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Trends and productivity improvements from commercial willow plantations in Sweden during the period 1986–2000

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ABSTRACT

The production trends of commercial willow plantations for bioenergy in Southern and Central Sweden were studied for the period 1986–2000 based on harvest records of the first cutting cycle after the establishment of 1512 plantations. The trends were modelled by using a mixed model in order to include the variability of management options by the growers, which were grouped into four classes according to their performance. The spatial variability of the productivity is included using an agro-climatic index based on the official estimates of oat yields. Results of the study show average yield increments of 2.06 odt ha^{-1} yr^{-1} per decade. Areas with high productivity have significantly increased the yields of willow during the period studied, from 1.3 to 5.4 odt ha^{-1} yr^{-1}. Regarding management, the best growers group shows a national average increment of 2.75 odt ha^{-1} yr^{-1} per decade, and the latest plantings reach an average of 6 odt ha^{-1} yr^{-1}. This group is formed by farmers with previous experience growing willow, who tend to have significantly higher yields. In addition, experienced farmers increased their yields an average of 0.34 odt ha^{-1} yr^{-1} regardless of the group they were classified in. It is expected that future improvements of the willow varieties will result in a significant increase in the mean yields in the near future.

1. Willow commercial plantations for bioenergy

Willow (*Salix*) plantations have been cultivated for bioenergy purposes in Sweden since the 1980s and since then have been regarded as an important crop for the production of wood fuel for the Swedish energy sector [1,2]. During the period 1986–2000, around 16000 ha of short rotation willow plantations have been established in Sweden, covering about 0.5% of the total arable land in the country [3]. These figures make Sweden the leader in commercial plantations of short rotation willow in Europe.

Since the 1970s, research on willow for bioenergy purposes has been given priority in Swedish energy policy [1]. Thanks to the Swedish experience, it is now one of the most developed crops for energy end use in Europe [4] and one of the few significantly planted commercial energy crops. During this development, numerous studies have revealed the high potential productivity of willow for bioenergy and shown the feasibility of average annual growth above 10 oven dry tonnes (odt) per hectare during the first cutting cycle, when optimal conditions of management are applied (a review of such studies can be found in Ceulemans *et al.* [5]). The studies on willow have also contributed to a better understanding of the establishment and tending of the commercial plantations. For example, during the 1990s the planting density has been gradually reduced, from 20000 cuttings per hectare in the beginning of the decade, to the 12000 cuttings per hectare in today's plantations. Additionally, since the 1990s the market for willow cuttings has been progressively dominated by bred varieties of willow, mainly crossings and hybrids of *Salix*

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viminalis, *S. dasyclados*, and *S. schwerinii*, which have been tested for productivity, pest resistance, frost hardiness, and shoot straightness [6].

Concerning productivity, there are clear overall increments in agriculture crops, through centuries of breeding and better management practices. During the last 40 years, cultivations of maize, wheat and rice have shown a general trend of yield growth, at an average rate of 62, 55 and 43 kg ha^{-1} yr^{-1}, respectively [7]. Although willow is a recent cultivation when compared to conventional agriculture crops, it is reasonable to expect that all the studies on plantation productivity and new breed varieties are having an impact on the yields of commercial willow plantations and experts in general agree that a significant improvement in biological productivity of willow is realistic as it has been in these other crops [8].

This study aims to analyse the production trends of short rotation willow plantations for bioenergy in Southern and Central Sweden for the period 1986–2000, based on harvest records of the first cutting cycle of 1512 commercial plantations. The models developed include 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 by exploring the variability of yield between growers in the same area and the production levels of the same grower over time.

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 administers the harvesting

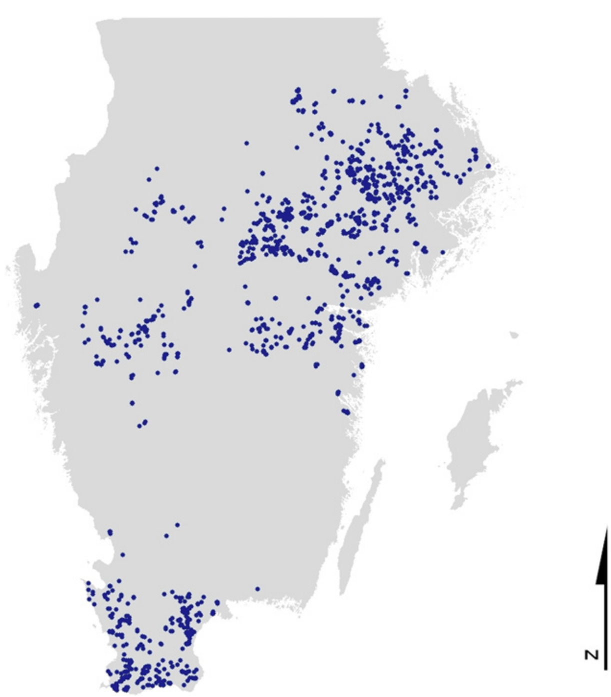

Fig. 1 – Commercial willow plantations in central and southern Sweden included in the models.

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
YIELD (odt ha^{-1} yr^{-1})	2.67	1512	1.90	20.54	0.03
RL (yrs)	5.73	1512	1.55	9.00	2.00
OAT_{sd}	4.15	1512	0.70	6.31	2.40
PLA (yr)	1994.5	1512	2.07	2000	1987

YIELD: average annual yield harvested from 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 (2005).

of willow plantations. The data were based on harvested biomass. 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 to 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 annual yield was calculated by dividing the first harvest record by the number of years since the cutback. This timeframe was defined as rotation length (RL). The original dataset was compiled from 1592 plantations during the period 1986–2000, to study the changes in the rotation length over time. For modeling the yield trends, records from plantations using rotation lengths longer than 9 years were excluded from the final calculations in order to avoid over-estimating the change in productivity from early plantations (in total, 80 records were excluded). The models were based on a total of 1512 plantations which cover 6779 ha, managed by 689 growers, during the period 1987–2000. All plantations studied had been cutback, in most cases after the first growing season.

Many growers managed different plantations planted across a wide range of times. Therefore, for each plantation, the number of years since the farmer's first plantation was calculated, in order to study the effect of earlier experience on the yields. The dates of planting were available for almost all Swedish commercial plantations.

2.2. *Statistical methods*

The predicted variable of the yield models was the mean annual growth per hectare, expressed as oven dry tonnes per

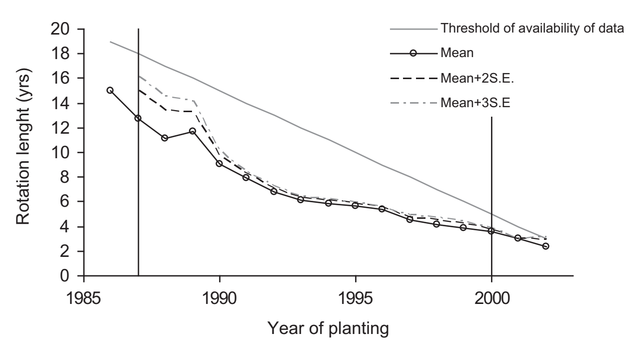

Fig. 2 – Averages and Standard Error of the rotation length of the first cutting cycle of commercial willow plantations in Sweden for 1986–2000 (the data is available till 2006).

Table 2 – Estimates, standard error (S.E.) and significance level of the parameters and variance components of the willow yield models.

Parameter	Estimate	S.E.	*p-value*	Estimate	S.E.	*p-value*	Estimate	S.E.	*p-value*
	Eq (1)			Eq (2)			Eq (3)		
β_0	1.058	(0.217)	0.000	0.874	(0.343)	0.011	2.213	(0.171)	0.000
β_1	0.049	(0.004)	0.000	0.865	(0.080)	0.000	0.075	(0.005)	0.000
β_2	−0.338	(0.116)	0.004				−0.204	(0.077)	0.008
GRO_I							−0.375	(0.027)	0.000
GRO_{II}							−0.298	(0.028)	0.000
GRO_{III}							−0.219	(0.028)	0.000
GRO_{IV}							−0.039	(0.027)	0.153
σ^2_{grower}	1.363	(0.135)	0.000	1.370	(0.139)	0.000			
σ^2_{pl}	1.844	(0.089)	0.000	1.890	(0.091)	0.000	1.563	(0.057)	0.000

S.E. Standard Error of the estimations are given in parenthesis.
p-value: Significance of the estimation of the parameter.

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 including fixed and random factors was used. The residual variation was divided into between-growers and between-plantations 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 oats yields (at 15% moisture content) made by the Swedish National Board of Agriculture [9]. The index was based on averages of district standard yields for 2003–2005 ($n = 47$). 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.

The yield of commercial Swedish willow plantations during 1986–2000 was modelled according to:

$$yield_{lkj} = \beta_0 + \beta_1 \times OAT_l \times PLA_{lkj} + \beta_2 \times EXP_{lkj} + \mu_{lk} + e_{lkj} \quad (1)$$

where *yield* is the mean annual growth of the plantations (odt ha^{-1} yr^{-1}), β_0- β_2 are parameters, OAT is the yield of oats by districts used as agro-climatic index (t 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 (no experience = 1). Subscripts *l*, *k*, and *j* refer to district, grower and plantation, respectively. $\mu_{lk,}$ is the between-grower random factor, independent and identically distributed with mean = 0 and constant variance (σ^2_{grower}). 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 $\sigma^2_{pl.}$

The growers were classified into four classes (defined as I, II, III, and IV) of equal numbers of farmers. This classification was based on the between-grower random factor of the Eq (2), which shows the differences of yield with respect to the district average, due to the grower effect.

$$yield_{lkj} = \beta_0 + \beta_1 \times OAT_l + \mu_{lk} + e_{lkj} \quad (2)$$

Class I was formed by the growers that achieved the lowest yields, and class IV by those who achieved the highest yields. The variation over time of each class of growers was included in the model of Eq (1), substituting the random between-grower factor by the resulting classes, included as a categorical predictor. The resulting model is as follows:

$$yield_{lkj} = \beta_0 + \beta_1 \times OAT_l \times PLA_{lkj} + GRO_c \times PLA_{lkj} + \beta_2 \times EXP_{lkj} + e_{lkj} \quad (3)$$

where GRO_c is a categorical parameter for each class of growers (I, II, III, IV) and β_0–β_2 are parameters.

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.

Table 3 – Classification of the farmers into 4 categories according to their assessment in growing willow.

GROWER Classes	N (Growers)	N (Plantations)	Mean μ_{grower}	Maximum μ_{grower}	Minimum μ_{grower}
I	172	473	−0.89	−0.59	−1.83
II	172	346	−0.37	−0.15	−0.58
III	173	332	0.10	0.41	−0.15
IV	172	361	1.15	5.40	0.41

$\mu_{k:}$ between-grower random factor according to the model of Eq (2), independent and identically distributed with mean = 0 and a constant variance σ^2_{grower}.

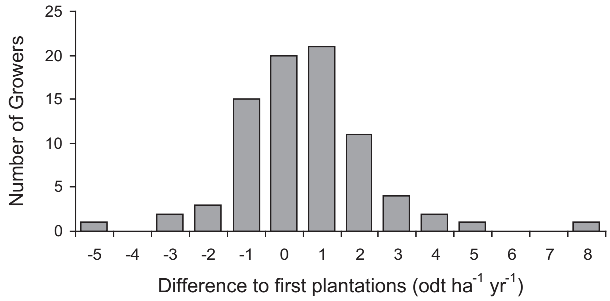

Fig. 3 – Results of grower experience (>1 year) and yield improvements of commercial willow plantations. For every grower, the average yields of later plantations were compared to the results of the first planted cultivations. N = 81; Mean: 0,55 odt ha^{-1} yr^{-1}; Standard Error:0,20.

Table 4 – Mean yield, area and percentage of plantations managed with at least 2 years of experience with willow by the grower for each one of the groups of farmers proposed. Figures in parenthesis refer to the standard errors of the means.

GROWER classes	Mean yield (odt ha^{-1} yr^{-1})	Mean area (ha grower^{-1})	Plantations managed with previous experience (%)
I	1.33 (0.04)	12.43 (1.22)	14.15 (2.43)
II	2.17 (0.05)	9.32 (0.95)	17.21 (2.61)
III	2.83 (0.06)	8.45 (0.61)	19.32 (2.74)
IV	4.76 (0.12)	9.17 (1.23)	31.08 (3.24)

3. Results

The resulting yield data from the harvest records included in the model is presented in Table 1. The total mean for the first cutting cycle was 2.67 odt ha^{-1} yr^{-1} for the period 1986–2000. The average rotation length was significantly shortened over the period studied (Fig. 2).

The parameter estimates of the yield model were significant (Table 2). The coefficients of determination (R^2) of the Eq (1) were 0.10 for the fixed part of the model, and 0.67 including the random part. In the case of the Eq (3), the coefficient of determination was 0.57.

A significant part of the variability was explained by the between-grower variation included in the random part of the models of Eq (1) and Eq (2). The resulting classes based on the between-grower random factor of Eq (2) are shown in Table 3. Growers of class I were managing more plantations than the other classes. The variability of this parameter was similar for classes II and III, and significantly higher in class IV, formed by the growers that performed highest yields.

In general, growers with at least 2 years of experience in growing willow achieved higher yields (Fig. 3), with an average of 0.34 odt ha^{-1} yr^{-1} increase over the rest of the growers. The classes of growers used in Eq (3) partially include this increment: the percentage of plantations managed with previous experience increases in the groups with higher yields (Table 4).

The bias of the fixed part of the yield model (Table 5) was examined by plotting the residuals as a function of the predicted variable and predictors of the model (Fig. 4). 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 of the model of Eq (1) is explained by the random grower and plantation factors. Fig. 5 shows the measured and predicted yields for the period studied.

The estimated willow yield at the first cutting cycle during 1986–2000 increased from 1.0 to 2.5 odt ha^{-1} yr^{-1} in the areas of low productivity (using the minimum yields of oats by district), and from 1.3 to 5.4 odt ha^{-1} yr^{-1} in the areas of high productivity (Fig. 6). The yields increased an annual average of 0.206 odt ha^{-1} yr^{-1} Fig. 7 shows predictions for each class of growers. Results of the best growers group (class IV) show an average increment of 2.75 odt ha^{-1} yr^{-1} per decade, and the latest plantings reach an average of 6 odt ha^{-1} yr^{-1}. In the areas of high productivity, the yields of the latest plantings for this group are around 8.37 odt ha^{-1} yr^{-1}.

4. Discussion

This study presents a yield model for biomass production from willow in southern and central Sweden, based on harvest records from 1512 plantations for the period 1986–2000. The data is based on final harvest records, which is a more realistic measure of productivity, since it only accounts for the biomass that is effectively harvested. Therefore, the estimations given already consider the biomass losses carried out during the harvesting operations. These losses can be around 5%–10% of the standing biomass by the time of the harvest [10]. The dataset available provides extensive information about commercial willow plantations, although it must 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 they are lacking information about the growth during individual years of the cutting cycle, and many factors related to the management

Table 5 – Absolute and relative bias and RMSEs, and coefficient of determination (R^2) of the yield models (Eq (1), Eq (3)).

	N	Bias (odt ha^{-1} yr^{-1})	% Bias	RMSE (odt ha^{-1} yr^{-1})	%RMSE	R^2
Eq (1)	1512	−0.104	−3.75%	1.81	65.1%	0.103
Eq (3)	1512	−0.000	−0.00%	1.25	46.8%	0.568

N: number of plantations.

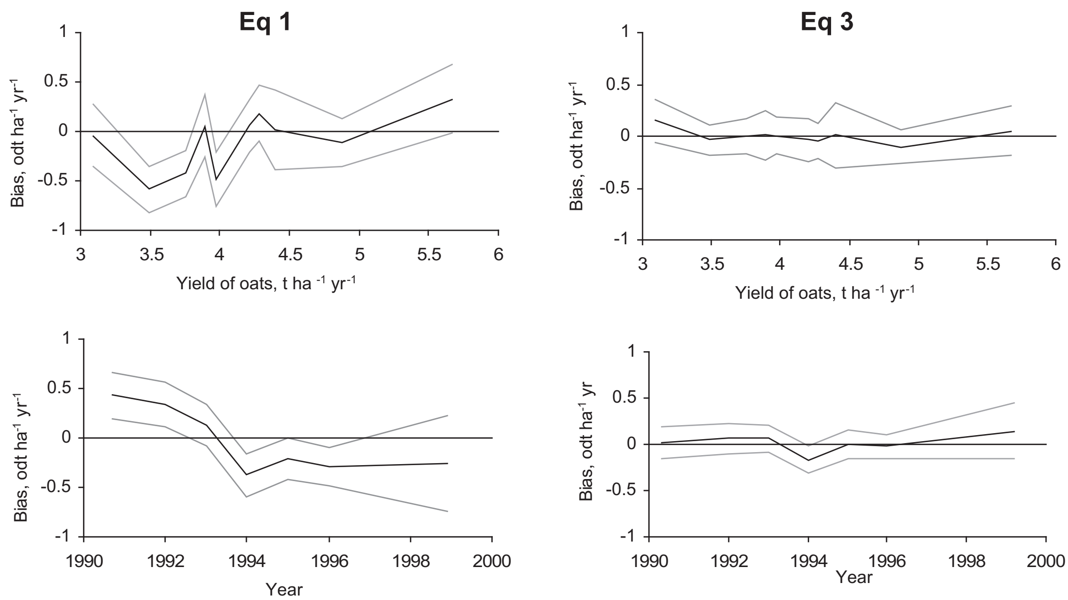

Fig. 4 – Mean residuals (bias) of the yield models as a function of yield of oats by agronomic district (divided in 10 tiles) and year of planting (grey lines indicate the standard error of the mean).

and care of the plantations are unknown. In addition, some human errors or missing values were detected and excluded from the calculations. However, these deficiencies are compensated for by the large amount of data available, covering almost 60% of the whole area planted with willow for bioenergy in Sweden during the period studied.

As with any other agricultural crop, willow shows different levels of productivity according to climate and soil conditions. In order to include this variation in the analysis, the yields of oats were used as indicators of agro-climatic conditions, assuming a linear relationship with the yield of willow for the range of data studied. Oats yields have proved to be a valid indicator of willow

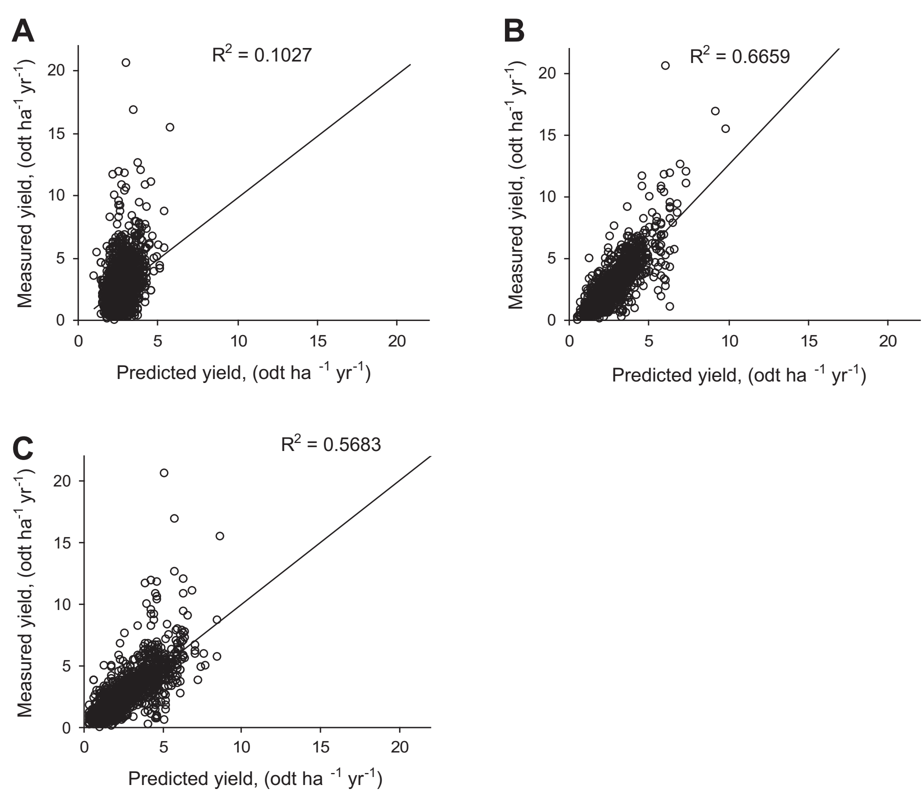

Fig. 5 – Measured and predicted average yield for willow plantations, according to the models proposed using the fixed part of the Eq (1) model (A), both fixed and random parameters of Eq (1) (B) and the model of the Eq (3) (C).

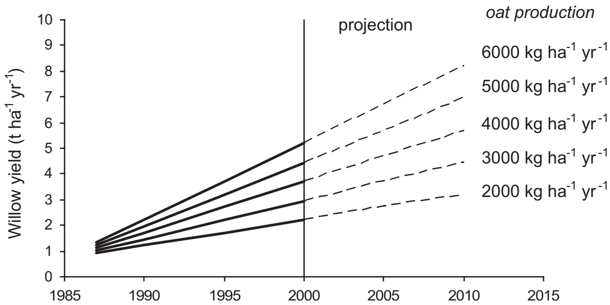

Fig. 6 – Mean annual harvestable yield of willow (odt ha^{-1} yr^{-1}) predicted by the model of the Eq (1), as a function of yield of oats. Predictors: EXP = 1; σ^2_{grower} = 1.148.

productivity; they are widely cultivated in Sweden and data regarding their yields are easily available. Ericsson and Nilsson [11] used wheat for estimating willow yields for different EU countries assuming the same linear relationship, which highly simplifies the modeling of willow yields; wheat was also used by Helby *et al.* [8] as a reference to calculate the farmer's opportunity costs for willow production in Sweden.

However, the natural site productivity of plantations may not be achieved because of limiting genetic and management factors [12]. In this respect, commercial willow plantations for bioenergy have a short history, and significant improvements both in genetics and in cultural treatments have been done during the last years. Early commercial plantations were dominated by old, non-bred willow varieties. The clones used were particularly affected by infections and frost damage [13]. However, the more recent plantings included new varieties which were more vigorous than the older clones and which resulted in shorter rotations (at intervals of 3–4 years [13]). For example, in the mid - 1990s the willow varieties *Jorr* and *Tora* were released, which have been very popular in Sweden. In both cases they yield more than the most widely used older variety (i.e. 78–183), with average increments of 21% for *Jorr* [14] and from 33% [6] to 59% [14] for *Tora*. In general, bred varieties also have greater resistance to pests and diseases. The willow varieties released after 1995, for example, are practically fully resistant to leaf rust (*Melampsora*), which is a common pest in willow plantations; this results in higher and more stable yields [3].

The success of plantations is not only dependent on improvements in plant material; management has also been proven to be a key factor in the success of plantations. In this respect, the genetic improvements of bred varieties during the last years can only show their full yield potential in plantations properly established and managed, and can only have a noticeable impact at the national level if a significant proportion of growers are willing to use them. As found in previous studies [15], the farmer's attitude is a factor that is difficult to measure but that has a significant impact on the final outcome of the plantation. The subsidies to plantations given during the period of 1991–1996 had an important effect on farmers' motivation to establish willow plantations. A specific subsidy of 1330 EUR ha^{-1} was available for willow growers, with an additional 530 EUR provided in some cases for fencing, covering almost all of the starting costs of new plantations [16]. Among other results, this support scheme led to planting large low productivity areas rather than smaller, high productivity areas [8]. The reduction of the subsidies in 1997 to one third of the previous amount meant that farmers had to put a significant amount of their own money into plantation establishment and maintenance, encouraging better management in order to increase the productivity and success of their own plantations [8].

Although this might explain part of the average increase in productivity in Sweden, the results of the study show that the productivity had already begun to rise before 1996, in parallel with a progressive reduction of the cutting cycle. In the models used, it is assumed that different management skills would partially explain the yield differences among growers in the same area. Management would explain the increase in yields on two levels: on a general level, the various studies carried out during the last years [17,18] have contributed to a better understanding of the proper practices and cultural treatments, with the spread of these practices improving the productivity of plantations; on the individual farmer level, the grower's attitude and experience in growing willow (*learning-by-doing*) has contributed to an improvement in yields. Experienced farmers account for a significant part of the group of high-yield growers, and the model shows an average increment of 0.34 odt ha^{-1} yr^{-1}, for all farmers.

The future evolution of yields is difficult to predict. In the early 90s, the genetic improvements of willow led to optimistic expectations for future developments of stocks yielding over 30 odt ha^{-1} yr^{-1} [19] and in general, energy scenarios have based their predictions and estimations for willow on a higher level of

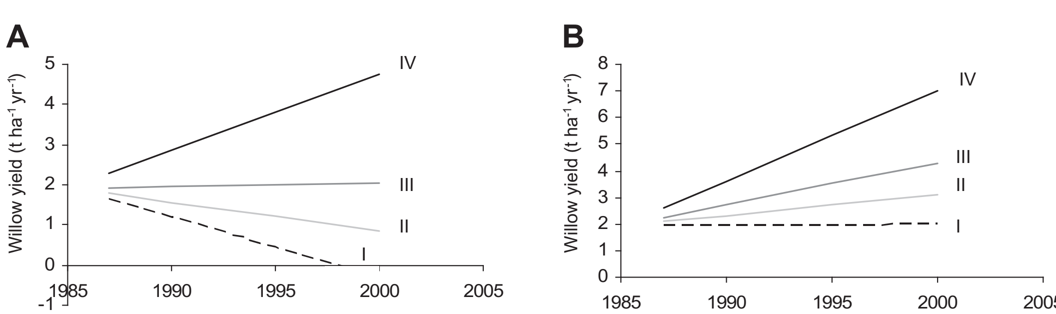

Fig. 7 – Modelled mean annual yield of a willow (odt ha^{-1} yr^{-1}) predicted by the model of the Eq (3) for the four groups of farmers. A) Average yield of oats 3000 kg ha^{-1} yr^{-1}; EXP = 0. B) Average yield of oats 5000 kg ha^{-1} yr^{-1}; EXP = 1.

biological productivity than that which can be effectively produced under present conditions [8]. According to the data analysed, these high yields do not seem to be possible in the near future in commercial plantations, although propagation of new and more productive varieties is accelerating. Within a few years most of the demand will be covered by new high-yielding and more resistant varieties [13], combined with a better knowledge of plantation management. Additionally, the establishment costs were reduced by 50% during the period 1990–1995, with new establishment and tending methods further decreasing costs [4,16], making the intensity of management necessary to achieve high productivity in an economically feasible way.

Although the results of this study must not be interpreted to suggest that future willow yields can be predicted by linear extrapolation, there are clear trends showing that production will increase during the next years. Several new varieties have been released in the market during the last years, especially after the year 2000 [14], and if the trends presented in this study continue, it is reasonable to expect averages close to 10 odt ha^{-1} yr^{-1} in recently established plantations with optimal management. However, future improvements of willow clones will rely on the development of a market for plant material that is of a critical size to stimulate investments and the introduction of new varieties into the market [8].

5. Conclusions

Willow for bioenergy is a fairly new cropping system, with lower levels of related experience and development than most other agricultural crops. The model developed in this study shows that the production of willow plantations in Sweden has increased during the last years at a good rate, starting with very poor results from plantations established in the mid-1980s but achieving significantly higher production levels in more recently established plantations. From this model, we can better understand the high variability of yields from plantations, resulting from changes in farmer attitudes and practices. Management, together with genetic improvements, are determining factors in the success of commercial plantations; it is expected that more experience among farmers, better advisory service, and improvements in varieties will result in a significant increase in mean yields during the next years. In this respect, the importance of breeding progammes 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.

Despite its limitations, this study is the first known to the author that analyzes the increase of productivity in commercial willow plantations based on extensive empirical data, and it is a starting point for further research on the topic and for informing economic and policy decisions.

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