Chapter 19

Development of Sustainable Willow Short Rotation Forestry in Northern Europe

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Additional information is available at the end of the chapter

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1. Introduction

Modern willow short rotation forestry is based on traditional woodland management which uses the ability of certain tree species to grow new shoots from the stump after being cut down. Depending on site fertility, growing season length, initial planting density and species, willows may be coppiced from once a year to every fifth year, and the stands may remain productive over several decades. Traditionally, small-scale willow plantations have been used for fuel, fodder, convenience wood, basked making, bee keeping, and for horticultural purposes. Willows also may be used for erosion control, including wind and water erosion, and to avoid snow drift along roads. While the traditional use of willow is declining rapidly in Europe, the use of willow as an alternative crop for farmers has led to an increasing interest in willow breeding and cultivation [1]. A renewed research effort on short rotation willow coppice plantations in Sweden commenced in the late 1960's due to a predicted shortage of raw materials for the pulp and paper industries, which turned out to be a false alarm. However, the 1970's energy crisis constituted a new driver to continue research on willows as a source of biomass for energy purposes. Additional drivers, such as employment issues in the Swedish country side, and environmental concerns also influenced research funding rates and directions towards willow short rotation coppice. In the late 1980's willow growing for energy was implemented at a larger scale and commercialized in Sweden. A tax on carbon dioxide emissions for the combustion of fossil fuel in heat production was introduced by the Swedish government during the 1990's and created more favorable market conditions for investment in and implementation of biofuel systems [2]. In 1996, Sweden joined the European Union, which employed an agricultural policy in which subsidy levels to farmers constantly were altered and adapted to short term market situations. As willow growing is a long term commitment which requires longer term investments, this EU-policy promoted the use of annual crops, and the exponential increase of areas under willow cultivation leveled out after 1996 and even started to decline.

In the meantime, the Swedish concept of large-scale willow cultivation for bioenergy purposes was exported to several EU-countries, notably to the UK and Poland, and a development of similar growing systems also was pursued overseas, in New Zealand and in the USA [3].

It was recognized early that willow growth concurs with potentially high evapotranspiration rates [4] and high nitrogen retention rates [5]. Willow species also may exhibit selective uptake of heavy metals [6], which underlies the potential to use willow as a phytoextractor for e.g. Cd from polluted soils [7]. These special traits of willow have allowed a further development of short-rotation willow coppice systems for environmental purposes [8]. Willow growing systems may be used as vegetation filters for purification of waste water [9], for cleaning of polluted drainage water from agricultural land [10] and as a recipient of nutrients from municipal sludge [11]. As willow stands are harvested at regular intervals, the pollutants are removed from the soil-plant system, while added nutrients and water enhance the systems' biomass production. These systems then function as multi-purpose systems, simultaneously aiming at biomass production for energy purposes and provision of environmental services, while producing clean water and neutralizing potentially hazardous compounds. Several efforts have been made to assess the economic gains of such multi-purpose systems [e.g. 12, 13], and Volk et al. [3] concluded that the economic valuation of the environmental benefits is necessary for a further deployment of woody crops.

In the following sections, a brief overview will be given of the plant material and growing system used in willow short- rotation forestry (SRF) and of the history of willow research, with a focus on the developments in Sweden. We then continue with a description of the development and implementation of willow SRF in commercial practice, and with the current guidelines for commercial willow growing. We also present an update of recent research, performed to improve the productivity and sustainability of willow short rotation forestry as an agricultural crop for bioenergy purposes, and include some results of ongoing research projects.

2. Species characteristics and natural distribution of willows

The genus *Salix* comprises about 350 to 500 different species worldwide [14] and is taxonomically complex and difficult to arrange in distinct sub-groups, probably due to intersectional and intersubgeneric polyploidy [15]. About 10% of the willow species consist of deciduous tree species, some of which may attain a height of > 20 meter. However, the vast majority consists of multiple stemmed trees and shrubs, and also a number of very short procumbent species can be found, not exceeding the height of the herb-layer in which they reside. Willow mainly is a boreal-arctic genus, with its natural distribution primarily in the northern hemisphere. Most willow species are found in China and in the former Soviet Union, and some indigenous species are present in India and Japan. The genus also occurs naturally in the southern hemisphere in Africa and in Central- and South America [14], and has been introduced in Australasia and New Zealand. Many species have been transferred beyond their natural range. The short rotation coppice systems currently in use in Sweden are mainly based on *Salix viminalis*, which was introduced in the 1700's from continental Europe for the purpose of basket making, and on their hybrids with *S. burjatica* and *S. schwerinii*, recently introduced from Siberia.

Early records of willow cultivation date from 2000 years ago in the Roman Empire and in modern times willow breeding and selection programs have been recorded from Sweden, the UK, Belgium, France, Croatia, Poland, Hungary, former Yugoslavia, Romania, Bulgaria and China, but also outside Eurasia in New Zealand, Argentina, Chile, Canada and in the USA. The development of molecular methods in plant breeding is likely to speed up the selection of new and viable material [16] and is envisaged to lead to a willow crop which is less prone to pests and diseases and which can be managed with lower inputs than the current systems [17].

The widespread interest in the willow genus is due to the fact that many of its species, which are light demanding pioneer trees, exhibit a very high growth rate in their juvenile stage. Many willow species can easily be propagated by means of cuttings, and most species and their hybrids will generate new shoots abundantly after cutting down older shoots and stems [18]. Under Swedish conditions, willow has a very high and well documented growth potential [19] which, though, is not completely realized in commercial short rotation forestry [20]. To fully exploit the growth potential of willows, a soil fertility level is required which is comparable with those found on conventional agricultural soils in Sweden. To maintain growth in the long term, dry sites have to be avoided and nutrients have to be added at a rate which balances nutrient removal by harvest. Compared to conventional forestry, willows require a relative intensive management, but compared to conventional agricultural practice, management input is much lower.

3. Growing systems & population dynamics

Given the huge range in size, growth form and coppice ability in the willow genus, production systems for willow may vary from single-stemmed systems with less than 500 trees ha^{-1} and a rotation period of over 20 years, to systems which contain over 4×10^4 plants plant which generate over half a million shoots ha^{-1} in a one-year coppice cycle. In the remainder of this chapter, we focus on growing systems which are generated from cuttings, at a planting density of 1×10^4 to 1.5×10^4 cuttings ha^{-1}, and treated as a coppice system, undergoing multiple cutting cycles. In Scandinavian conditions, one season may be too short to replenish carbohydrate reserves in willow stubs after harvest, and a one-year harvest cycle may deplete a plantation and compromise its viability [21]. Cutting cycle lengths in Swedish practice have been 3 to 5 years, and with the introduction of faster growing clones, cutting cycle lengths now are being decreased to 2 to 4 years. In commercial practice, a double row system is employed (Figure 1). However, Bergkvist and Ledin [22] showed that planting design could be adjusted, within certain limits without losing yield potential, to the requirements of tractors and machines used in managing the *Salix* stand.

Figure 1. Machine planting of willow by means of a Woodpecker 601, using long rods and planting three double rows at a time (Photo: Nils-Erik Nordh).

The development of a population of willow stems is constrained by competitive interactions which lead to self-thinning, yield-density effects and to skewed size-frequency distributions of stems [23, 24]. Those effects of competitive interactions need to be accounted for when determining optimal plant spacing and harvest frequency. Especially in dense willow coppice, not only shoot mortality but also extensive stool mortality may occur [25], thereby leading to lasting gaps and production losses [26]. Studies on the long term dynamics of willow coppice have shown that an initial variability in plant size becomes enlarged over time, that self-thinning leads to mortality of the initially smallest stools [27], and that the competitive hierarchy between stools is preserved over harvest [26]. As soil factors are known to be important determinants of willow growth [28, 29, 30, 31], differences in soil at field scale likely underlie the initial size variability between plants. Differences in cutting quality also may cause an initial variability in growth performance between plants (see section 4.2). To be able to detect possible effects of cutting quality and to separate those from soil factors, it is advantageous to perform controlled experiments which allow the relative variation to be attributed to only a few factors. Verwijst et al. [32] compared the relative variation in shoot height of willow populations grown in the field with the relative variation of populations grown in boxes which had a standard soil and were treated as similar as possible with regard to fertilization and irrigation (Figure 2). The controlled experiments showed a decreased relative variation and enhanced the detection of cutting quality traits with relevance for early establishment success.

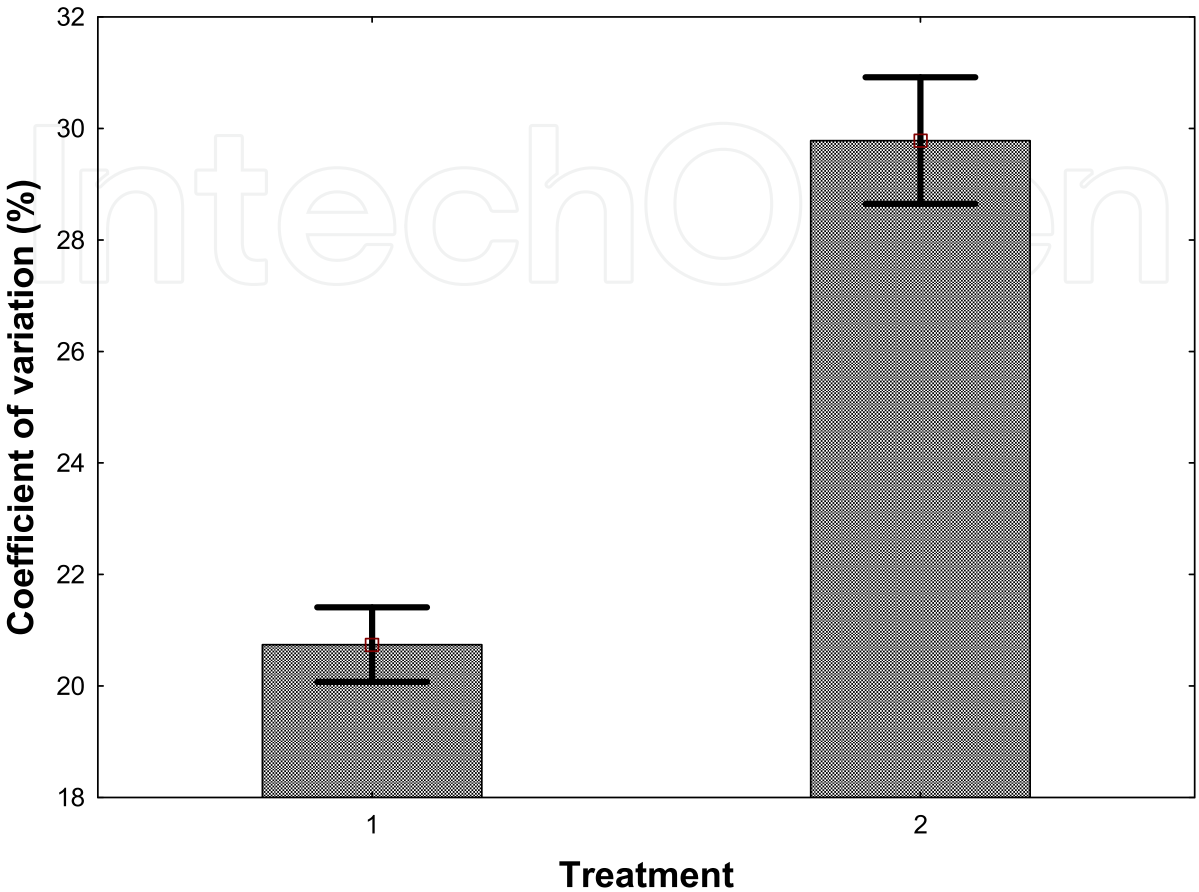

Figure 2. Relative variation (%) and its standard error in plant height for shoots from cuttings planted in a controlled environment (Treatment 1) versus shoots planted in the field (Treatment 2).

As willow is a relatively new crop, advances in willow breeding generate a steady increase in potential and attainable yield [33, 34]. This increase in biomass yield is estimated to be 50 to 100% since the 1970s'. This means that spacing, harvest frequency and fertilization have to be adapted to the rapidly evolving new plant material, in order to avoid mortality and ensure a high productivity also during the later cutting cycles. Most of the planted willow stands in Sweden consist of monoclonal stands or blocks of monoclonal units. However, such monoclonal stands are vulnerable to pathogen adaptations [35] and it has been shown that clone mixtures may be effective against the spread of diseases [36]. However, the relative competitive power of willow clones does differ, which means that certain clones may be outcompeted by other ones in mixtures of clones. If a mixture consists of only a few clones and one of the components is attacked by a pathogen, the susceptible clone is likely to be outcompeted by the others, thereby causing gaps, a delayed stand closure and lower productivity in later cutting cycles [37]. Furthermore, as clone-site interactions have been reported for willow, and the performance of clones in mixtures can not be predicted from their performance in pure stands [24], successful clone combinations are expected to be highly site specific.

3.1. Site choice and preparation

Many willow species do have abroad ecological amplitude. However, to obtain a high productivity, willow has specific site requirements. Being a pioneer species, willow is light demanding, and a rapid establishment can only be achieved without competition by weeds for light. Once established, the leaf area index of a willow canopy will exceed 6 $m^2 \times m^{-2}$ [4, 38] and will suppress weed growth. Willow thrives on most agricultural soils, as long as the pH is in the range of 5 to 7 [39]. Water use efficiency of a willow crop is about 4 to 6 $g \times kg^{-1}$ [4]. This is a high value compared to values of other tree species, but given the potentially high biomass production of willow, water availability is conceived as a critical factor in willow SRF [40]. Consequently, lighter soils, especially in drier areas, should be avoided for willow growing. A low precipitation during the growing season can be compensated for if winter precipitation is abundant and soils have a good water holding capacity or do have access to groundwater. While many willow species have a boreal-arctic origin and are native to northern temperate regions, fast-growing hybrids may be susceptible to frost damage from bud-burst and onwards. If planted at frost-exposed sites, a single night frost may decrease a single year's productivity by 50% [41] and will also impact negatively on the biomass production in the following years. Therefore, sites prone to late spring frost should be avoided and it is important to choose clones which have a site-adapted phenology with regard to timing of bud burst. Willow can be harvested with a reasonable cost-efficiency on sites which are 5 ha or larger, and even on slightly smaller sites if willow is harvested on adjacent sites. Planting and harvest equipment for willow requires a relatively widely spaced headland (10 to 12 m in width), which means that single willow fields should not be smaller than 2 ha, and easily could be reached by the harvest machines [42]. Larger stones also should be removed from the soil surface, as they may damage harvest equipment. As planting (see section 4.2) requires a well prepared seed bed, autumn plowing and early spring seedbed preparation are common measures prior to planting. Such preparation has to go along with adequate weed control (see section 4.3). Another selection criterion for willow growing sites is the proximity to a consumer, usually a combined heat and power plant. As moist willow chips do have low energy content per volume, transportation distances by road should be minimized [43]. Finally, willow growing is a form of land-use, and as such, it may interfere with a range of other interests than sheer biomass production. Short rotation forests may affect landscape views, the environment and biodiversity in a positive or negative way, depending on the functions that we require from a semi-natural landscape element, and on how we choose to integrate such functions in a single growing system [1, 44].

3.2. Planting & cutting quality

One of the large advantages of most willows is that they can be propagated vegetatively by means of cuttings. Traditionally, cuttings of about 20 cm in length were produced manually from 1-year old long rods. These cuttings were taken during the winter period, when willow is dormant, and could be stored in a fridge until planting in spring. During commercialization of the growing system in Sweden in the late 1980s, manual planting was replaced by machine planting. Establishment costs for short rotation willow coppice decreased substantially during the initial phase of commercialization in Sweden [45]. This was mainly achieved by mechanisation of planting, employing equipment which, in one process, cuts willow rods (1.8 – 2.4 m. long) into cuttings and then plants them (Figure 1). These cuttings are around 18 to 20 cm long, and the cutting is pressed down into the prepared soil so that only 1-2 cm protrudes above soil surface. This is believed to provide the cutting with good soil contact, thereby minimizing the risk of drying out [46]. Field storage of cuttings can result in water loss and reduce shoot survival and biomass production. This problem has partly been overcome by the use of entire shoots, which are considered to be more resistant to desiccation than cuttings [47]. Volk et al. [48] also pointed to risks of desiccation and showed that a prolonged time of field storage after cold storage may lead to a decrease in survival and growth rate.

Stage	**Description**
1	No sign of bud swelling, the tip of the bud is tightly pressed to the shoot.
2	The tip of the bud starts to bend from the stem, bud scales are starting to open and the length of the shoot tip is 1–4 mm.
3	The shoot tip is 5 mm or longer, protruding leaves are put together.
4	New leaves start to bend from each other.
5	One or more new leaves are perpendicular to the shoot axis.

Table 1. Assessment criteria for bud burst stages.

Cutting size (length and diameter) has positive effects on subsequent willow growth. The positive effects of cutting size on growth and survival decline with increasing sizes ([49, 50, 51], and Rossi [52] found that the differences in cutting length with relevance for establishment in practice are to be found between lengths of 10 and 20 cm. Positive effects of cutting size generally are attributed to the size of the carbohydrate pool available for allocation to roots and shoots [53]. The effect of cutting length may also be associated to the ability of longer cuttings to withstand soil desiccation [54]. The phenological development of buds and shoots is affected by cutting size and also by the height above ground from where the cuttings were taken [51]. Using the simple assessment criteria for bud development as described in Table 1, bud development, a few weeks after planting, is a function of the diameter size of the planted cutting (Figure 3). However, cuttings derived from apical positions along shoots display for a given diameter a higher shoot biomass production than cuttings derived from the more basal parts (Figure 4). As willow rods display a taper, the question arises which of the two factors (cutting size or position) is the strongest determinant of shoot biomass production during early establishment.

A further evaluation of produced shoot biomass on the cuttings showed that cutting size by far is the single most important determinant of early biomass production, which led to the recommendation to employ thicker cuttings and to discard the thinner apical parts from long rods. While the introduction of planting machines has increased the speed of planting and reduced planting costs, ongoing research indicates that planting machines may cause damage to cuttings, especially when planted in compacted soils. Preliminary results by Verwijst et al. [32] and by Edelfeldt et al. [55], suggest that that undamaged cuttings had a better growth performance than visibly damaged cuttings. Planting by machine on hard soil resulted in a relatively large number of cuttings landing on the soils surface. Soil compaction and machine planting interacted with cutting dimensions, the poorer performance of thinner cuttings being more pronounced in compacted soil (Figure 5).

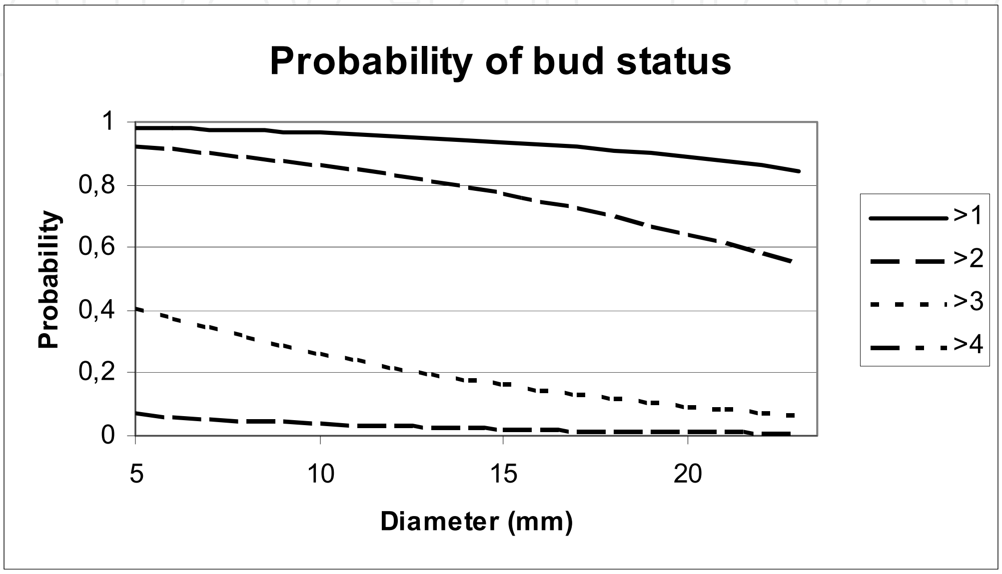

Figure 3. Probability of bud status (see Table 1) at average values for five clones and cuttings derived from a position of 95 cm above soil surface, a few weeks after planting. Probability of high bud status decreases with diameter.

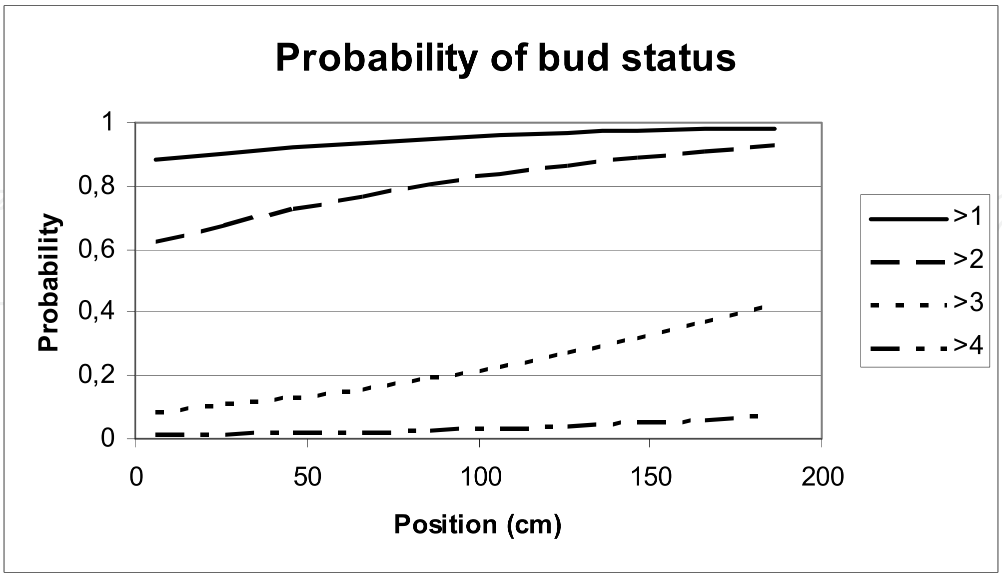

Figure 4. Probability of bud status (see Table 1) at average values for five clones and diameter 12.5 mm, a few weeks after planting. Probability of high bud status increases with the original height position of the cutting along the rods from which is was derived.

Furthermore, machine planting also increased the relative variation of shoot height (Figure 6) compared to hand prepared and planted cuttings. Consequently, to obtain a faster and more even establishment of willows, Edelfeldt et al. [55] recommend thorough soil cultivation prior to planting, further development of planting machines to minimise damage to cuttings at planting, and the use of cuttings with a diameter of at least 10-11 mm.

Figure 5. Cuttings planted by machine in a hard soil were transformed to a soft soil to isolate the effect of machine planting from other factors. The thinner cuttings were visually damaged and displayed a lower sprouting performance than the thicker ones (Photo: Nils-Erik Nordh).

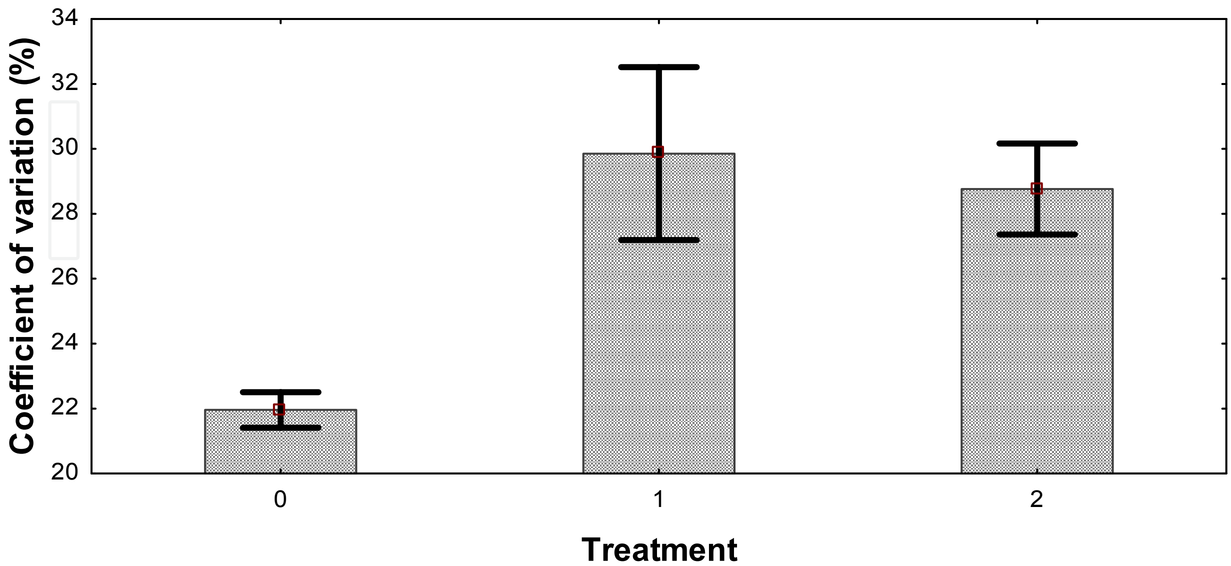

Figure 6. Relative variation (%) and its standard error in plant height for manually planted cuttings (Treatment 0) versus machine planted cuttings in Soft and Hard soil (Treatments 1 and 2, respectively).

3.3. Weed control

Weed control is necessary when establishing willows from cuttings, because its takes a relatively long time for willow cuttings to develop attributes which make them competitive against weeds. Competition is an interaction between plants which require the same limited resources like nutrients, water and light. Harper [56] defines competition as 'An interaction between individuals brought about by a shared requirement for a resource in limited supply and leading to a reduction in the survivorship, growth and/or reproduction of the individuals concerned', and thereby points to the effects of competition. The aim of weed control is to ensure that as much resources as possible are accessible for the crop and not for the weeds, and to reduce or delay growth and development of the weed flora [57].

Willows under establishment from cuttings have a relatively low competitive power against weeds because it takes a while for willows to develop roots needed for the uptake of nutrients and water. Consequently, perennial weeds, which have a developed root system prior to the onset of leaves, have to be removed completely before planting willows. This commonly is done by means of one or two applications of a glyphosate-based herbicide, applied at the appropriate rate, during the summer/autumn prior to spring planting. If the area has not been used for agricultural purposes for a number of years before planting, it is recommended to grow cereals there for at least one season to ensure an adequate weed control [42]. The relative competitive ability is also affected by seed rate (plant density), which is low for willow (between 1 and 2 cuttings m^{-2}), in comparison to the amount of germinating annual weeds triggered by seed bed preparation. Such weeds may germinate only a few days after seed bed preparation, while it may take a week or more for willow cuttings to exhibit a first bud burst after planting. This implies that the time between the last seed bed preparation and willow planting should be minimized. To counteract the effects of the inherent differences in relative emergence time between willow and weeds, soil cultivation by different types of cultivators, rototillers or harrows are recommended as a weed control measure during willow establishment [46, 58]. There are also different soil-applied herbicides that are permitted to be used at planting or shortly thereafter. Given the low planting density of willow cuttings, a full canopy closure, which for willow implies a leaf area index > 6 $m^2 \times m^{-2}$ [4, 38] is hardly ever reached during the establishment year, which means that if weeds are not kept back during the establishment year, they may establish and compete with willows for light. The use of mechanical weeding may therefore proceed even after bud burst and early shoot formation in willows. As the cuttings are well fixed in the soil and young willow shoots are flexible, they will not become damaged by this treatment. The current recommendation is to perform these control measures at least three times during the first year [46].

Weed control might also be necessary to perform the year after planting depending on weed management success the first year, clones and site conditions. As the willow plants will be better established by then, it is usually enough to perform mechanical weeding two times early in the season [46]. Another possibility is to spray a soil-applied herbicide well before bud burst [42] or to use a selective herbicide during spring or early summer [46]. Weed control the second year usually requires that the first year shoots are cut back. This practice has been questioned [59] and is no longer recommended in Sweden [42]. If weed control has been efficient during the establishment phase, no additional measures are required to control the weeds the following years. If early plant mortality has led to gaps in the stand, weeds may establish and maintain themselves below canopy gaps (Figure 7). In case weeds survived below such gaps, weeds may be controlled directly after each harvest.

If the weeds are not controlled during the establishment phase, willow growth might be dramatically reduced. Field experiments conducted in Southern Sweden by Albertsson in 2010-2012, with 10 modern willow varieties, grown both with- and without weeds, have shown that weeds can increase plant mortality, and reduce growth the first year by more than 95% [42], see Figure 8. Several other studies have also shown that willow, in the establishment phase, is very sensitive to competition from other plants [60, 61, 62]. Preliminary data from the Swedish study also suggest that there is an interaction between voles and weediness, since plots with weeds show more damage by voles than plots without weeds, thereby making weed control even more important.

Figure 7. Poor establishment of willow leads to gaps in which weeds may establish, thereby causing the need for prolonged weed control after a first harvest (Photo: Nils-Erik Nordh).

Weeds in willow short rotation coppice might, in the future, be controlled with other measures than the above mentioned. Studies are ongoing to investigate if willow clones differ in their ability to compete with weeds. Fast initial growth, early bud burst, fast canopy closure and the ability to tolerate or release allelophatic substances might be favorable weed competing traits. If differences exist, it might be possible to breed for these traits or to use competitive willow varieties that combine well with a specific weed control measure.

Different cover crops such as rye (*Secale cereale* L.), dutch white clover (*Trifolium repens* L.), buckwheat (*Fagopyrum esculentum* Moench) and caragana (*Caragana arborescens* Lam.) have been studied as a way of controlling weeds and improve nutritional management in willow [63, 64, 65]. However, there is still more research to be conducted in this area before a suitable willow cover crop system is ready for commercial use. Mechanical weeding techniques are under constant development and recent results indicate that automatic intra-row weeding is possible [66]. Hence, these techniques may be further developed to be used in willow since weeds within the rows are hard to control mechanically with conventional equipment.

Figure 8. Weeds were removed mechanically and by hand in the willow stand to the left while no weed control measures were performed in the willow stand to the right. The photo was taken five months after planting (Photo: Johannes Albertsson).

3.4. Fertilization

Most field-based cropping systems do have an actual production which is well below their potential production. The potential production of a crop is determined genetically by its nutrient-, water- and light use efficiency. But given those efficiencies, a field environment hardly ever constantly provides optimal supply of water, nutrients and light to the crops. The production which is attained after restriction by abiotic factors such as light, water and nutrients is called attainable production, and can be regulated by site choice and fertilization. Actual production is usually lower than the level of attainable production, being utterly restricted by the effects of biotic agents, such as herbivores and pathogens.

Consequently, plant breeding and selection partly strive to generate plant material with a high resistance against pests and diseases, but also to generate material with a positive response for treatments such as fertilization. From a farmers' perspective, fertilization may be applied if it enhances profitability of the cropping system. Profitability then is a function of costs for fertilizers, the net value of the crop, and of the fertilization effect, i.e. the additional biomass increment per unit added fertilizer. The willow clones that have been released during the last decades in Sweden display a higher actual productivity that the earlier ones [45, 67], and this seems amongst others to be the result of a clonal selection towards a higher shoot/root allocation patterns, resulting in a higher harvestable biomass increment per unit fertilizer. While selection thus promotes a positive response to fertilization and irrigation, it may also increase the susceptibility of clones for incidental drought periods [68].

Recommendations for farmers with regard to fertilization of willow coppice on agricultural land during the last decades in Sweden have been subject to a great deal of confusion, due to the fact that fertilizer costs, net crop revenue and fertilization response of the crop all rapidly have been changing through time. Early recommendations by Ledin [69] were based on fertilization trials with older willow clones and on economic calculations which accounted for projected crop values which were not met by the market. Net values for different fertilization strategies under different scenarios with regard to fertilization costs and actual net crop values recently have been calculated [70] after field based parameterizations of the fertilization response of more recent willow clones. It was found that fertilization responses differed widely between clones and sites and that fertilization should be adapted to the local conditions. Under current market conditions and using recently released willow clones, fertilization can greatly enhance profitability. The need for fertilization of modern clones in a first cutting cycle could not be assessed due to lack of data. However, fertilization during the first year may positively affect weed growth, and is therefore not recommended. Plantations with modern willow clones should be fertilized with at least 220 kg N ha^{-1} during the second and consecutive cutting cycles. Annual fertilization in willow stand would require a further machine development, as conventional machinery cannot enter tall willow stands.

Fertilization may also be performed with nutrient-rich residues such as municipal wastewater and sludge to willow short rotation coppice [71] and may render a more cost-effective and sustainable cultivation. Rosenqvist and Ness [72] provide an economic analysis of leached purification through willow coppice vegetation filters and showed that economic gains were made compared to conventional purification, while an increased biomass production led to additional economic gains. It also is concluded that willow vegetation filters are more cost-effective than conventional treatment methods and may facilitate recycling of valuable products in society [5]. This conclusion is sustained by other assessments of the economic gains of such multi-purpose systems [e.g. 12, 13]. Volk et al [3] even concluded that the economic valuation of the environmental benefits is necessary for a further deployment of woody crops.

3.5. Control of pests and diseases

Attainable biomass production of a crop, as determined by its genetics and actual resource levels provided in a particular field situation, is usually reduced by the action of pathogens and herbivores. Especially in genera with species that hybridize easily, such as willow, the relationship between plant breeding and pest and disease control is strong, because such genera in general attract many kinds of insects and pathogens. Plants may be well adapted to a specified range of abiotic conditions, which display a site specific variation. However, pests and diseases are biotic factors which not only vary in space and time, but may also co-evolve with plants. Consequently, potentially pathogenic organisms may be present and may do little harm for longer periods in a willow stand, until virulent strains develop which may be very clone specific. For instance, susceptibility to defined pathotypes of leaf rust (*Melampsora epitea*) is rather clone specific [73]. Consequently, it is important that new clones are released constantly by breeding programs and that a broad genetic base is used, targeting a broad tolerance to a range of pathogens. Poplar breeding programs in Western Europe previously have underrated this issue, resulting in the destruction of many poplar stands by leaf rust varieties that managed to adapt to the poplar clones [74]. In willow breeding, this issue was acknowledged early. Development of new high producing willow clones was initiated in Sweden in 1987 by Svalöf-Weibull AB [33]. The main purpose of the breeding program was to develop high yielding clones resistant towards pests, frost, and diseases, and with morphology suitable for mechanical harvesting. From 1996 to 2002 several new clones were developed in cooperation between Svalöf-Weibull and Long-Ashton research in UK, also with a strong focus on pest and disease resistance [34]. Strong advances were made early with regard to leaf rust in willow [75] and resistance of willow to several insect species has also been exploited [76, 77]. Production losses between 20 and 40% have been recorded in willow after defoliation by insects [78]. Willow, however, usually recovers well after defoliation, and as the population dynamics of many insects is erratic, and under control of very many factors, damage prevention by means of breeding towards resistance has been chosen, instead of the use of pesticides. Salix has probably the best environmental profile among the arable bioenergy crops available today, partly because neither fungicides nor insecticides are used in the production. This environmental profile is largely an outcome of plant breeding because resistance to pests and diseases, such as leaf rust and certain insects, has been highly prioritized since commercial breeding started in Sweden 25 years ago [79, 80].

3.6. Harvest and logistics

During early commercialization of the willow coppice system as an agricultural crop in Sweden, funding agencies made the decision to put the far majority of the development costs for harvest machines on the account of commercial machine developers. This resulted in a situation in the early 1990s where many willow stands needed to be harvested before self-thinning would lead to an irreversible mortality among willow stools and long-term production losses, while harvest machines still had to be developed and assembled. This is one of the reasons for the early commercial yields to be disappointingly low (see section 4.7).

Fortunately, a variety of willow harvest machines are on the market now, and recent technical improvements greatly enhance harvesting speed while lowering the costs for willow harvesting. In Sweden, willow is usually harvested during the winter, when the soil is able to carry heavy machinery and when willow chips can be transported to district heating plants for direct use, without long-term storage (Figure 9).

Figure 9. Willow harvest by means of a self-propelled chipper which blows the willow chips in an adjacent container (Photo: Nils-Erik Nordh).

However, mild and wet winters may prohibit the use of heavy harvesters, which means that either lighter equipment has to be developed or that the harvest season has to be extended. Expanding the harvesting season for willow biomass crops would expand the time period over which it can be a part of the fuel supply and increase the number of acres that a single harvesting machine could cover in a single year. This would likely increase the demand for willow and certainly reduce harvesting costs, because capital expenditures for a harvester would be spread across more tons of biomass. Nordh [81] investigated the possibility to extend the harvest season, focusing on the re-growth capacity of willow coppice after harvesting , and found that willow (clone Tora) could be harvested from autumn, prior to the onset of dormancy, until late spring, when bud burst already had commenced. Early and late harvest did not increase plant mortality, but it could result in a slight production decrease in the consecutive season.

Apart from direct chipping (Figure 9), willow biomass can be baled (Figure 10) and fragmented in a later stage, possibly after storage, which will decrease moisture content of the willow biomass.

Figure 10. Willow harvest may be performed by means of a machine which produces bales that can be transported by conventional machines. Bales may be stored to obtain biomass with lower moisture content (Photo: Nils-Erik Nordh).

To harvest willow rods for conventional planting by means of a machine, equipment has been developed which can harvest entire one-year old shoots. Mature stands can also be harvested by means of a whole-shoot harvester (Figure 11) which may carry its load to the headland for further transportation. Special equipment has been developed to make bundles from a pile of whole shoots, thereby improving further transportation logistics. As willow is a low-density fuel, willow should preferably be cultivated in the proximity of the consumer, to decrease transportation distances and costs.

3.7. Yield levels

Biomass productivity of short rotation coppice has been studied for several fast growing species in many places of the world, showing an average annual production of 10 to 20 oven dry tonnes (odt) ha^{-1} in most places [82]. In intensively irrigated and fertilized willow plots

Figure 11. A tractor-pulled whole shoot harvester, unloading willow shoots at the headland (Photo: Nils-Erik Nordh).

in southern Sweden, growth rates of > 30 odt ha^{-1} yr^{-1} have been recorded [83]. The potential production of a certain genotype can only be reached if resources (light, water and nutrients) are permanent available and without limitations, and in the absence of pests and diseases. An analysis of short rotation coppice yields in Sweden over the period 1989-2005 showed disappointingly low mean annual production figures of 2.6, 4.2 and 4.5 odt ha^{-1} during the first, second and third cutting cycles, respectively [20]. These low figures can partly be explained by the use of old clones, which have a much lower potential production than those which were released later [34] and which have a relatively high susceptibility to pathogens. Other reasons for this low productivity are site choice, as farmers have been reluctant to use the better soils for willow plantations, and a very poor management. Many of the early plantations never received fertilizer and suffered from a poor establishment due to inadequate weed control. However, annual average yields over 10 odt ha^{-1} have been reached in commercial plantations if fertilization was applied and adequate weed control performed [84], and did not require more than an average availability of water. Taking account of the water use efficiency of willow and precipitation during the growing season, Lindroth & Båth [85] calculated 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. Studies confined to the new willow clones which have been developed in cooperation between Svalöf-Weibull and Long-Ashton research in UK between 1996 and 2002 confirm that willow breeding has been leading to higher yields in commercial practice. For the new clones, reported yields vary between 5 and 12 odt ha^{-1}, with extremes between 2 and 18 odt ha^{-1} yr^{-1} [34, 86, 87, 88]. This large variation seems to be related to interactions between clones and sites [33, 89].

4. Conclusion

Willow short rotation coppice systems are relatively new as a farm crop and both farmers and extension workers in Sweden have gone through a learning process which is now leading to higher yields in commercial plantations. Traditional willow breeding and selection are already greatly contributing to increasing yields, and it is expected that future improvements of the willow varieties will result in a significant increase of the yields in the near future. Many of the early field research results are currently extended with more controlled experiments, and help to improve short rotation coppice management. Although the early commercial implementation of willow coppice did not meet the expectations with regard to yield, profitability and areal expansion of willow coppice, analyses of the early commercial fields contribute to the improvement of stand management, and of the planting, harvest and transport logistics. Further developments of willow coppice as multi-purpose systems, including environmental functions, are promising. Current research suggests that there is room for further improvements with regard to cutting quality, planting, weed control and fertilization, all of which will contribute to higher future yields.

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