t $ha^{-1} yr^{-1}$)	2082	−0.06233	−1.7	1.82	53.6	0.303

N: number of plantations; BAR_{sd}, WHE_{sd} and OAT_{sd}: average for 2003–2005 of standard yields of spring barley, winter wheat and oats by agronomical districts as calculated by the Swedish Board of Agriculture [17].
BAR_c, WHE_c, OAT_c: official yield of spring barley, winter wheat and oats using the average county yields for 1990–2005 as published by the Official Statistics of Sweden [16].

Table 4 – Estimates of the site index (β) as predictor of length of cutting cycle as expressed in Eq. (2), based on the yield of barley, oats and wheat

Parameter	Estimate	S.E.	d.f.	t	p-Value
BAR_{sd}	−0.106	0.098	1203.3	−1.084	0.279
BAR_c	−0.107	0.055	1349.7	−1.932	0.054
OAT_{sd}	−0.033	0.103	1207.5	−0.318	0.450
OAT_c	−0.082	0.589	1358.4	−1.384	0.167
WHE_{sd}	0.006	0.059	1236.4	0.097	0.923
WHE_c	−0.034	0.039	1330.5	−0.857	0.392

BAR_{sd}, WHE_{sd} and OAT_{sd}: average for 2003–2005 of standard yields of spring barley, winter wheat and oats by agronomical districts as calculated by the Swedish Board of Agriculture [17].
BAR_c, WHE_c, OAT_c: official yield of spring barley, winter wheat and oats using the average county yields for 1990–2005 as published by the Official Statistics of Sweden [16].
S.E.: standard error of the estimations.
d.f.: degrees of freedom; p-value, significance of the estimation of the parameter.
Growers for a t cutting cycle.

Table 5 – Estimates of the parameters and variance components of the cutting cycle (Eq. (2))

	Estimate	S.E.	d.f.	T (Wald Z)	p-Value
α	4.232	0.087	100.7	48.393	0.000
CUT_1	1.951	0.113	264.6	17.249	0.000
CUT_2	0.313	0.102	182.9	3.056	0.002
CUT_3					
$\sigma^2_{pl,1}$	1.267	0.060		(20.910)	0.000
$\sigma^2_{pl,2}$	0.722	0.045		(15.885)	0.000
$\sigma^2_{pl,3}$	0.491	0.081		(6.061)	0.001
$\sigma^2_{grower,1}$	2.947	0.201		(14.630)	0.000
$\sigma^2_{grower,2}$	0.925	0.099		(9.376)	0.000
$\sigma^2_{grower,3}$	0.596	0.149		(4.002)	0.053

The model excludes the predictor β used as a site index.
S.E.: standard error of the estimations; d.f.: degrees of freedom.
p-Value: significance of the estimation of the parameter.
CUT_t refers to first, second and third cutting cycles.
$\sigma^2_{pl,t}$: estimations of the variance between plantations for a t cutting cycle.
$\sigma^2_{grower,t}$: estimation of the variance between-growers for a t cutting cycle.

assuming a linear relationship with the yield of willow for the range of data studied. Cereals are widely cultivated in Sweden and their yields are easily available, which highly simplifies the modeling of the yield of willow. Ericsson and Nilsson [15] used wheat for estimating willow yields for different EU countries assuming the same linear relationship, and wheat was also used by Helby et al. [18] to calculate the farmer's opportunity costs for willow production in Sweden. The final version of the model in our study used oat yields, since oats covered a wider area and provided a slightly better correlation than the other cereals tested.

Commercial willow plantations are not annual crops, and the length of the cutting cycle has an effect on average yields [19]. In general, cycles from 3 to 6 years have been broadly recommended, since that means less weed control and harvesting costs, as well as higher yields [1]. However, the length of the cutting cycle is ultimately a decision of the grower, and many factors other than yield efficiency may play an important role. Our observations have showed higher average annual yields in those plantations that used short rotations, although the casual effect cannot be stated. On one hand, initial good growth levels may encourage growers to reduce the cutting cycle, while poor results would contribute to its prolongation, in order to maximize profitability. On the other hand, intensive management and fertilization are more likely to be done when the cutting cycle is short. In plantations not properly fertilized, the mortality of the stools in long cutting cycles can mean a reduction of the yields, since it is not compensated by the remaining plants [9,20]. Another factor that may have reduced yields in long cutting cycles is the risk of infections [21].

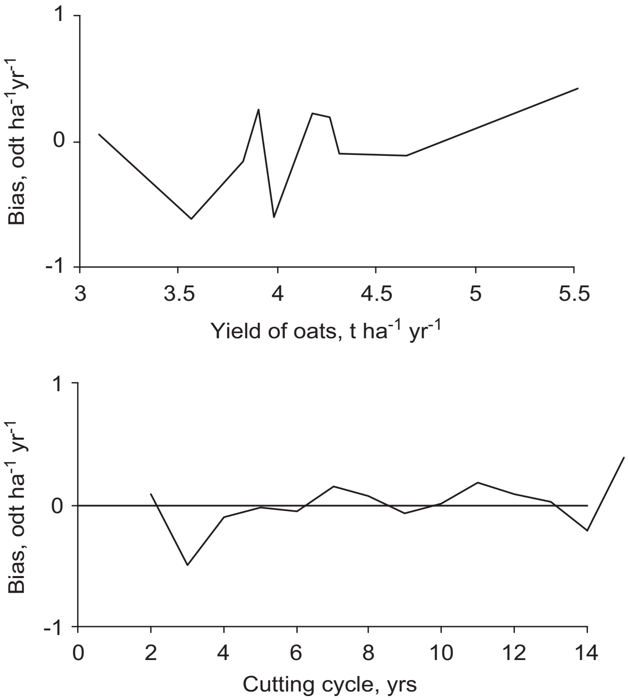

Fig. 3 – Mean residuals (bias) of the yield model as a function of yield of oats by agronomic district (divided in 10 tiles) and rotation length.

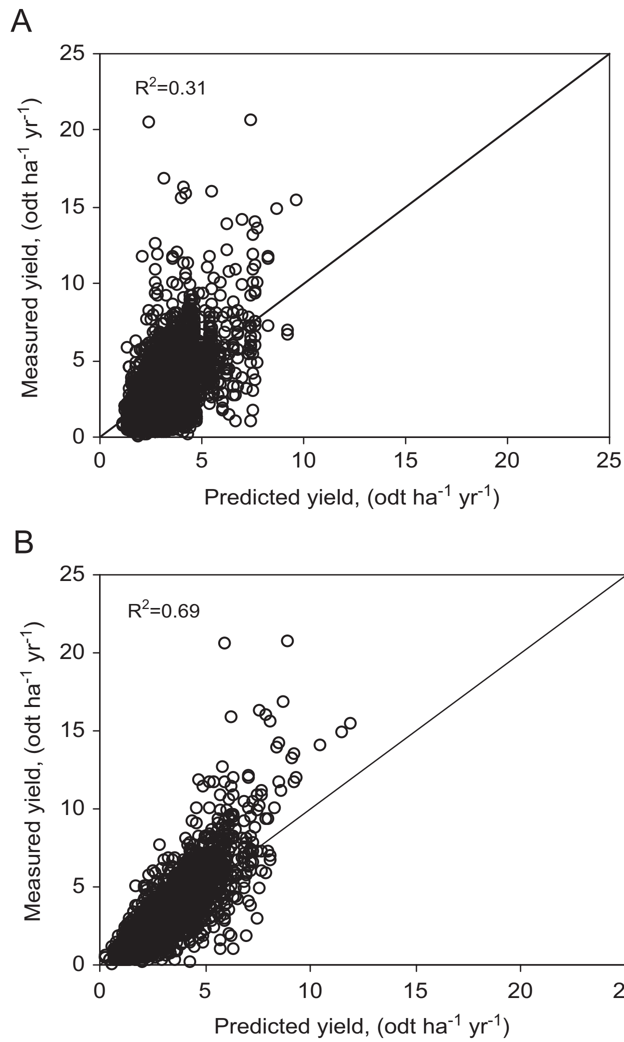

Fig. 4 – Measured and predicted average yield for willow plantations, according to the model proposed (Eq. (1)) using the fixed part of the model (A) or both fixed and random parameters (B).

The results indicate 60% higher yields after the first cutting cycle. During the second cutting cycle, the stools have developed a root system and are already established, which makes them more productive. Some studies have found substantial increments of average annual yields during the second harvest [9,22,23]. The model predicts increments of almost 1 odt $ha^{-1} yr^{-1}$ during the second harvest for a fixed rotation length. Although lower yields have been reported during the third cutting cycle due to high mortality of the stools [9], our results reveal no significant differences in average annual yield between the second and third cutting cycle.

The estimates of average annual yield showed wide differences of production that were also found in previous studies on plantations managed directly by farmers. In Sweden, the average annual yields of willow varied from 1.25 to 11.25 odt ha^{-1} in around 130 ha, surveyed during 1986–1991 [24]. In Finland, the annual yield varied from 0.37 to 8.35 odt ha^{-1} in 35 plantations during 1993–1995 [25]. The experience of these studies showed that proper establishment and tending of the cultivation were key factors in the success of the plantations that had a clear effect on production. In the Finnish study, it was also shown that establishment on poor soils would result in a reduction of productivity or even a complete failure of the plantation. In addition, insufficient weed control, lack of fertilization or poor water availability, resulted in very low yields.

We propose the hypothesis that differences in annual yield of willows between growers in the same area are partially attributed to different management practices. It has been shown that nitrogen fertilization significantly increases the yield of willows. In two Swedish fertilization trials the relative yield increase, relative to that of unfertilized plots, was found to be 0.5–1.2% per kg N applied (processed data from Nordh [9] and Ledin et al. [26]). Among the commercial willow plantations the application of sewage sludge is very common, but proper nitrogen fertilization is rare. In fact, practitioners estimate that only 1–10% of the plantations have been fertilized with nitrogen [27,28].

A possible explanation for the lack of fertilization of commercial willow plantations is to consider it as a result of logical economical considerations by the farmer. Applying 100 kg N ha^{-1} costs around 100 € ha^{-1} in Sweden whereas the marginal value of the increased yield is in the order of 30 € odt^{-1} [29]. Thus, the farmer must expect a yield increase of, at least, 3.3 odt ha^{-1} in order to gain a net income from the nitrogen application. If considering a growth response in the order of 0.5% per kg N applied, the average farmer would increase the yield with less than 3 odt ha^{-1}, and accordingly, lose money on the operation.

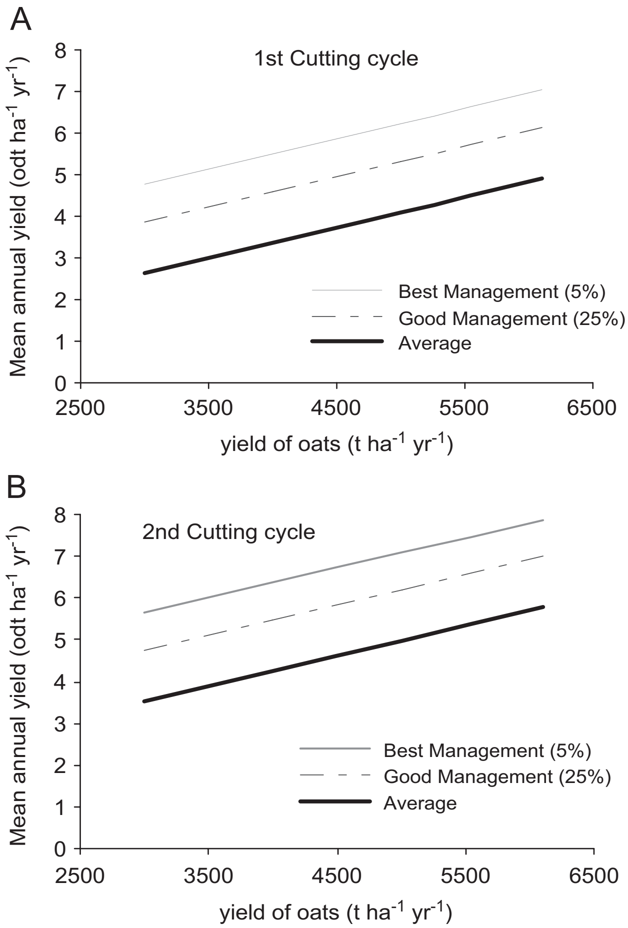

Fig. 5 – Modeled mean annual yield (odt ha^{-1} yr^{-1}) of willow in Sweden for the first and second cutting cycles as a function of oats production by districts, and achievement done by the growers. Used predictor values in (A): CUT = 1, rotation length of cutting cycle = 5 yrs; $\sigma^2_{grower} = 1.148$. In (B): CUT = 2, length of cutting cycle = 4 yrs; $\sigma^2_{grower} = 1.110$.

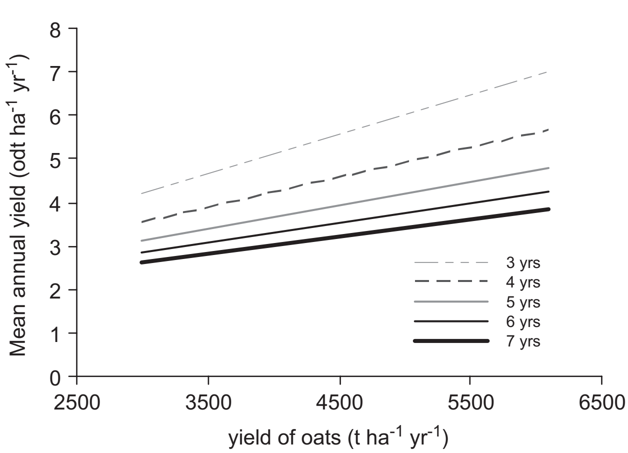

Fig. 6 – Mean annual yield of a willow (odt ha^{-1} yr^{-1}) as predicted by the model for different rotation lengths during the second cutting cycle, as a function of yield of oats.

Another, possibly important factor, for the low average yields recorded in the commercial plantations is the dominance of old, not especially bred short rotation willow varieties in the data. More than 55% of the plantations included in the study were planted in 1995 or before. The willow varieties released after 1995 are practically fully resistant to leaf rust (*Melampsora*), which is a common disease in willow plantations, and yield considerably more than old varieties. As an example, since 1995 the variety *Tora* has been very popular in Sweden and it yields 33% more than the reference variety (i.e. 78–183) in the first cutting cycle [10]. However, it is important to stress that the poor average results of the first cutting cycle hide the success of many growers who achieved high production levels by using good practices.

Willow for bioenergy is a fairly new cropping system when compared with the experience and development of most other agricultural crops. Our proposed model shows that a great number of plantations in Sweden have achieved high production levels, and we propose that management and good practices are determinant factors in the success of commercial plantations. 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 in the near future. In this respect, the importance of training programs for growers could be stressed, as well as mechanisms to encourage best practices in order to reduce the gap between actual and potential yield in commercial willow plantations.

Despite its limitations, this study is the first known by the authors concerning the yield of commercial willow plantations based on extensive data. It is a starting point for further research on the topic and for economic considerations.

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