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A conceptual framework for the introduction of energy crops

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ABSTRACT

There is currently limited experience on the introduction of new commercial crops as a source of raw material for energy uses. The present paper analyses the introduction and development of commercial willow plantations in Sweden during the period 1986–2005. A general framework is constructed in order to identify all the factors and interrelations that can describe the introduction and expansion of willow as an alternative crop for the production of raw material for energy. The factors are identified and analysed based on a broad database of information from commercial plantations, covering almost all existing plantations, and on documents referring to existing academic literature or official reports. The analysis provides with lessons that can be useful for the introduction of new energy crops in other countries and shows the possible contradictions in policy applications. The analysis confirms that stable policies and long-term contracts reduce the uncertainties associated with the cultivation. The results of this study can be of value for other countries aiming at the introduction of new crops for bioenergy.

1. Introduction

Biomass from short rotation plantations with woody crops is an important option for meeting renewable energy targets in the expected shift towards a more sustainable energy supply infrastructure. It has been speculated that a large amount of land for fast growing wood species will be needed in order to accomplish the goals targeted in the energy policy [1,2]. Estimates by the European Environmental Agency show that most of the potential biomass production in the European Union will rely on energy crops, which can account for more than half of the total biomass supply in 2030 [3].

The estimates of the importance of short rotation woody crops is based on its potential role in the reduction of the CO_2 emissions through the production of biomass for fossil substitution and CO_2 storage in vegetation and the soil (e.g. Ref. [4]). In addition, the advantages they present are wide: for example, efficient land use in combination with the increasing demand for renewable energy resources, potentially positive effects on rural economies as the result of the diversification of farm crops [5], and additional possibilities for environmental control and wastewater treatment [6,7].

Today, out of the different fast-growing woody crop species proposed for energy uses, willow (*Salix*) is one of the few planted commercially to a significant extent in the EU [8]. Willow cultivation presents several characteristics that favour its use for energy production: it is a high-yield species, providing large amounts of lignocelluloses in a short interval after establishment, it has a broad genetic base which allows potential for improved and adapted varieties, it is easy to breed and to expand through vegetative propagation, it has the ability of re-growth (coppice) after multiple harvests, and it requires low economic investments after its establishment [9]. Also, the energy efficiency of willow plantations has been estimated to be higher than alternative crops. For instance, the energy input needed in a willow production chain is about 4% of their energy output, whereas the equivalent value for a chain based on forest logging residues or straw is about 5%, and in the case of cereals or oil seed plants, is estimated to be 15%–20% [10]. In addition, among other fast growing species, willow has shown better energy profiles than e.g. poplar in terms of energy requirements, estimated about 11.3–17.4 MJ ha^{-1} yr^{-1}, compared to poplar 12.8–15.5 MJ ha^{-1} yr^{-1} [10].

In Northern Europe, the cultivation of willow provides additional advantages: good yield performance even in cold conditions,

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management practices that are already familiar to most farmers and winter harvests that reduce the impact on other agricultural operations and minimise soil compaction resulting from the use of heavy machinery, as the ground is invariably frozen during the harvesting period [11].

The plantations are mainly established on agriculture land, involving less intensive practices than most of the conventional agricultural crops. However, the use of short rotations translates into more intensive management practices than in conventional forestry. The plants are usually cut back after the first growing season in order to promote sprouting. Whole-shoot harvesting is usually conducted every three to five years [8,12]. The plantations are established between late April to early June, using one-year old cuttings, and the most widely used current design in Sweden is the double-row system, with distances between rows of 0.75 m and 1.5 m, which permits the use of machinery, and spacing between cuttings, within the rows, of 0.6 m.

Currently, Sweden is the leader in short rotation plantations for energy in Europe [13,14]. Since its introduction at a commercial level in the mid-1980s, Sweden has planted about 14–16,000 ha [8]. In this context, Sweden is a unique case in Europe for its experience regarding the introduction, at a commercial level, of a new energy crop on agricultural land, both concerning years of research and area planted. The performance and expansion of the Swedish willow plantations is, therefore, an invaluable precedent and source of information for analysis, and dissemination to other suitable countries. The present paper analyses the introduction and development of commercial willow plantations in Sweden since the first commercial plantations were established. In order to achieve this, different aspects are examined, e.g.: the yield performance of the plantations, the changes and trends of productivity, the role of the policy framework and the different actors involved in the development of the sector. Finally, the paper aims at drawing concepts and lessons in a conceptual framework that can be useful for the introduction of new energy crops in other areas.

2. Material and methods

A general framework was constructed to conceptualise and analyse the introduction of willow cultivation in Sweden, based on data analyses as well as on a review of existing literature. The framework aims to identify all the factors and interrelations that can describe the introduction and expansion of willow as an alternative crop for the production of raw material for energy. The identification of the factors and the interrelations were based on a broad database of information from commercial plantations (Table 1). Concerning the details affecting the cultivation and the policy framework, the data was based on documents referring to existing academic literature or official reports. Regarding the analysis of quantitative data (e.g. the specific location of the plantations, yields and performance, number of growers) the data was based on a series of datasets, the most important one provided by Lantmännen Agroenergi AB (formerly known as Agrobränsle AB), which manages planting and administrates the harvesting of commercial willow plantations. The data included, among others, the location of the plantations, the harvest records from the first, second and third cutting cycles, as well as data concerning the ownership of the plantations, the area planted, and the establishment and harvesting dates, during the period 1986–2005. Some human errors were detected resulting in inconsistent records, and were excluded. In other cases, some information regarding the ownership, harvesting dates, total area planted or the location of the plantation, was missing, resulting in their exclusion from the calculations according to the needs of the studies where they were used.

All plantations were geo-referenced to a 1 km precision, covering the area from 55° 20' N to 61° 29' N and from 11° 33' E to 18° 56' E. The biomass production of the willow plantations was calculated by dividing the total harvested biomass of the cutting cycle by the planted area. The yield (mean annual growth) was calculated by dividing the biomass production by the rotation length of the cutting cycle (the number of years since the previous harvest or cut back). The number of growers across time was also derived from the datasets, as well as their experience in growing willow (see Ref. [20]).

Additional datasets were also collected to analyse other factors identified in the analysis. The consumption of wood chips by district heating and power systems during the period studied was based on records by Svensk Fjärrvärme AB. The release of willow varieties to the market was based on [18]. The land uses were based on the Corine land uses map 250 m [17].

Table 1
Sources of the main datasets used in the analysis.

Data	Source
Size, yield, location of plantations	Agrobränsle AB (1986–2005)
Ownership of the plantations	Agrobränsle AB (1986–2005)
Consumption of wood chips and location of district heating systems	Svensk Fjärrvärme AB
Location and establishment of district heating systems	[15,16]
Land uses	Corine land uses map [17]
Yield and release of commercial varieties	[18]
Economics and cost reductions	[19]

3. Results

3.1. Conceptual framework for the introduction of a new crop

The resulting framework (Fig. 1) assumed that the area planted with the crop is a result of the adoption of the crop by the local farmers, subject to different incentives. One clear incentive is the profitability of the cultivation, being a result of the cost and the revenues, including incentives. Those are defined by the productivity, which is a result of a combination of local climatic and soil factors and restrictions, management practices, and by the effects of the economies of scale, as well as by the demand for the resulting chips. The resulting level of productivity affects the profitability of the plantations and the willingness of local farmers to plant willow, and thus to expand the initial area planted. In addition, the existence of a local demand and market for willow chips, the local perception of the cultivation and the costs of management significantly affect the adoption and therefore the expansion of the cultivation. This amount of planted area with willow will determine the development of an economy of scale, which will reduce costs, release higher yielding varieties, and contribute to a better understanding of willow management, which will in turn result in higher yields.

The role of the policies implemented to develop the sector directly affect adoption, e.g. through subsidies. In addition, policy affects the market, e.g. through taxation of alternative energy sources, subsidies on wood-fuelled district heating plants, promoting a framework for long-term contracts between the farmers and the wood-fuel consumers. Finally, the policies also affect the yield performance, e.g. through investments on research of new plant varieties and better management practices.

3.2. Changes in the policy framework

The introduction of willow cultivation in Sweden was stimulated by the government through the implementation of different

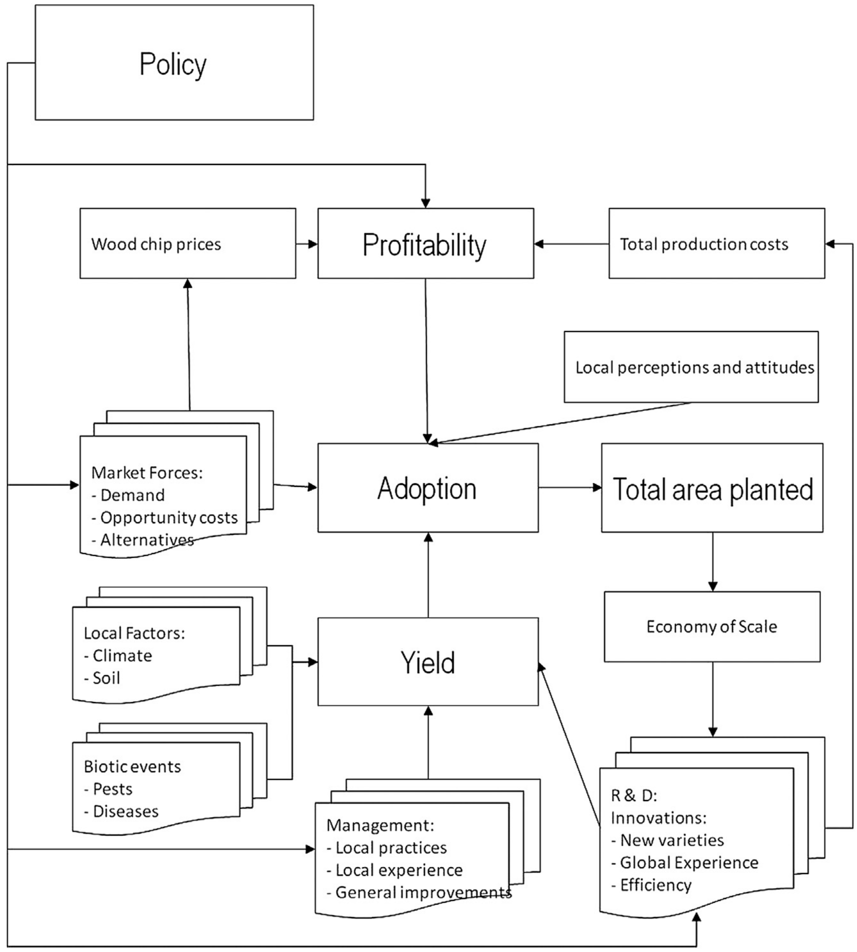

Fig. 1. Factors affecting the development of energy plantations in Sweden, as a result of interactions between the policy framework, the yield levels and adoption and spread of the cultivation by farmers.

measures and policy incentives. According to the application and effects of these measures, the spread and expansion of commercial willow cultivation can be divided into three periods: start-up period (1986–1991), expansion period (1991–1996), and stagnation period (1996–2006).

The start-up period, or early adopters, started in the late 1980s. The first commercial plantations were established in 1986, and the number of farmers establishing willow plantations grew slowly until 1990, especially in central Sweden (Fig. 2).

In 1991 there was an important change in the agricultural policy in Sweden, with a set of incentives being introduced in order to promote the establishment of willow plantations, which lead to a significant expansion of the cultivated area. During the period 1991–1996, a specific subsidy to establish willow plantations of 10,000 SEK ha^{-1} was available (at 1991 exchange rates, approximately 10 SEK = 1.33 EUR). In addition, further subsidies for fencing were also available in some cases [21]. Parallel to these measures, taxes on sulphur and CO_2 for fossil fuels for heat production were introduced, and were progressively increased in subsequent years: 0.25 SEK/kg CO_2 in 1991, 0.32 SEK/kg CO_2 in 1993, and 0.36 SEK/kg CO_2 in 1996 [22,23]. Since biofuels were exempted from these taxes, they became more competitive versus fossil fuels. As a result of these changes, the planted area with willow increased almost exponentially during this period in parallel with an increased demand for wood by district heat and power plants (Fig. 3).

However, 1996 signalled a turning point in the willow expansion. In that year, the planting subsidy was initially reduced to a third of its previous amount (Fig. 3), and the number of new plantations dropped significantly. This was in part as a result of the inclusion of Sweden in the EU and the implementations of the regulations of the Common Agriculture Policy (CAP), which stated, among other regulations regarding set-aside land, that the maximum level of the subsidy could not exceed 50% of the planting cost [22], which triggered a reduction in the subsidies. The subsidy for the establishment of willow plantations was raised again in 1999 to 5,000 SEK ha^{-1} (slightly over 50% of the pre-1996 value), and new willow plantations were again established. During this period, the taxes on CO_2 increased again to 0.52 SEK/kg CO_2 in 2001, while energy taxes were reduced [22]. Despite these conditions, the total area planted in Sweden was more or less constant around 14,000 ha, due to the fact that many plantations that were poorly established in the 1990s were removed at the same rate as for the establishment of new plantations.

3.3. Expansion and location of willow plantations

The willow plantations in the start-up period (1986–1991) were concentrated mainly around the area of Örebro, in central Sweden, and a less prominent concentration of plantations was identified in the northernmost area of distribution of willow plantations. Plantations established in the expansion period (1991–1996), were

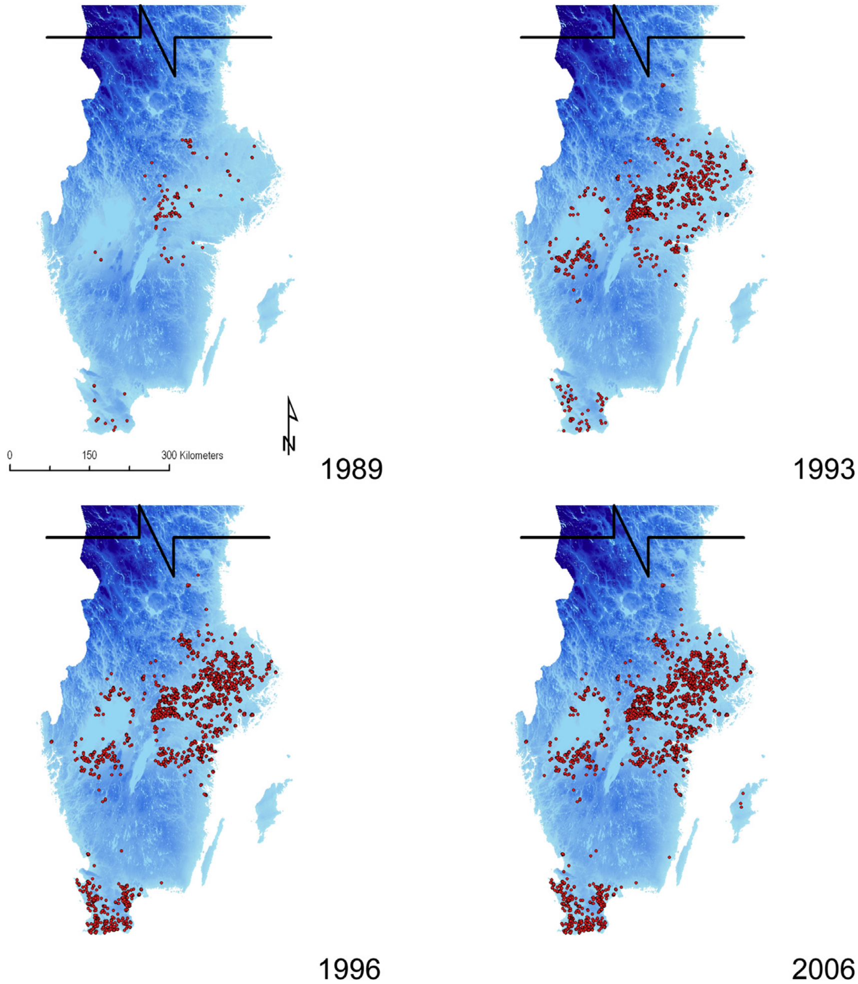

Fig. 2. Development of commercial willow plantations for bioenergy established in Sweden during 1986–2006.

concentrated around the areas of Örebro, Enköping and Kristianstad, in central, east-central and southern parts of the country, respectively (Fig. 2). In these cases, the area planted with willow increased parallel to the establishment of a demand for wood chips by the district heat and power plants (Fig. 4). In the case of Örebro, the plant was already using wood chips for energy since the 1980s, and the progression of the area planted was steady. In the case of Enköping and Kristianstad, the area planted with willow showed important increments after the adaptation by the plants to use wood chips as raw material. In the 1990s, in these three cases, the level of concentration (density of plantations) was increasing with the geographical proximity to the plants [24].

Finally, the willow expansion in southern Sweden took place later than in central Sweden, parallel to changes in wood fuel consumption of the district heat and power plants that were constructed or converted to use wood biomass during the mid-1990s. This distribution was similar during the final period studied (1997–2005). In these cases, the concentration of plantations was also increasing with the proximity, and moderate concentrations around the heat and power plants of the municipalities of Eskilstuna and Sala were identified. The shares of plantations established during the three periods were 13%, 70%, 17% of the total number [24].

3.4. Yield improvements

The initial yields of the first plantations were significantly lower than expectations, with averages close to 2 odt ha^{-1} yr^{-1} during the initial period in the first cutting cycle (Fig. 5, Fig. 6). There were, however, constant improvements in the average yields with time, and several new varieties were released to the market, resulting in yield increases of over 100%. In addition, there was evidence of higher yields during the second and third cutting cycles as the annual average yield for that period was 2.63, 4.19 and 4.47 odt ha^{-1} yr^{-1} for the first to third cutting cycles, respectively [8]. 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, and from 1.3 to 5.4 odt ha^{-1} yr^{-1}, in the areas of high productivity in the southern part of Sweden [20]. In general, yields increased an annual average of 0.206 odt ha^{-1} yr^{-1}.

In addition to overall increases in productivity, an effect due to the growers' increasing experience with the cultivation was noticed. In general, growers with at least 2 years experience in growing willow achieved higher yields, with an average of 0.34 odt ha^{-1} yr^{-1} increase over inexperienced growers [20].

3.5. Changes in the cultivation practices

During the two decades studied there were changes in the management of the plantations. For instance, while the average length of the cutting cycles for the whole period were 6.0, 4.5 and 4.2 years for the first, second and third cutting cycles, respectively [8], there was a reduction of the length with time [20], with initial rotations for the cutting cycle of around 8 years in the early 1990s, and an average of 5.38 years in 2000s.

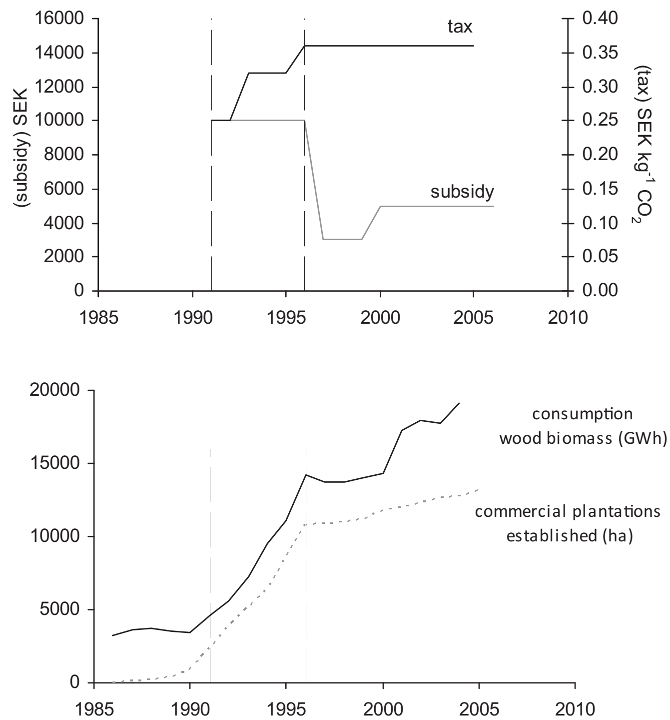

Fig. 3. Changes in the support schemes in the studied period (up) and changes in the consumption of wood biomass compared to the establishment of commercial willow plantations.

The planting densities were also reduced over time, starting from 20,000 at the beginning of the 1990s, to approximately 13,000 cuttings per hectare of the most recent plantations [14]. Additionally, the fertilisation recommendations were changed: for a standard cutting cycle, the recommendations (in kg N ha^{-1}) in 1996 were 60, 100 and 60 for the first, second and third year after harvest [15] respectively. In 2007, the respective recommendations were 100–150, 100 and 0 [25]. It was, however, estimated that only about 25% of the plantations follow the fertilisation recommendations [18], resulting in much lower yields [26].

Finally, these changes and the development of the sector resulted in important cost reductions. For instance, the planting costs by the end of the start-up period in 1992 were about 65% lower than in 1988 [27]. Rosenqvist et al. [19] estimated that the total cost of willow production is reduced by 10% when the scale effects of expanded willow area are considered, and by 35% when also the learning effects of the farmers are included. In 2009, the gross margin of willow plantations excluding subsidies was estimated to be positive above 9 odt ha^{-1} yr^{-1} [28] corresponding to a total production cost of about 5 EUR GJ^{-1}. However, it was also estimated that alternative cultivation practices, e.g. applying sewage sludge, would reduce the profitability threshold to 8 odt ha^{-1} yr^{-1} [28].

4. Discussion

4.1. Market forces and policies

The framework presented in this study reflects the complexities of the introduction of a new cultivation for energy purposes and helps at the same time the understanding of the different mechanisms and stakeholders involved, as well as the inter-connected effects of their actions. Introducing a new energy crop is a complex task, with many factors determining its success or failure. It is clear that if a new crop is to be adopted by local farmers, the decisive factor will be the profitability of the crop.

Compared to other promising energy crops (e.g. miscanthus, reed canary grass and triticale), willow shows the lowest production costs [29]. Concerning alternatives for the farmer such as grain production, a study in Northern Ireland showed similar gross margins, assuming average yields in both cases [27]. In Poland, the profitability was estimated to be similar to barley and lower than wheat at current wood chip prices [30], although the gross margins were higher than alternative energy crops like miscanthus and triticale [31]. Comparisons with cereals, however, must be cautious as their price has been during the 2000s highly volatile, providing large uncertainity in economic evaluations [29].

Among the factors that could affect profitability, the planting subsidies during the period 1991 to 1996 had an important effect on the farmers' motivation to plant willow [32]. However, there are other variables that must be also analysed. For instance, during the period studied, the obtained experience to optimize management practices, as well as the development of a market for improvements, resulted in lower plantation costs compared to the pioneer growers. In fact, the new establishment methods developed during recent years seem to decrease the costs even further [19]. The lower establishment costs were mainly due to large-scale rationalisation, and a similar reduction can be expected in other countries when significant areas are planted [33].

For instance, the cultivation costs were estimated to be 4–5 EUR GJ^{-1} in the 2000s, and to be reduced to 3–4 EUR GJ^{-1} by 2020 [29]. In fact, when the estimates include large scale utilization and yield increases, the costs of willow plantations can be 40–50% the costs alternatives in almost all Europe [29] However, in general the prospects of cost reduction for perennial crops such willow are estimated to be substantially larger than conventional annual crops [19], and it must be taken into account, that the production costs per unit of energy are already much lower than those of annual crops [11]. As shown by the Swedish experience, the paradox is that the cost reductions due to economies of scale are subject to the development of the sector itself, and some authors have shown the difficulties and needs of policy incentives during the early stages of development, before a critical mass is reached and the sector develops its own momentum (e.g. Ref. [34]).

These policy incentives can be implemented through different actions. For instance, one approach is introducing an establishment subsidy for willow plantations, as they correspond to a significant part of the total investment during the lifespan of the plantations. Since the first cutting cycle means lower yields and incomes, an establishment subsidy can help to reduce the initial investments, reducing the risks taken by the farmer [22], and making the option of planting willow more appealing. The use of establishment subsidies was one of the options taken in Sweden, and it clearly helped the promotion of willow after its introduction in 1991 [32]; in fact, the subsequent reduction of the subsidy in 1996 had drastic effects in the sector.

However, the results also reveal the fundamental role of woodfuel demand as a driving force to spread willow cultivation. In this respect, no policies other than taxation on fossil fuels were specifically implemented in order to ensure a demand for energy crops in Sweden [11]. In general, the demand for willow chips was left to market forces. Nevertheless, during the 1990s oil and electricity prices were quite low, impacting on demand for willow chips, and as for many other biomass sources, the willow plantations were not competitive against fossil fuels [11]. This was despite the fact that biomass prices were declining in real terms over most of the decade [22]. In addition, the use of fixed establishment subsidies (i.e. not linked to plantation's productivity) as a main tool to promote willow cultivation affected the motivation and commitment of the

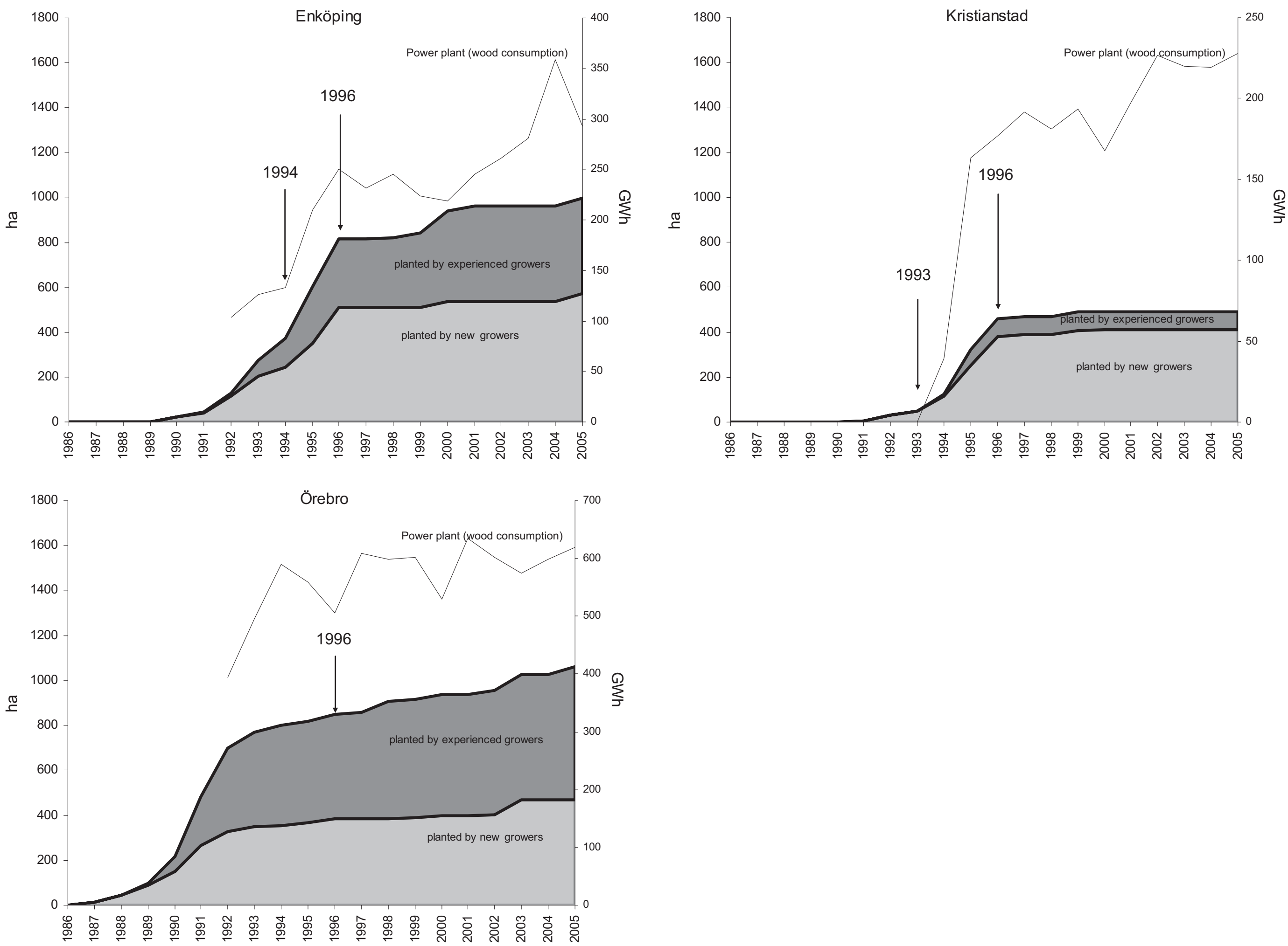

Fig. 4. Areas planted with willow in the municipalities of Örebro, Enköping and Kistrianstad, compared to the consumption of wood chips in the local district heating and power plants.

farmers, did not contribute to farmers' incentive to produce biomass, and did not necessarily promoted proper management practices. Subsidies were a very important tool for rapidly increasing the areas, but it many cases it led to plantations with low productivity, established in remote fields, far from the end users.

One proposed measure that can also promote the expansion of willow is the establishment of long-term contracts between district-heating companies and farmers, with the state as facilitator and sponsor [11]. This would contribute to the reduction of risks taken by the farmer and therefore would promote adoption. This has been one of the characteristics of the model followed in Enköping, central Sweden, based on agreements between the main actors involved in the biomass supply and demand [35,36]. The mutual agreements include the obligation of the district power plant to buy the harvested willow at the current market price, with the farmer being expected to sell their willow chips to the plant. In addition, the plant is encouraged to recycle the wood ash back to the plantation, and there are some other rather informal agreements between the power plant and the sewage plant operators [37].

Another approach could include a long-term stable EU agricultural policy, which promotes cultivation systems with environmental benefits. This could be a very important factor for encouraging the expansion of perennial energy crop cultivation. In general, the use of wood for heating can be considered a prerequisite for the expansion of energy plantations, as it develops the infrastructure and network for the process and distribution of wood fuels to the district heating plants [22]. This also implies additional pressure on the wood stocks that can provide impetus for the search of new raw material sources [38] including willow plantations. Therefore, the establishment of large areas of plantations in countries such as Denmark and Finland can theoretically be easily implemented, since the wood-fuelled district heat and power plants already play a very important role, as it covers around 60% and 50% of the market share, respectively [39], the proximity to Sweden can facilitate the inter-change of technology and experience, and the expected productivity would be high in broad areas [40].

4.2. Crop productivity as a key factor

High yielding crops at a lower cost than conventional alternatives directly affect the final profitability, and thus the expansion of the crop. The Swedish experience shows that the initial yields of the plantations were significantly lower than earlier predictions (mostly based in process models and simulations, or resulting from pilot trials and laboratory tests). For instance, in the 1980s, predictions of yields above 10 odt ha^{-1} yr^{-1} were expected on several

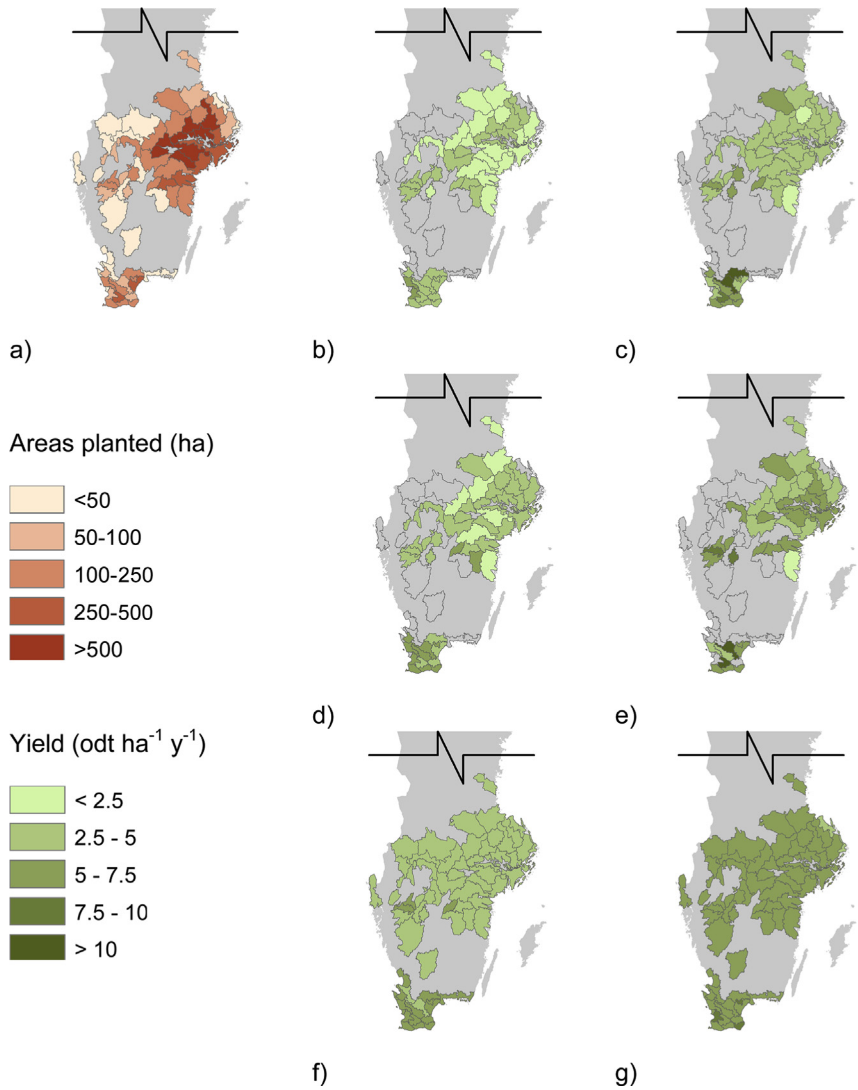

Fig. 5. Yield and location of the plantations by agronomic districts. a) Area planted with willow. b) Average for the 1st cutting cycle (districts over 50 ha planted). c) Average for the 2nd cutting cycle (districts over 50 ha planted). d) Upper 25% for the 1st cutting cycle. e) Upper 25% for the 2nd cutting cycle. f) Modelled averages for the period 1986–2005, 5 cutting cycles (21 years). g) Modelled upper 25% for the period 1986–2005, 5 cutting cycles (21 years).

studies in Sweden based on process models [41,42] or showed production potentials ranging from 8 to 9 odt ha^{-1} yr^{-1} in the north-east of Sweden, to 16 to 17 odt ha^{-1} yr^{-1} along the west coast [43]. Ericsson and Nilsson [44] presented average projected yields from 9 to 12 odt ha^{-1} yr^{-1} for the whole country.

One of the main limitations of these estimations was the difficulty to predict the many and various factors that can affect productivity, other than general site conditions and climate. The overall experience from the Swedish case reveals a wide spatial variation [45] and determines the influence that management has on the performance and success of the plantations [8,20]. The selection of the site and clone, sufficient weed control, proper fertilisation and water availability are variables difficult to model, but these must be considered in the estimations of productivity in order to have reliable data. The support schemes introduced in 1991 led to the planting of large low-productive areas rather than smaller high productivity areas, among other effects [11,14]. The reduction of the subsidies in 1997 implied that farmers had to invest a significant amount of their own capital, and thus would encourage better management, in order to increase the productivity and success of their own plantations [11].

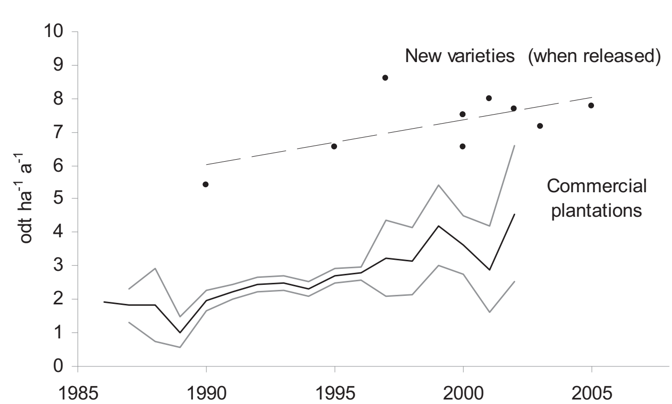

Fig. 6. Average yields of commercial willow plantations in Sweden, during the period 1986–2005. Grey lines represent the Standard Error (x2). Dots represent trial yields of commercial varieties the year of their release.

Initial yield predictions have therefore to be cautious and realistic in order to avoid future overestimations. However, it must be also taken into account that short rotation willow is a fairly new cropping system (compared with most other agricultural crops). The Swedish experience also shows that the yield can be increased at a good rate, starting with very poor results from early plantations, but achieving significantly higher production levels in recently established plantations. In the period 1995–2005 several new willow varieties have been released in the Swedish market, in parallel with the establishment of new plantations. 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 [46]. More recent plantings included new varieties more vigorous than the older clones, which resulted in shorter rotations, greater resistance to frost, pests and diseases, and higher productivity. These new varieties have increased the relative yields on trials by 60% compared to the levels reached in the early 1990s [18].

In this sense, 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. For most of the tree species, typical gains for first and second generation breeding programmes are around 10–20% and 20–30%, respectively [47]. Also, improvements on planning and management of plantations would explain the yield increases on two levels: on a general level, the various studies carried out during that time (e.g. Refs. [48,49]) would contribute to a better understanding of the appropriate practices and cultivation treatments, and the spread of these practices would improve the productivity of the plantations; on the individual farmer level, the grower's attitude and experience in growing willow (*learning-by-doing*) contributes to yield improvement [20].

The genetic improvements of breed varieties during recent years would only show their full potential in properly established and managed plantations, whose owner is willing to adopt them. Therefore management, together with genetic improvements, are decisive factors in the success of commercial plantations. It is expected that more experience among farmers, better advisory service as well as improvements of the varieties will result in a significant increase of the mean yields during the next few years. Hence, the importance of breeding programmes together with training for growers is stressed, as well as mechanisms to encourage best practices in order to reduce the gap between actual and potential yield in commercial willow plantations.

4.3. Future trends and recommendations

Sirén [50] listed as pre-requisites for the successful development of short rotation cultivation schemes the spread of know-how based on research, skilled growers, existence of an infrastructure and favourable policies. The overall analysis of the Swedish experience largely confirms these conditions as being fundamental for the expansion and development of the sector. Concerning the policy framework, the role of the CAP will play a key role in the development of energy crops, as it has a major impact on farm-level economics [29]. Some latest developments have increased the appeal of energy crops e.g. the new subsidy schemes in 2000 and 2003 [29]. On the other hand, sudden changes e.g. in the set-aside schemes in recent years due to the volatility of the cereal prices [29] suppose a risk for the farmer that has to plan the cultivation for a period of about 20 years. It is therefore difficult to foresee new CAP regulations and their direct influence in the establishment of new plantations, but it must be taken into account as an additional risk factor.

Concerning present yields and trends, future analysis must take into account more detailed variables regarding the actual management and clones used. In Sweden, the European Environment Agency [51] estimates about 212,300 ha available for energy crops (about 8% of the total arable land [52]). Current plantation schemes, such as the case of Poland, where c 170,000 ha are expected to be planted with energy crops [53], or in UK, planning c 350,000 ha by 2020 [54], must consider the needs for developing realistic models at a regional or local scale, also considering the regional trends in wood demand and supply, the role of the local district heat and power plants, and alternative uses as raw material, e.g. pellets [55].

In addition, positive externalities provided by willow plantations must be taken into account in the future development of the areas planted. There are many positive effects derived from willow cultivation, as the plantations can be also used as vegetation filters to treat and utilise municipal and industrial wastewaters, municipal sludge and landfill leachate [7,56,57], or for phytoremediation of soils [58].

Furthermore, willow cultivation has positive effects on water [59] and soil quality [60] when compared to traditional agricultural crops, can be used as shelter belts in order to prevent soil erosion [61], and provides space for fauna diversity and hunting opportunities increasing biodiversity when planted in open spaces [62]. In general, the Swedish plantations are energetically efficient and present mostly positive effects from an environmental point of view [63], especially when compared to conventional farm crops [64]. However, technological advances are required in order to enhance the overall performance of these bioenergy systems, mainly in terms of bioethanol production [63,65].

In this sense, Börjesson [61] estimated that up to 19 TWh could be produced in Sweden from perennial crops at 50% lower costs when all the multi-functional potential of the cultivations are fully utilised. Economic estimations have already showed the higher profitability of the crop when, for instance, sewage sludge and wastewater fertilisation is used [28]. However, future research should focus on developing economic systems where willow cultivation can take full advantage of these externalities in a way that make its expansion more appealing to the farmers. In this sense, efforts must be placed into a more coordinated mapping of the potential crop area for willow plantations prior to the establishment of the first fields, based on the existing models developed with the commercial experience in Sweden (e.g. GIS mapping, feasibility analysis, market studies, as well as locations with more promising additional environmental services).

Although there is currently already a high level of understanding of the management requirements of willow cultivation, and the crop is to a large extent technically developed, farmers' perceptions can be a major barrier to wider expansion that must be considered and analysed [66]. This requires a deeper understanding of the motivations and attitudes of farmers towards adaptation (e.g. Refs. [14,21]), including marketing and sociological studies at regional and national levels.

As many previous studies have concluded, there are no significant climatic, technical or environmental constraints for the rapid development of energy crops in Northern Europe, but the main barriers for large plantation schemes are socio-political, including agricultural and energy policies, market developments and public perceptions and attitudes [67,68]. The Swedish development during the last years provides an invaluable experience to make this expansion a reality, and shows the possible contradictions of policy implementation. One of the main conclusions is that stable policies and long-term contracts between the different actors can reduce the uncertainties associated with the cultivation [69]. In this respect, the development of new financial models, oriented to reduce the risks taken by the farmers and to encourage the adoption of short rotation plantations with woody crops, require further exploration.

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