WEED PROBLEMS AND POSSIBILITIES FOR THEIR CONTROL IN SALIX FOR BIOMASS

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Preface

This introductory paper is part of my PhD project: "Weed competitiveness in salix clones for biomass". The project is conducted at the Swedish University of Agricultural Sciences, Alnarp, at the department of Plant Breeding and Biotechnology, and funded by Formas. My supervisors are Inger Åhman, Nils-Ove Bertholdsson and David Hansson.

Summary

Salix is a dedicated arable bioenergy crop that is presently grown on 12,000 ha in Sweden. It has probably the best environmental profile among the arable bioenergy crops grown in Sweden partly because neither fungicides nor insecticides are used in the production. However, herbicides are used routinely, because salix plants are very sensitive, especially during the first growing season, to competition from weeds. Hence, to improve the environmental profile of salix even further, alternative weed control methods that complement or for substitute the use of herbicides are desired. Some of these alternatives might be to improve the mechanical weeding techniques, using cover crops, applying herbicides more accurately or to breed for weed competitiveness. The purpose of this introductory paper is therefore to review what is known about weeds in relation to biomass salix. To put this subject into context there will first be a general overview of salix and the current production system.

Introduction

The genus Salix

Salix (willow) belongs to the Salicaceae family together with *Populus* (poplar, aspen and cottonwood). The genus is taxonomically complex; something already Linnaeus recognised; with a huge variation in growth forms ranging from tall trees, bushes to dwarf plants (Karp *et al.*, 2011). Several attempts have been made to estimate the number of species in the genus. However, due to interspecific hybridization and variation between individuals, figures range between 330 and 500. Most of the species are found in the Northern hemisphere, with its centre of diversity in China hosting around 275 species (Argus, 1997; Kuzovkina *et al.*, 2008). *Salix* is dioecious and thus has male and female flowers on separate individuals. The flowers are clustered in catkins and are insect- and to some extent wind-pollinated (Karp *et al.*, 2011; Karrenberg *et al.*, 2002).

Salix as a bioenergy crop

The Swedish government has stated that more than 50 % of the energy should come from renewable sources by 2020 (Regeringskansliet, 2009). An agricultural production system with potential to provide part of this energy is willow shrubs (*Salix* spp.) managed as short-rotation woody coppice (SRWC).

Salix SRWC is a perennial agricultural crop grown commercially to produce a renewable feedstock for bioenergy, usually as wood chips. During the last 25 years more than 16,000 ha of *Salix* plantations have been established in Sweden. *Salix* has historically been used for many purposes but *Salix* cultivation for biomass production to produce renewable energy has to a large extent been developed in Sweden (Åhman & Larsson, 1994). Nowadays this crop is named salix and the cultivation is practised in many other countries like Poland, UK, Denmark, Germany and Slovakia to name a few. In Sweden there has been little interest to establish new commercial salix plantations during the last few years. For example in 2011 less than 100 ha were planted (Gabriele Engqvist, pers. comm.). Furthermore several poor plantations have been terminated in Sweden and not seldom do these plantations have severe weed problems (Helby *et al.*, 2006). The total acreage in Sweden is now ca. 12,000 ha (Jordbruksverket, 2012).

Several studies have shown that salix in a short-rotation system has the potential to produce large quantities of wood biomass. Extremes of 36 oven dry tonnes (odt) ha $^{-1}$ year $^{-1}$ have been obtained in intensely irrigated and fertilised experiments in southern Sweden (Christersson, 1987). However, such data are from small and well maintained research plots, something which often greatly overestimates yield levels compared to commercially managed fields. Therefore, the yield would typically be lower in commercial plantations (Bullard *et al.*, 2002; Hansen, 1991). A yield model based on recorded production of more than 2,000 commercial plantations in Sweden during the period 1989–2005 estimates that growers utilizing efficient cultivation methods in favourable locations obtain between 4.0 to 6.3 odt ha $^{-1}$ year $^{-1}$ in the first rotation. Yields from the second and subsequent rotations are often higher and could, if the salix plantation is well managed, yield between 5.4 and 7.1 odt ha $^{-1}$ year $^{-1}$ (Mola-Yudego & Aronsson, 2008). Some Swedish plantations yield between 10-12 odt ha $^{-1}$ year $^{-1}$. These plantations are planted with new varieties, on good soils, are fertilized and have undergone a thorough weed control program (Larsson & Lindegaard, 2003).

The salix SRWC energy ratio, i.e. energy produced divided by energy input, has been estimated by various models (Börjesson, 1996; Heller *et al.*, 2003). The outcome varies between 11-21, depending on model boundaries and assumptions made regarding processing methods, yields and management practices (Rowe *et al.*, 2009). However, even if the results differ, the ratios for salix SRWC are always well above the energy ratios for annual energy crops such as oilseed rape, wheat and maize (Börjesson, 2007; Cocco, 2007).

In Sweden, salix SRWC biomass production systems for energy purposes are sometimes combined with various types of phytoremediation. Phytoremediation is described as the use of living plants to decrease the impact of pollutants on the environment (Mirck *et al.*, 2005). Salix can, for example, be used to clean agricultural land from cadmium since it is considered to be one of the most efficient crops for absorbing heavy metals (Lewandowski *et al.*, 2006; Schmidt, 2003). Sludge and waste water, containing macro- and micronutrients, are commonly applied in salix plantations. This practice increases biomass production and decrease the need for additional fertilizers. A shift from a pure biomass production system to a multi-purpose system might therefore both reduce production cost and transform waste products to valuable resources (Mirck *et al.*, 2005; Rosenqvist *et al.*, 2010).

Salix grown as SRWC has been considered as one of the most promising energy crops grown on agricultural land (Weih & Bonosi, 2009). Some of the reasons for this are that most willows are easy to propagate vegetatively, they are easy to breed, they are nutrient efficient, and they produce high biomass yields with low inputs (Karp & Shield, 2008; Ledin, 1996). The production system has an environmental profile because neither fungicides nor insecticides are used (Gustafsson *et al.*, 2009). The environmental profile of salix is to a large extent a result of breeding aimed to increase the resistance to the most devastating pests and diseases (Åhman & Larsson, 1994). The only pesticides applied are herbicides before planting and in the establishment phase (Abrahamson *et al.*, 2002; Gustafsson *et al.*, 2009).

The salix biomass production systems

Site selection and preparation

The size of the plantation should be as large as possible, ideally not smaller than 5-10 hectares, since a large plantation will use the land and machines more efficiently. The distance between the SRWC plantation and the end-user should be as short as possible because the biomass transportation accounts for a large part of the total energy input. For example, a 50 km transport by truck is equivalent to 10-30 % of the total input of energy in salix SRWC production (Börjesson, 1996; Larsson *et al.*, 2007).

Salix has been shown to grow well on sandy, clayey, silty and organic soils provided that the management practises are adapted to the different sites (Ledin, 1996). However, organic soils might cause problems due to difficulties to manage the weeds. The soil pH should be between 5.5 and 7.5 (Larsson *et al.*, 2007).

There are various handbooks available with advice on how to grow salix SRWC (Abrahamson *et al.*, 2002; Danfors *et al.*, 1997; Larsson *et al.*, 2007; Gustafsson *et al.*, 2009; Jordbruksverket, 2012). In the following the predominating methods for planting, growing and harvesting salix are described. The preparation is usually started in summer or autumn the year before planting and involves spraying with glyphosate and ploughing to a depth of approximately 25 cm. The following spring, just before planting, the field is harrowed and right after planting sprayed with a pre-emergence herbicide. During the first growing season, additional herbicide treatment and/or mechanical weeding is often required (Abrahamson *et al.*, 2002).

Planting

The current cultivation system consists of double-row planting, with alternate 1.5 and 0.75 m spacing between the rows and approximately 0.60 to 0.75 m between plants within the rows. The planting is commonly done by machines that cut one year old salix shoots into 18-20 cm cuttings and plant them in the soil. The planting should preferable be done in early spring, with a total number of ca. 13,000 cuttings per hectare. Salix shoots to be used for planting are harvested in the winter and stored at - 4 Cº (Gustafsson *et al.*, 2009; Larsson *et al.*, 2007).

Coppicing one year old shoots

The predominating practise in Sweden has been to coppice the salix plants during the first winter after planting. The reason for this is to increase the number of shoots from each stool and to facilitate fertilization and weeding the second year (Gustafsson *et al.*, 2009; Sennerby-Forsse & Zsuffa, 1995; Volk, 2002). Apart from increasing number of shoots, coppicing also increases leaf size, net photosynthetic rate (shown in *Populus* sp.) and growth rate of shoots (Sennerby-Forsse *et al.*, 1992; Tschaplinski & Blake, 1989; Volk, 2002). Scientific documentation about the long term effect of first year coppicing on salix biomass production is rather weak. However, Verwijst and Nordh (2010) found no positive effect on biomass production of such coppicing when three different Swedish trials were analysed. Another study made in the USA compared coppicing versus not coppicing after the first growing season (Volk, 2002). The result from this study showed no increase in yield from the first rotation harvest and no improved weed-competitive ability where the plants were coppiced. Since no positive effects of biomass production or weed competition have been found it could be questioned if coppicing after one growing season should be a routine measure. In the new handbook for salix growers, the Swedish Board of Agriculture is not recommending this measure any longer (Jordbruksverket, 2012).

Harvesting

Harvest, which takes place in the winter, is performed every three to five years depending on how well the plantation has been managed, growth conditions and if the winter conditions allow mechanical harvest. The plantation is considered ready for harvest when stems with a diameter of 60 mm at 30 cm height are easily found. However, the harvest efficiency will be negatively affected if the shoot diameter exceeds 70 mm (Gunnar Henriksson, pers. comm.). The shoots are usually converted into wood chips at harvest (Figure 1) and transported wet to heat and power plants for conversion into energy. There are also other harvesting systems available, e.g. Biobaler which cuts and compress the shoot into dense round bales (Sten Segerslätt, pers.comm.) and another harvester which cuts whole shoots and makes bundles out of them. Both shoot harvesting systems enable storage of the harvested salix on field for later use (Magnusson, 2009). Forest cutting machines have been tested in salix SRWC but they are not cost-effective compared to the other harvesters unless the shoots are very large (Bergström *et al.*, 2011).

Instead of transporting the wood chips to a power plant there is the alternative to have a furnace stationed at the farm. This makes the farmer independent of wood chip prices and lowers the need for long way transportation (Gunnar Henriksson, pers. comm.). Thanks to the ability of salix to produce new shoots after coppicing there is no need to replant after harvest. The plantation maintains its productivity for at least 20-25 years, which means that it will be harvested 5-6 times during its life time (Gustafsson *et al.*, 2009).

Figure 1. Harvest and chipping of salix shoots. (Photo Stig Larsson)

Removal of the plantations

After the final harvest the stools are left to regenerate new shoots during spring. The growing shoots are killed by spraying a combination of MCPA and glyphosate (Gustafsson *et al.*, 2009). When the salix plants are dead the land is worked with a rototiller which cuts the stools and salix roots into smaller parts. The deeper the rototiller is working the better, but it must at least be working in the top 5 cm of the soil. The land can then be replanted with new salix or be used for other agricultural crops like winter oilseed rape or winter barley. Several salix growers have experienced high yields of rapeseed and barley after removal of salix plantations (Gunnar Henriksson and Sten Segerslätt, pers. comm.). During 2009 a project was started that studies different types of equipment to cut the stools and roots. It will also quantify the salix yield effect on the following crops, in this case spring barley and winter wheat (Nils-Erik Nordh, pers. comm.).

Pests and diseases

Even though no pesticides or fungicides are currently used in plantations of willow there are both pests and diseases that may threaten the production. Prior to successful resistance breeding efforts, *Melampsora* leaf rust has destroyed salix plantations, and insects such as leaf beetles, gall midges and aphids have severely damaged others (Forsberg et al., 1991; Åhman & Larsson, 1999). Below, some of the most important pests and diseases are described in more detail.

The most important pathogen on salix is leaf rust caused by *Melampsora* spp. The disease can reduce the biomass production by up to 40 % and make the plants sensitive to secondary diseases and abiotic stress like frost injuries (Karp *et al.*, 2011; Pei *et al.*, 2004; Verwijst, 1990). There are various species of rust on salix but the most widespread and most devastating is *Melampsora larici-epitea* Kleb. which during its life cycle alternates on willow and larch (Karp *et al.*, 2011). There are also other fungal diseases such as *Marssonina* spp., *Fusicladium saliciperdum* (Allesch. & Tubeuf) Lind and *Glomerella miyabeana* (Fukushi) Arx that can infest salix. However, they are usually considered much less severe than *Melampsora* spp. (Ramstedt, 1999)

At least three species of leaf beetles, *Galerucella lineola* F., *Phratora vulgatissima* L., and *Lochmea caprea* L. have made severe damage in Swedish salix plantations (Höglund *et al.*, 1999). Heavy defoliation by *P. vulgatissima* larvae have reduced salix growth with up to 39 % (Björkman *et al.*, 2000). Common for all three species are that both the adults and the larvae feed on the leaves (Höglund *et al.*, 1999). In recent years several studies have been made to develop and suggest new non-chemical measures to control the leaf beetles, especially *P. vulgatissima* (Dalin *et al.*, 2011; Stenberg *et al.*, 2010). There are differences in levels of attack between varieties, with lower levels in *Salix dasyclados* Wimm. (variety Gudrun) (Stenberg *et al.*, 2010). The leaf roll gall midge, *Dasineura marginemtorquens* Bremi, which forms pocket galls on the leaf margins, can be found in large numbers in salix plantations. There are indications of biomass reductions when the attacks are severe (Larsson, 1998). Several clones have shown partly or complete resistance to this insect by inducing both hypersensitive and non-hypersensitive responses (Höglund *et al.*, 2005). The larvae of another gall midge, *Dasineura ingeris* Sylvén & Lövgren, induce forking of salix shoot as larvae feed in the terminal leaf buds (Sylvén & Lövgren, 1995). This damage makes cutting production difficult since shoots attacked by the gall midge must be discarded or pruned before use (Forsberg *et al.*, 1991). Several lepidopteran species, such as *Earias clorana* L., do also induce forking of salix shoots (Forsberg *et al.*, 1991). This damage can be distinguished from gall midge damage since shoots damaged by gall midges usually have shorter leaf and side shoot internodes (Åhman & Bertholdsson, 2001). Various aphid species might also infest salix plantations. Common aphids in Swedish plantations are *Aphis farinosa* Gmelin, *Ptercomma* spp. and *Chaitophorus* spp. (Forsberg *et al.*, 1991).

A salix plantation may be a source of food to many mammal herbivores and also a place where to hide (Forsberg *et al.*, 1991). There is variation in the attractiveness to game between clones. Loden has been found to be very attractive to feed on by game whereas Tora is not (Åhman & Bertholdsson, 2001). Elks can do a lot of damage in a plantation since salix is one of their favorite food sources. They feed on the shoots and the damage is characterized by bitten and broken shoots at 1 - 2.5 m height. Roe deers like to hide in the plantation but are usually causing less damage compared to elks since they feed on leaves and side branches in the lower parts of the salix plant (Forsberg *et al.*, 1991). In winter both hares and rabbits may feed on bark and bite off salix shoots, especially when there is snow cover. This can be distinguished from elk and roe deer damage since hares and rabbits make a sharp cut at an angel of the shoot whereas elk and roe deer take a more rough bite (Forsberg *et al.*, 1991). The water vole and the field vole might also cause problems. The water vole lives in subterranean burrows and cause damage by gnawing on the roots. The field vole on the other hand creates shallow burrows in the vegetation and gnaws on the bark at the base of the salix shoots (Forsberg *et al.*, 1991).

Plant breeding

Research on salix SRWC has been going on in Sweden since the beginning of the 1970s (Nordh & Verwijst, 2004) and commercial breeding since the end of the 1980s (Larsson, 1998). Breeding programs have also been established in the UK, in the USA, and in Canada (Kuzovkina *et al.*, 2008; Smart & Cameron, 2008). Most of the commercial varieties from these breeding programs are listed in Table 1.

In Sweden hybrids with *Salix viminalis* L. background are dominating among the commercial clones for biomass production (Table 1). Examples of other species introgressed in the Swedish varieties are *Salix schwerinii* E. Wolf and *Salix triandra* L.. Also, *S. dasyclados* Wimm. is used as a pure species or hybridised with others (Larsson, 1998). However, there is some confusion about the distinction between *S. dasyclados* and *Salix burjatica* Nazarov (Larsson & Bremer, 1991; Pohjonen, 1991). Presently ca. 10 commercial varieties are available for planting from the Swedish breeding program carried out by Lantmännen Lantbruk. Breeding of salix is relatively easy compared with other agricultural crops and other tree species since: (1) there exists a great genetic variation; (2) there is no need of emasculation since salix is dioecious; (3) uniformity is obtained by cloning; (4) salix hybridizes readily (at least within subgenera); and (5) the seed set can be very high and takes place also on young plants (Karp *et al.*, 2011; Åhman & Larsson, 1994).

Table 1. Many of the commercial varieties and their genetic background (Smart & Cameron, 2008; Gabriele Engqvist, pers. comm.; Inger Åhman, pers. comm.; Lawrence Smart, pers. comm.)

Variety	Genetic background
Sweden	
‘Orm’, ‘Jorr’, ‘Jorunn’	*S. viminalis*
‘Tora’, ‘Björn’, ‘Torhild’, ‘Tordis’	*S. schwerinii, S. viminalis*
‘Sven’, ‘Olof’, ‘Lisa’	
‘Loden’, ‘Gudrun’	*S. dasyclados**
‘Inger’	*S. triandra, S. viminalis*
‘Karin’, ‘Klara’	*S. dasyclados*, S. schwerinii, S. viminalis*
‘Stina’, ‘Dimitrios’	*S. aegyptiaca, S. schwerinii, S. viminalis,*
UK	
‘Endeavour’, ‘Discovery’, ‘Resolution’, ‘Quest’	*S. schwerinii, S. viminalis*
‘Terra Nova’	*S. linderstipularis, S. triandra, S. viminalis*
‘Ashton Stott’	*S. dasyclados*, S. viminalis*
‘Nimrod’	*S. linderstipularis, S. schwerinii, S. viminalis*
USA	
‘Fish Creek’, ‘Onondaga’, ‘Allegany’	*S. purpurea*
‘Millbrook’, ‘Oneida’	*S. miyabeana, S. purpurea*
‘Sherburne’, ‘Canastota’	*S. miyabeana, S. sachalinensis*
‘Otisco’, ‘Tully Champion’, ‘Owasco’, ‘Fabius’	*S. miyabeana, S. viminalis*
‘Preble’	*S. miyabeana, S. viminalis, S. sachalinensis*
Canada	
‘SX61’	*S. sachalinensis*
‘SX64’, ‘SX67’	*S. miyabeana*
‘S25’	*S. eriocephala*
‘India’	*S. dasyclados**
‘Hotel’	*S. purpurea*
‘Alpha’	*S. viminalis*

* Sometimes referred to as *S. burjatica*

Selection criteria

One of the most important selection criteria when breeding salix is high stem biomass yield. However yield is a complex trait. Tharakan *et al.* (2005) suggested that high yielding varieties may be divided into two distinct groups, characterized by either a large number of stems, relatively low specific leaf area (SLA) and LAI (Leaf Area Index); or few large diameter stems, high SLA and high LAI. Weih and Rönnberg-Wästljung (2007) found, when six commercial varieties were compared, that a low vertical N leaf gradient is correlated to a high shoot biomass yield. Salix breeding material is also selected based on morphological traits. Plants with straight and erect shoot growth are preferred (Figure 2) since they are easier to plant, harvest and weed mechanically (Larsson, 1998; Åhman & Larsson, 1994).

Figure 2. Erect and straight salix shoots. (Photo Johannes Albertsson)

Resistance to pest and diseases is something that has been stressed in the breeding programs. The resistance selection has been really successful since neither fungicides nor insecticides are used in commercial salix plantations today. Selection has been made for resistance to rust, gall midges, lepidopterans and leaf beetles. The greatest efforts have been devoted to introduce resistance to the most devastating disease in salix, *Melampsora* rust (Åhman &

Larsson, 1999). The major source of resistance to *Melampsora* in modern varieties is coming from *S. schwerinii* (Larsson, 2001) but resistance has been found in other species as well such as *S. sachalinensis* (Karp *et al.*, 2011). During the last five years the interest in growing salix has increased in other parts of the world. Due to warmer and dryer climate in some of these areas, work is in progress to breed for varieties that are tolerant to drought and heat (Berlin Kolm *et al.*, 2011). So far, no selection has been made to improve weed competitive abilities in salix.

Breeding methods

Commercial varieties have been bred by classical methods relying on field tests for selections. With such an approach, characteristics that are difficult to measure in the field and/or are expressed late in the life cycle are neglected at selection. However, the achievements so far have been great, with 60 % higher yield, improved rust resistance and less shoot tip damage made by insects compared with clones found in nature (Kuzovkina *et al.*, 2008; Åhman & Larsson, 1999). The success and speed of progress may partly be explained by the fact that the breeding started with wild plant material. However, more elaborate methods are suggested to be utilized in the future to speed up the process and make it possible to improve the breeding material even further (Berlin Kolm et al., 2011; Karp *et al.*, 2011; Kuzovkina *et al.*, 2008). With the help of DNA markers plants can be screened for specific traits early in the breeding process. This will reduce the plant number needed to be planted in the field compared to traditional breeding and hence speed up the whole process.

Weeds

A number of authors have attempted to describe what a weed is (Radosevich *et al.*, 1997). Harper (1960) defined weeds as 'plants which are a nuisance' whereas Salisbury (1961) defined a weed as 'a plant where we do not want it'. A more recent definition is 'any plant that is objectionable or interferes with the activities or welfare of man' (Vencill, 2002).

Weed classification

There are different methods to classify weeds. One common method is to classify them as **dicots**, plants whose seedlings produce two cotyledons or seed leaves, or **monocots**, plants whose seedlings bear only one cotyledon. The dicots are commonly called broad-leaved weeds. The name grassy or grasslike is commonly applied to monocot weeds, which can further be divided into two groups namely; grasses and sedges (Aldrich & Kremer, 1997; Radosevich *et al.*, 1997). Weeds are also classified according to their life cycle. **Annuals** are plants or weeds that complete their life cycle in less than one year, **biennials** live longer than one year but less than two years and **perennial** weeds live longer than two years. This classification must be executed with some care because the environment may greatly influence the duration of the life cycle (Aldrich & Kremer, 1997). Grime (1974) classified plants based on their evolutionary strategies. This model, called the C-S-R model, has also been used for weeds (Radosevich *et al.*, 1997) and divides plants into three distinct types, **competitors**, **stress-tolerators** and **ruderals** (Grime *et al.*, 1988). The theory behind the model holds that two basic external factors, stress and disturbance, affect the vegetation. Stress is in this context environmental conditions that limit the photosynthetic production, such as light, nutrient and water deficiency, or too high or too low temperature. The second factor, disturbance, is described as the destruction of biomass and includes activities by herbivores, pathogens and humans, and phenomena such as wind-damage, soil erosion and fire. The resulting three plant strategies; competitors, stress-tolerators and ruderals; from the extremes of these factors are shown in Table 2 (Grime *et al.*, 1988). Many weeds share characteristics both with competitors and ruderals and are therefore often referred to as competitive-ruderals (Radosevich *et al.*, 1997). There are two dominating theories about how plants compete for resources. Grime’s theory predicts that the species with the greatest capacity for resource capture will dominate a plant community while Tillman’s theory predicts that the species with the lowest minimum resource requirement will be the better competitor (Grace, 1990). The debate about the two theories has so far not been resolved even though other authors have proposed that the two theories are actually complementary (Zimdahl, 2004). There are also other classification systems were the weeds are classified by their habitat, physiology or ecology (Radosevich *et al.*, 2007)

Table 2. Plant evolutionary strategies resulting from disturbance and stress (From Grime *et al.,* 1988).

Intensity of disturbance	Intensity of stress	
	Low	High
Low	Competitors	Stress-tolerators
High	Ruderals	(No viable strategy)

Weed seed bank and seed viability

Seeds from most annual, biennial and perennial weeds may persist in the seed bank for at least a couple of years (Aldrich & Kremer, 1997). However, the longevity of weed seeds can be considerably longer. In one experiment initiated in 1879 three out of 21 species were viable after 100 years when buried in moist well aerated sand outdoors (Kivilaan & Bandurski, 1981). The size of the seed bank and the species composition are greatly influenced by crop rotation and other management methods (Ogg & Dawson, 1984; Roberts & Neilson, 1981). Studies have shown that the number of viable seeds in the seed bank of cultivated soils in England ranges between 15-670 million seeds/ha (Roberts & Neilson, 1981) and that 2 – 10 % of these seeds emerge each year (Zimdahl, 2007). Even though the seed banks of cultivated soils contain weed seeds from numerous species they are usually dominated by one or two (Forcella *et al.*, 1992).

Weed competition

Farmers, even prior to biblical times, observed that the occurrence of weeds negatively influenced crop yields (Upadhyaya & Blackshaw, 2007). Quantitative data on the global effect of weeds are, however, very limited due to time-consuming experiments and large variations between growth seasons and regions. Despite difficulties to obtain valid data, Oreke (2006) estimated the yield loss potential due to weeds and actual losses for six major crops worldwide in 2001-03; namely wheat, rice, maize, potato, soybean and cotton. Maize had the highest loss potential due to weeds, 40 %, while wheat had the lowest, 23 %.
The mean actual crop losses due to weeds varied between 7 to 10 % in this study, despite that crop protection practices had been employed.

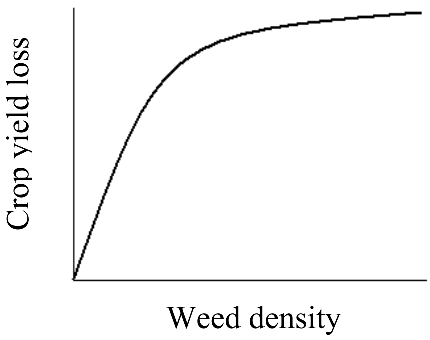

Figure 3. Relationship between weed density and crop yield loss.

Weeds limit the crop yield by competing for limited recourses such as water, nutrients and light. The extent of the competition is closely related to the number of weeds and their weight but precise relationships between crop yield losses and weed densities are not possible to obtain under field conditions (Aldrich & Kremer, 1997). Still, generally the relationship may be described by a rectangular hyperbola, see Figure 3 (Cousens, 1985). Weed competition at crop emergence or shortly thereafter causes greater yield losses than competition from weeds emerging later (Zimdahl, 2004). One explanation for this might be that weeds are then bigger and hence compete more for the available resources later in the season. However, crop yield losses have been seen even though weeds have been removed after that the crop, at an early stage, has been exposed to competition from weeds. The reason for this is not fully understood but one explanation could be that neighbouring weed plants trigger a shade avoidance response in the crop by changing the red to far-red light ratio (Liu *et al.*, 2009). Maize plants with shade avoidance response have reduced photosynthetic rates, reduced water and nutrient absorption and consequently a reduced grain yield compared with non-triggered plants (Clay *et al.*, 2009).

The weed competitiveness of crops is determined by two components; weed suppression ability (WSA) and weed tolerance (WT). WSA is the ability of a crop to reduce growth of weeds, while WT is the ability of a crop to produce high yields despite competition from weeds (Murphy *et al.*, 2008). WSA is a more desirable trait than WT because cultivars with high WSA reduce weed seed set and/or seed germination, with long term effects on the seed bank (Lemerle *et al.*, 2001; Murphy *et al.*, 2008).

There are of course also differences in competitiveness between different weed species. For example, grasses or grasslike weeds tend to reduce crop yield less than broad-leaved weeds. Still, several of the most difficult weeds to control are grasses (Aldrich & Kremer, 1997). From a farmers economy point of view the most important question is when the cost of a control measure is equal to the return of the yield increase. This level, referred to as the economic threshold has been studied in a number of crop and weed combinations (Cowbrough *et al.*, 2003; Jones & Medd, 2000).

Weeds may severely reduce growth of salix SRWC on agricultural land (Clay & Dixon, 1997; Danfors *et al.*, 1997; Parfitt *et al.*, 1992; Sage, 1999) and is one of the primary factors for a non-successful SRWC establishment (Labrecque *et al.*, 1994). A growth reduction of 90 % has been recorded by the end of the first year after planting compared with weed-free plots (Clay & Dixon, 1997). Studies have also shown that a poor establishment, caused by weed competition, could have a negative effect on the biomass production over the entire first rotation (Willebrand *et al.*, 1993) and possibly on the following rotations as well (Volk, 2002). Some weed species can cause more damage to the crops than others (Grime *et al.*, 1988; Sage, 1999). Handbooks for salix growers state that weeds such as couch grass (*Elytrigia repens* (L.) Desv. ex Nevski) and thistle (*Cirsum* spp.) could be really problematic if not controlled in a proper way (Abrahamson *et al.*, 2002; Gustafsson *et al.*, 2009). However, controlled experiments showing different weed species' ability to compete with salix are lacking.

To the author's knowledge no one has studied if clones of salix have different abilities to compete with weeds. However, several studies have shown genetic variation among cereal cultivars in their abilities to suppress weeds (Bertholdsson, 2005; Mason & Spaner, 2006; Wicks *et al.*, 1986). The differences have in some studies been large; e.g. Murphy *et al.* (2008) evaluated 63 wheat varieties and found that the best cultivars suppressed weed biomass with more than 500 % compared to the not so competitive cultivars. The reasons might be differences in leaf shape, stem angle and growth strategy (Jordan, 1993). Phytotoxins from crop residues or from living crop plants have also been shown to reduce weed growth. This phenomenon, called allelopathy, may explain weed suppressing variations within several crop species (Bertholdsson, 2004, 2005; Olofsdotter *et al.*, 2002) and is discussed in more detail later in this chapter. Some varieties of crops have in addition the ability to tolerate weeds better than others, i.e., they have relatively small yield losses in the presence of weeds (Callaway & Forcella, 1993; Jordan, 1993). An ideal crop type, which has all the desired traits for weed competition, is probably not possible to achieve through classical or other types of breeding. However, cultivars that have different competitive abilities suitable for specific management systems, weed floras, soil characteristics or climates might be attainable (Hoad *et al.*, 2008; Makela *et al.*, 2008).

Figure 4. A three months old salix plantation with a cutting density of approximately 13,000 cuttings per hectare. The plantation has been weeded several times. (Photo Inger Åhman)

The ability of a crop to compete with weeds is also affected by the plant/cutting/seed density. Salix managed as SRWC is usually planted with a cutting density of one to two cuttings per m^2 (Figure 4) which is low compared to e.g. cereals, with 150 to 450 seeds per m^2 (Korres & Froud-Williams, 2002). The density of germinating weed seeds in a plantation may be hundredfold higher (unpublished data) than the density of salix cuttings. Hence, the competition from weeds may be severe the first growing season.

According to Radosevich *et al.* (1997), factors that influence plant growth and competition between plants can be divided into two categories, resources and conditions. Resources can be consumed (water, light, carbon dioxid, oxygen and nutrients), while conditions (temperature, soil pH) cannot be consumed but do still affect the plant growth and thus competition. Competition may occur between species (interspecific) and between individuals of the same species (intraspecific) (Monaco *et al.*, 2002). However, due to the large distance between the salix plants in a plantation, intra specific competition is not likely to occur early in the establishment phase.

Plants in nature cannot respond separately to the competition resources (light, water, nutrients, carbon dioxide and oxygen) because they live in an environment where all of these elements are occurring at certain rates at a specific time. However, scientists commonly separate these resources to make their experiments and trials simpler to interpret (Zimdahl, 2004). In the following section plant responses to each of the resources are described in more detail.

Light

Competition for light occurs more or less in every cropping situation. The only exception is when plants are very young and small or when the distance between the plants is large (Radosevich *et al.*, 1997). Plants respond not only to the quantity of light but also to the spectral quality of light, to changes or fluctuations in the light environments, and to transient light (sunflecks) (Holt, 1995). The plant canopy architecture (Figure 5) determines the competition for light between the crop and the weeds and hence influences the crop yield. Some of the most important properties decisive for the outcome of the competition are LAI, angel of leaf inclination and plant height (Zimdahl, 2007). Liu *et al.* (2009) proposed that the red to far-red light ratio originating from neighbouring plants acts like an early trigger signal for plant competition and thus the start of a shade avoidance response. The shade avoidance includes molecular, physiological and morphological changes of the plant such as elongation of internodes, increase in plant height, leaf area and changes in chlorophyll concentration (Liu *et al.*, 2009).

Figure 5. Salix canopy. The shoots are two years old on three years old stools. (Photo Johannes Albertsson)

Water

Plants constitute a link between the water in the soil and the atmosphere. Lack of water is usually considered to be the primary element limiting crop production if irrigation is not applied (Zimdahl, 2007). The amount of water available for plant growth is dependent on the amount of seasonal water supply, plant morphology and root development, and plant physiology such as the water use efficiency (g carbon dioxide fixed/g water used) of the species (Radosevich *et al.*, 1997). Several plant species exposed to water deficiency have been found to decrease their stem height, root length and total leaf area and increase their root:shoot ratio. In conditions with severe water stress plants may arrest their photosynthesis, have disturbance in their metabolism, and finally die (Shao *et al.*, 2008). In biomass salix, clonal differences have been found in water use efficiency both when a natural salix clone was compared with a commercial clone (Weih, 2001) and when different commercial salix clones were compared (Wikberg & Ögren, 2007).

Nutrients

Nutrients may be divided into three groups: (1) Macronutrients, (2) micronutrients and (3) beneficial elements. The macronutrients consist of carbon, oxygen, hydrogen, nitrogen, potassium, calcium, phosphorous, magnesium and sulfur and are usually found in concentrations greater than 1 g/kg dry weight in plants. The micronutrients consist of iron, chlorine, copper, manganese, zinc, molybdenum and boron and are typically present in concentrations less than 100 mg/kg dry weight. The beneficial elements such as sodium and cobalt could promote growth and may be essential for some plants but not to all (Pilon-Smits *et al.*, 2009). If some of the above elements are lacking or exist in too low concentrations plants may not be able to complete their life cycle (Radosevich *et al.*, 1997). Weeds generally have a large nutrient requirement and will absorb about the same amount or more than many crops. Nitrogen is usually the first nutrient to become a limiting factor in weed-crop competition and if fertilization is applied weeds will, in some cases, gain more than the crop (Zimdahl, 2007; Zimdahl, 2004). This was shown in a study where 23 weed species and two crops, wheat and canola, were given six different rates of nitrogen. All species increased their shoot and root growth with increasing nitrogen rate. However, 15 weed species increased their shoot biomass and eight increased their root biomass more than wheat. Ten weeds had shoot biomass increases similar to canola and five increased their root biomass more than canola (Blackshaw *et al.*, 2003). A similar study, where different phosphorus rates were applied, showed similar results (Blackshaw *et al.*, 2004).

Competitive traits in plants

It is obvious that plants with a higher plant growth rate, a taller plant height and/or greater lateral shoot extension than neighboring plants have a competitive advantage. Aarssen (1989) proposed mechanistic and ecological relationships between different attributes of competitive abilities in plants (Figure 6). Traits such as low tolerance to water deficiency and low tolerance to mineral deficiency may have a large impact in salix-weed competition if the initial weed control has been insufficient in SRWC plantations. However, if the weed control has been managed well initially the ability of the established salix plants to deplete water, nutrients and light will probably disfavor the weeds. For the same reasons other traits such as greater ability to attract pollinators or greater ability to attract dispersal agents will probably not affect the salix-weed competition in SRWC.

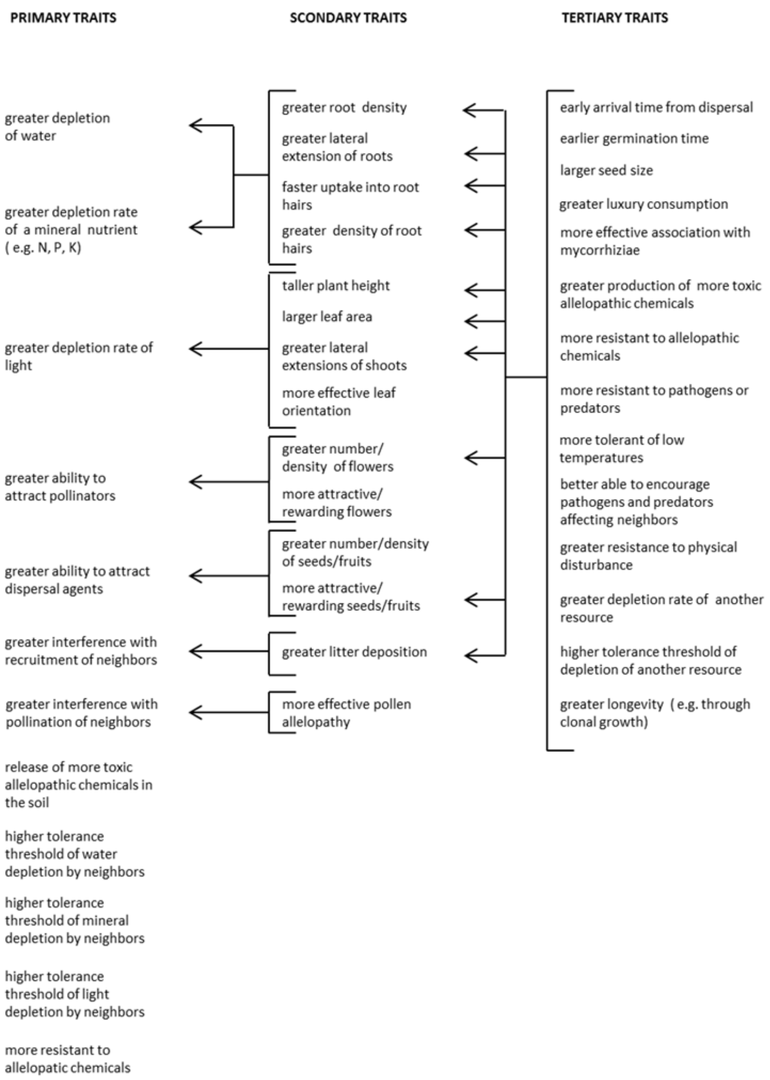

Figure 6. A proposed relationship among attributes of competitive ability in plants. (From Aarssen, 1989; reproduced with permission)

Weed control

The annual energy harvest per hectare of salix SRWC is lower that of certain annual bioenergy crops (Börjesson, 2007). However, the amount of energy that is put into the salix SRWC is lower since the harvest intervals are 3-4 years, no insecticides or fungicides are used, plantation is done once each 20-25 years and weeding is normally only needed at the first and second year after establishment and possibly after harvest (Börjesson, 2007). The economic benefit for the grower is dependent on that this system is kept as a low input system. Increasing the number of weeding occasions or investment in expensive new weeding equipment might reduce the economic return for the grower. Hence, the possibilities to apply labour intensive and/or new ways of controlling the weeds are to a certain extent limited. Below, different weed control methods are presented.

Mechanical weeding

In the beginning of the 1990s mechanical weeding equipment such as row cultivators (Figure 7) and multi-row rototillers were tested in five Swedish salix plantations with locations differing in both soil properties and weed composition. Common for all these machines were that they could not weed between the plants in the row. Since the weeds not removed by the mechanical weeding compete with the salix plants, a side-delivery rake was also tested to remove the weeds within the row. However, the salix shoots then became heavily damaged (Danfors, 1991a, b). Danfors (1991a) concluded that new weeding methods must be developed before it is possible to decrease the use of herbicides in salix SRWC. In organic farming of other crops several techniques such as finger weeders, torsion weeders and weed blowers have been developed during the last decades to remove weeds between and within the rows (Van der Weide *et al.*, 2008). To the author's knowledge none of these techniques have been tested for weeding purposes in salix. Experiments should be performed where capacity, efficiency and economy are evaluated and compared with conventional weed management by herbicides. Several research groups are also currently working with digital sensors and vision systems that in the near future could facilitate mechanical weeding by distinguishing weeds from crops (Van der Weide *et al.*, 2008). However, these techniques must be developed further to be adopted for salix weed management.

Figure 7. Row cultivator used for mechanical weeding in salix plantations. (Photo Johannes Albertsson)

Herbicides

There are several herbicides that are permitted to be used in Swedish salix plantations. Roundup (glyphosate) is usually sprayed in the field the autumn before planting, after harvest of the previous crop, to manage weeds such as couch grass and thistles (Gustafsson *et al.*, 2009). At planting or soon thereafter one of the soil herbicides Bacara (flurtamone and diflufenican) or Cougar (isoproturon and diflufenican) is usually sprayed to manage broad-leaved weeds and a few grass weeds. However, these herbicides will not have any effect on couch grass, which is one of the most severe weeds in salix. There are also two other soil herbicides that are permitted for use in salix SRWC, Kerb flo 400 (propyzamide) and Fenix (aclonifen). Herbicides are also permitted for spraying in growing salix; Focus Ultra (cycloxydim) against grasses and Matrigon 72 SG (clopyralid) against certain broad-leaved weeds (Gustafsson *et al.*, 2009; Kemikalieinspektionen, 2012). The herbicides are usually sprayed on the entire plantation with a boom sprayer, but there are also several other options for applying the herbicide. One option is to use a band sprayer which applies the herbicide either between or within the double row, depending on which herbicide is used. A band sprayer decreases the amount of herbicide per hectare when compared with a boom sprayer and, if used only within the double rows, it can be complemented with mechanical weed control such as a row cultivator. Another alternative is to use a pesticide wiper between the double rows. The pesticide wiper is not spraying the herbicide. Instead a fabric, soaked with an herbicide, is touching the weeds. The advantage of this method is lower amount of herbicide needed compared with spraying (Danfors, 1991a). Studies are on-going in Denmark to evaluate new herbicides for salix SRWC (Landbrugsinfo, 2012)

Cover crops

Cover crops alone or in combination with mechanical weeding and/or herbicides have been studied for a long time as a way to suppress weeds in agricultural production systems (Mennan *et al.*, 2006; Teasdale, 1996). Cover crops reduce weed density, number of weed species that emerge, and total weed dry biomass when compared with bare soil systems (Mennan *et al.*, 2006). Other advantages of cover crops are reduced runoff and soil erosion, improved infiltration, soil moisture retention and increase in soil organic matter; and nitrogen fixation if the cover crop is a legume (Mennan *et al.*, 2009; Teasdale, 1996). However, trees and woody crops have been shown to suffer from competition with living cover crops such as ryegrass (*Lolium multiflorum* L.), tall fescue, (*Festuca arundinacea* Schreb), crimson clover (*Trifolium incarnatum* L.) and chinese bush clover (*Lespedeza cuneata* (Dumont) G. Don.) in North America (Cogliastro *et al.*, 1990; Malik *et al.*, 2001). Biomass reduction of more than 40 % has been reported for sweetgum (*Liquidambar styraciflua* L.) planted as SRWC (Malik *et al.*, 2001). Studies have also been conducted with salix SRWC and living cover crops. In a study made in the USA, plots with Dutch white clover (*Trifolium repens* L.) or buckwheat (*Fagopyrum esculentum* Moench) significantly decreased salix production compared with hand weeded or herbicide treated plots (Lawrence Smart, pers. comm.). However, Moukoumi (2012) showed that salix biomass increased when salix was planted on low productive land together with *Caragana arborescens* Lam.

Studies have also been made with cover crops that have been killed or mowed at planting or shortly thereafter. Volk (2002) used rye (*Secale cereale* L.) as a cover crop to reduce soil erosion in the establishment phase of salix and poplar plantations. The rye was sown the autumn prior to planting and killed with herbicides or mowed the following spring. However, in this experiment rye residues alone did not result in an acceptable weed control because the biomass production was significantly lower than with the other weed management methods. Research has also been conducted with Dutch white clover. White clover sown one week after planting and mechanically killed three weeks later was found to increase the foliar nitrogen concentration of four months old salix plants without compromising aboveground biomass (Arevalo *et al.*, 2005).

Allelopathy

Allelopathy is defined as any direct or indirect effect on one plant (or microorganism) on another mediated through the production of chemical compounds that escape to the environment (Rice, 1974). Allelopathy is considered to be a promising component of biological control measures and could be used as one way to reduce the use herbicides in agricultural systems, especially those including cereals (Belz, 2007; Bertholdsson, 2005). Allelopathic abilities in relation to weeds have been found in several crops. Most attention has been paid to rice, wheat, barley and sorghum but a lot of other species have also been studied (Belz, 2007). Biochemicals responsible for the allelopathic effect, called allelochemicals, have been identified as simple phenolic acids, quinones, mono- and sesquiterpenes and flavonoids, among others (Macías *et al.*, 2007). To the best of my knowledge, no comprehensive research has been conducted to investigate if salix is affected by allelopatic substances from weeds or if salix release substances that affect weeds.

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