Impact and Control of Weeds in Biomass Willow Clones

Johannes Albertsson
Faculty of Landscape Architecture, Horticulture and Crop Production Science
Department of Plant Breeding
Alnarp

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Cover: The effect of no weed control on willow growth five months after planting.
(photo: J. Albertsson)

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Abstract

Willow (*Salix* spp.) grown on arable land as short-rotation coppice (SRC) produces renewable energy in the form of woody biomass. This perennial crop has a high ratio of energy output to input and a good environmental profile. However, weed control is mostly dependent on herbicide use. Therefore, this thesis examined the possibility to further improve the environmental profile of willow SRC by omitting the use of herbicides during establishment. If genetic variation in willow competitiveness to weeds exists, more weed-competitive cultivars might be bred. However, in a study performed at three different sites in southern Sweden, only small differences were found between 12 clones tested for their ability to compete with weeds. Depending on site, weeds reduced stem biomass yield by between 68 and 94% after the first harvest cycle and increased plant mortality at all sites. The practice of cutting the first-year shoots either reduced or did not affect the ability of the willow plants to compete with weeds. Hence, this measure should be omitted provided this is compatible with other management actions. A study on the efficiency and economic returns from four different non-chemical weed control methods during willow establishment of two different cultivars showed that it is possible to establish an agriculturally and economically viable willow plantation without the use of herbicides. The most promising non-chemical weed control method involved repeated passes with a row crop cultivator equipped with torsion weeders, while the least promising method was a living clover cover crop.

Yield data were obtained from the weed competition study for the willow SRC clones when subjected to thorough weeding. Cultivars Sven and Tordis were found to be among the highest yielding at all three sites, although site x clone interactions were found. However, these two clones did not yield significantly more than two more recently bred clones, Klara and Linnea, at any site.

Biomass estimates from destructive and non-destructive methods have been shown to differ and the magnitude of these differences may depend on clone. A study with six different clones showed that assumptions regarding harvest height and dry matter content of clones might explain part of these differences.

Keywords: biomass estimations, biomass yield, clones, growth reduction, *Salix*, weed, weed competition, weed control

Author's address: Johannes Albertsson, SLU, Department of Plant Breeding,
P.O. Box 101, SE-230 53 Alnarp, Sweden
E-mail: johannes.albertsson@slu.se

Dedication

To my family

The pessimist complains about the wind; the optimist expects it to change; the realist adjusts the sails

William Arthur Ward

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Albertsson, J., Hansson, D., Bertholdsson, N-O. & Åhman I. (2014). Site-related set-back by weeds on the establishment of 12 biomass willow clones. *Weed Research,* 54(4), 398-407.

II Albertsson, J., Verwijst, T., Hansson, D., Bertholdsson, N-O. & Åhman I. (2014). Effects of competition between short-rotation willow and weeds on performance of different clones and associated weed flora during the first harvest cycle. *Biomass & Bioenergy*, DOI: 10.1016/j.biombioe.2014.08.003

III Albertsson, J., Rosenqvist, H., Verwijst, T., Hansson, D., Bertholdsson, N-O. & Åhman I. Effects of mechanical weed control or cover crop on growth and economic viability of two short-rotation willow cultivars. (Manuscript).

IV Verwijst, T. & Albertsson, J. Assumptions made in protocols for shoot biomass estimation of short-rotation willow clones underlie differences in results between destructive and non-destructive methods. (Manuscript).

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The contribution of Johannes Albertsson to the papers included in this thesis was as follows:

I Planned the study in collaboration with the co-authors, performed the experimental work, evaluated the data and wrote the main part of the manuscript.

II Planned the study in collaboration with the co-authors, performed the experimental work, evaluated the data and wrote the main part of the manuscript.

III Planned the study in collaboration with the co-authors, performed the experimental work, evaluated the data and wrote the main part of the manuscript. The economic calculations were performed by a co-author.

IV Contributed significantly to the data collection, evaluation of the data and writing of the manuscript.

Abbreviations

DM	dry matter
DMC	dry matter content
GWh	gigawatt hour
IPM	integrated pest management
MWh	megawatt hour
SRC	short-rotation coppice
TWh	terawatt hour

1 Willow as a bioenergy crop

1.1 Background

Emissions of greenhouse gases into the atmosphere, mainly from combusting of fossil fuels, have already increased the global air temperature (Hansen *et al.*, 2010) and will continue to do so in the foreseeable future (Peters *et al.*, 2013). This global warming is predicted to influence precipitation patterns and increase the frequency of extreme weather events, among other effects (Wheeler & von Braun, 2013), and will thereby substantially affect businesses such as the food industry. To mitigate these climate changes, emissions of greenhouse gases need to be reduced significantly (Peters *et al.*, 2013). Efforts aimed at lowering energy consumption and replacing fossil energy sources with renewable forms are ongoing. As one example of this, the Swedish government has stated that by the end of 2020, more than 50% of the energy used within the country should come from renewable sources. Furthermore, it has expressed an ambition that Sweden should have no net emission of greenhouse gases by 2050 (Swedish Government, 2009). The roadmap to fulfil the latter goal is not finalised as yet. However, one of the domestic renewable energy sources that could be part of this transition is woody biomass from willow (*Salix* spp.) grown on arable land as short-rotation coppice (SRC).

1.2 Origin and history

The genus *Salix* (willow) belongs to the Salicaceae family together with *Populus* (poplar, aspen and cottonwood). The number of species of the genus *Salix* reported in the literature ranges between 330 and 500, since the genus is complex (Argus, 1997). There are huge variations in the growth form of willow, ranging from tall trees to bushes and to dwarf plants (Karp *et al.*, 2011). It is the bushy form that regrows after cutback (coppice) which is used for short-rotation production of wood biomass. Willows are primarily native to the northern hemisphere, but there are a few species native to the southern hemisphere (Kuzovkina *et al.*, 2008). Most willow species are diploid, but ploidy levels can reach up to dodecaploid. Willows are usually dioecious, meaning that male and female flowers occur on separate individuals (Kuzovkina *et al.*, 2008). However, individuals with flowers that have both male and female parts can be found (Stig Larsson, pers. comm. 2014).

Willows have been used by man throughout history as materials for traps, fences, ropes and furniture. Baskets made from willow shoots are considered to be among the first articles manufactured by humans (Kuzovkina *et al.*, 2008). These traditional uses of willow have declined over time, but new uses have emerged. In the 1960s, the Swedish paper and pulp industry predicted a shortage of raw material (Verwijst *et al.*, 2013). Therefore, research was initiated to investigate whether willows grown as SRC could become a viable complement to other sources. However, the need for such short fibres for pulp was never realised and instead the oil crisis in the 1970s justified the development of willow SRC production as a domestic and renewable source of energy.

The first commercial breeding programme of willow SRC was initiated by the Swedish company Svalöf AB in 1987 (Larsson, 1998) and is still ongoing as part of plant breeding activities within the agricultural division of Lantmännen. Since 2011, the company European Willow Breeding AB has also been breeding willow in Sweden. The breeding work performed over the years has been successful. New cultivars can yield up to 60% more biomass than plant material available at the beginning of the breeding phase (Aronsson *et al.*, 2008). Species hybrids with *Salix viminalis* L. in their background dominate the Swedish cultivars. Species commonly introgressed with *S. viminalis* are *Salix Schwerinii* E. Wolf, *Salix triandra* L., *Salix aegyptiaca* L., *Salix eriocephala* Michx. and *Salix dasyclados* Wimm. There are also cultivars of pure *S. dasyclados*. Breeding of willow SRC has been established in the UK, USA and Canada too, with somewhat different germplasm (Kuzovkina *et al.*, 2008; Smart & Cameron, 2008). Willow SRC is propagated vegetatively and thus each cultivar is a clone.

1.3 Cultivation

Cultivation of willow SRC became commercial in the late 1980s (Nordh, 2005). The cultivation system is fully mechanised and willow SRC was grown on 12,000 hectares in Sweden in 2012 (Swedish Board of Agriculture, 2012). Willow can be grown successfully on a variety of soil types, including sandy, clayey, silty and organic soils, if the management is adapted to the local conditions (Ledin, 1996). Willow SRC is a perennial cropping system with an expected productive life time of approximately 20 years. Willow shoots are usually harvested every 3-4 years (one harvest cycle), but cycles can be longer or shorter depending on willow growth, harvesting conditions and demand for wood chips. Since new shoots sprout from the cut stools there is no need for replanting after harvest (Swedish Board of Agriculture, 2012; Gustafsson *et al.*, 2007).

In the autumn before a willow SRC plantation is established, the field is sprayed with a broad spectrum herbicide, followed by ploughing a couple of weeks later. In the following spring the field is harrowed and dormant unrooted stem cuttings, approximately 18 cm long, are planted in a double row system. The spacing between the double rows in the current system is 1.5 m and the spacing between rows within the double rows is 0.75 m. A spacing of 0.60-0.70 m between plants within the row gives a planting density of approximately 13,000 plants ha^{-1}. The recommended practice is to apply a pre-emergence herbicide shortly after planting to control weeds. This should be followed by additional mechanical or chemical weed control measures later in the season. If the weed control has been efficient and the willow plants have successfully established, there is usually no need for weed control in subsequent seasons (Swedish Board of Agriculture, 2012; Gustafsson *et al.*, 2007). A common practice is to cut back the willow shoots after the first growing season in order to increase the number of shoots per plant and to facilitate fertilisation and additional weeding during the second growing season. However, the need for this practice has been questioned (Verwijst & Nordh, 2010) and it is currently not recommended in Sweden (Swedish Board of Agriculture, 2012).

The willow plantation should be fertilised with nitrogen during the first harvest cycle and already during the first growing season, but only if the weeding has been successful (Swedish Board of Agriculture, 2012). For the subsequent harvest cycles, a recently published Swedish study recommends the following: 60 kg N ha^{-1} in the spring after each harvest, 100 kg N ha^{-1} in the spring one year after harvest and 60 kg N ha^{-1} in the spring two years after harvest (Aronsson *et al.*, 2014).

Harvesting usually takes place during winter, when the demand for wood fuel is high. There are currently three harvesting systems available for use in Sweden. The most common one is a harvester that cuts the shoots and processes them into wood chips in a single pass (direct chip harvesting). The wood chips produced are then usually transported wet to a heat plant. The second system is a harvester that cuts and compresses the shoots into round bales (Biobaler), while the third system cuts entire shoots (Stemster). The latter two systems enable storage (drying) of the harvested willow shoots outdoors for use mainly in furnaces without flue gas condensation.

1.4 Environmental profile

Willow SRC has probably the best environmental profile of any energy crop grown on arable land in Sweden. One of the reasons is that breeding for resistance to pests and diseases was one of the main breeding goals when the development of this crop was initiated (Larsson, 1998; Åhman & Larsson, 1994). Consequently, no insecticides and fungicides are used in Swedish willow SRC (Åhman, 2001). Another reason is that herbicides are commonly only used during the establishment and termination phases of a plantation. This means that herbicides are generally only applied during 2-3 years out of 20. The energy output:input ratio for willow SRC is also high compared with that of other bioenergy crops and varies between 11 and 24 depending on system boundaries and assumptions (Börjesson & Tufvesson, 2011; Rowe *et al.*, 2009). Willow SRC plantations have also been found to be inhabited by more plant species (Augustson *et al.*, 2006) and bird species (Sage *et al.*, 2006) than conventional arable fields. Other studies have shown that the abundance of earthworms and the diversity of carabids increase when conventional arable fields are converted to SRC plantations (Baum *et al.*, 2009). This increase is possibly due to the high litter supply and the fact that SRC plantations are not tilled during most of their productive years. Other advantages are that willow SRC plantations result in a higher concentration of carbon in the topsoil and subsoil and a lower cadmium concentration in the topsoil compared with annual crops in adjacent fields (Dimitriou *et al.*, 2012).

1.5 Willow in the Swedish energy system

The annual energy contribution from Swedish willow SRC plantations to the energy system is between 200 and 300 GWh (Aronsson *et al.*, 2008). This corresponds to less than 0.1% of Sweden's total annual energy consumption, which was 379 TWh in 2011 (Swedish Energy Agency, 2013). The contributions of other renewable energy sources in 2011 were: biomass (including willow) 115 TWh, hydro power 67 TWh and wind power 6 TWh

(Swedish Energy Agency, 2013). Photovoltaic cells (solar cells) contribute approximately 40 GWh year^{-1} (Swedish Energy Agency, 2014)

The mean annual estimated yield from commercial Swedish willow SRC plantations is below 5 t ha^{-1} dry matter (DM) (Mola-Yudego & Aronsson, 2008). However, plantations of bred cultivars in which strict weed control and a good fertilisation regime have been applied can annually yield above 10 t ha^{-1} DM (Larsson & Lindegaard, 2003). The harvested biomass then corresponds to approximately 44 MWh ha^{-1}.

Sweden has potentially 300,000-500,000 ha arable land available for SRC (Rytter, 2012), and also has the cultivation techniques and the infrastructure, such as well-developed district heating systems, to allow for increased biomass production from willow SRC. However, the current trend in Sweden is for a decreasing area of willow SRC, due to very few new plantations being established and to existing plantations being terminated prematurely. Economic uncertainties in combination with a perennial crop and the dependence on specialist equipment might be some of the reasons why farmers generally have little interest in investing in new willow plantations (Paulrud & Laitila, 2007). The reason why some growers have decided to terminate their willow plantations before their expected economic life span is probably to some extent over optimistic market expectations in the 1990s. However, the most important factors, according to a Swedish survey, are agronomic, especially low willow production due to competition from weeds (Helby *et al.*, 2006).

2 Weed competition

2.1 Weed characteristics

There are numerous definitions of what a weed is, examples being ‘a plant where we do not want it’, ‘higher plants which are a nuisance’, and ‘any plant that is objectionable or interferes with the activities or welfare of man’ (Zimdahl, 2007). While there is no universal definition on which all agree, all the definitions aim to describe weeds as plants that are not wanted. Consequently, farmers apply different measures to reduce the viability of these weeds. Since choice of control measure is partly dependent on weed species, identification of the weeds usually occurring in the field is important. To facilitate the decision about which control measure to apply, weeds can be classified according to their life cycle (*annuals*, *biennials* or *perennials*), their economic importance or if they are *monocotyledons* or *dicotyledons* (Lundkvist & Verwijst, 2011; Radosevich *et al.*, 1997). Sutherland (2004) concluded that life span was the most significant life history trait that distinguished weeds from non-weeds and that weeds in general were more likely to be annuals or biennials and less likely to be perennials than non-weeds. However, Lundkvist & Verwijst (2011) pointed out that weeds occurring in a certain crop generally have the same life span as the crop. Hence, a number of the weeds in willow SRC can be expected to be perennials. There are only approximately 250 species in the world that are sufficiently troublesome to be called weeds (Cobb & Reade, 2010). However, depending on crop, these are responsible for crop losses of 7.5-10.5%, despite weed control measures having been applied (Oerke, 2006).

2.2 Competition

Plants growing close to each other interact and this *plant interference* can be positive, negative or neutral for a particular plant (Radosevich *et al.*, 1997). Interactions that have a negative effect can be divided into *competition*, where all individuals are depressed, *amensalism*, where some individuals are depressed while some are not affected at all, and *parasitism*, where some individuals are depressed while others benefit (Radosevich *et al.*, 1997). However, the terminology used by weed scientists is not always consistent. For example, Håkansson (2003) defines competition as ‘any interaction between plants in a stand that causes a weaker growth of all or some of the individuals in this stand in relation to their growth as solitary individuals under comparable external conditions’. Therefore, this is a broader definition of competition which includes all negative interactions presented above. Since it is difficult to distinguish between the different mechanisms underlying plant interactions under field conditions, the Håkansson definition of competition is used in this thesis. In the context of crop-weed interactions, the aim of weed control strategies is to reduce the competition effect from the weeds and thereby ensure that as much of the resources as possible are made available for the crop. However, weeds that are not sufficiently suppressed or killed by the control measures will still compete with the crop for light, nutrients and water. Plants can also produce chemicals that inhibit the growth of other plant species, a phenomenon known as *allelopathy* (Tesio & Ferrero, 2010). Apart from the interactions described above, plants can also interact via a shared enemy such as a herbivore (Connell, 1990).

2.3 Competitive ability

A cultivar’s weed competitive ability is determined by: 1) its weed suppressing ability, *i.e.* the ability of a cultivar to reduce weed growth and 2) its weed tolerance, *i.e.* the ability of a cultivar to produce high yields despite competition from weeds (Murphy *et al.*, 2008). An ideal cultivar, in the context of weed competition, would suppress weeds significantly and would also tolerate weeds. However, while studies in wheat have shown that these two traits are broadly correlated (Lemerle *et al.*, 1996), they are not always present in the same cultivar (Lemerle *et al.*, 2001). Weed suppressing ability is probably the most desirable trait of the two, since this trait decreases the viability of weeds and thereby negatively affects the production of weed seeds (Murphy *et al.*, 2008; Lemerle *et al.*, 2001).

Traits such as plant height, shoot angle, leaf morphology, early vigour and allelopathic activity have been shown to be genetic traits that affect crop competitive ability (Bertholdsson, 2005; Lemerle *et al.*, 2001). Murphy *et al.* (2008) found that genetic differences between wheat cultivars affected their weed suppressing ability substantially, with the mean weed weight in the five best cultivars being 121 kg ha^{-1}, while it was 815 kg ha^{-1} for the bottom five cultivars. Differences between cultivars have also been found in barley (Bertholdsson, 2005; Christensen, 1995) and rice (Olofsdotter *et al.*, 1999). Although most of the studies reporting differences in weed competitive ability between cultivars have been performed with cereals, genetic differences have also been found in soybean (Vollmann *et al.*, 2010) and maize (Roggenkamp *et al.*, 2000). However, the two latter studies concluded that the differences were too small to be of any importance for weed control purposes. Other factors that might influence the ability of a crop to compete with weeds are crop plant density, the spatial arrangement and the relative emergence time of the weed and the crop (Weiner *et al.*, 2001; Aldrich, 1987). Studies have shown that increased crop plant density increases the ability of the crop to suppress weeds (Weiner *et al.*, 2001; Lemerle *et al.*, 1996). However, if the crop plant density is high, intraspecific competition can affect crop yield negatively (Weiner *et al.*, 2001).

2.4 Ability of willow to compete with weeds

In nature, the species of willow used for breeding SRC cultivars are found invading river banks and other land with bare, moist soil (Isebrands & Richardson, 2014). At such sites, there are few other plant species present initially. From this, it can be deduced that the competitive ability of willow is comparatively low. This combined with the low plant density (1.3 plants m^{-2}) compared with other arable crops are probably the main factors explaining the severe weed problems experienced in willow SRC. The low plant density limits the possibility for the willow plants to suppress weeds during the first season (Fig. 1), at which time they are very sensitive to weed competition (Clay & Dixon, 1995; Labrecque *et al.*, 1994). The plant density of emerging weeds within a willow plantation can be more than 100 plants m^{-2} (Albertsson, unpublished). Some of these weeds typically germinate only a few days after seedbed preparation, while it usually takes more than a week after planting until the first buds of the willow plants burst. Consequently, if weeds are not controlled properly, they will outnumber the willow plants and probably suppress the willow plants more than the willow suppresses the weeds (Fig. 1).

Weed tolerance is therefore probably a more important competitive trait in willow than weed suppressing ability during the establishment phase. However, in subsequent seasons, when full canopy closure is obtained and the willow plants have developed a proper root system, the opposite might be true.

Willow SRC clones have been shown to differ in time of bud burst (Rönnberg-Wästljung, 2001), number of shoots per stem (Tharakan *et al.*, 2005), leaf morphology (Robinson *et al.*, 2004), canopy structure (Karp *et al.*, 2011), growth habit (Weih & Nordh, 2002) and drought resistance (Wikberg & Ögren, 2007). All these traits might affect their weed competitive ability. However, only a few studies have quantified the effect of weeds during willow establishment (Clay & Dixon, 1995; Labrecque *et al.*, 1994) and during subsequent seasons (Sage, 1999; Clay & Dixon, 1997) and to our knowledge no previous study has investigated whether willow clones differ in their ability to compete with weeds.

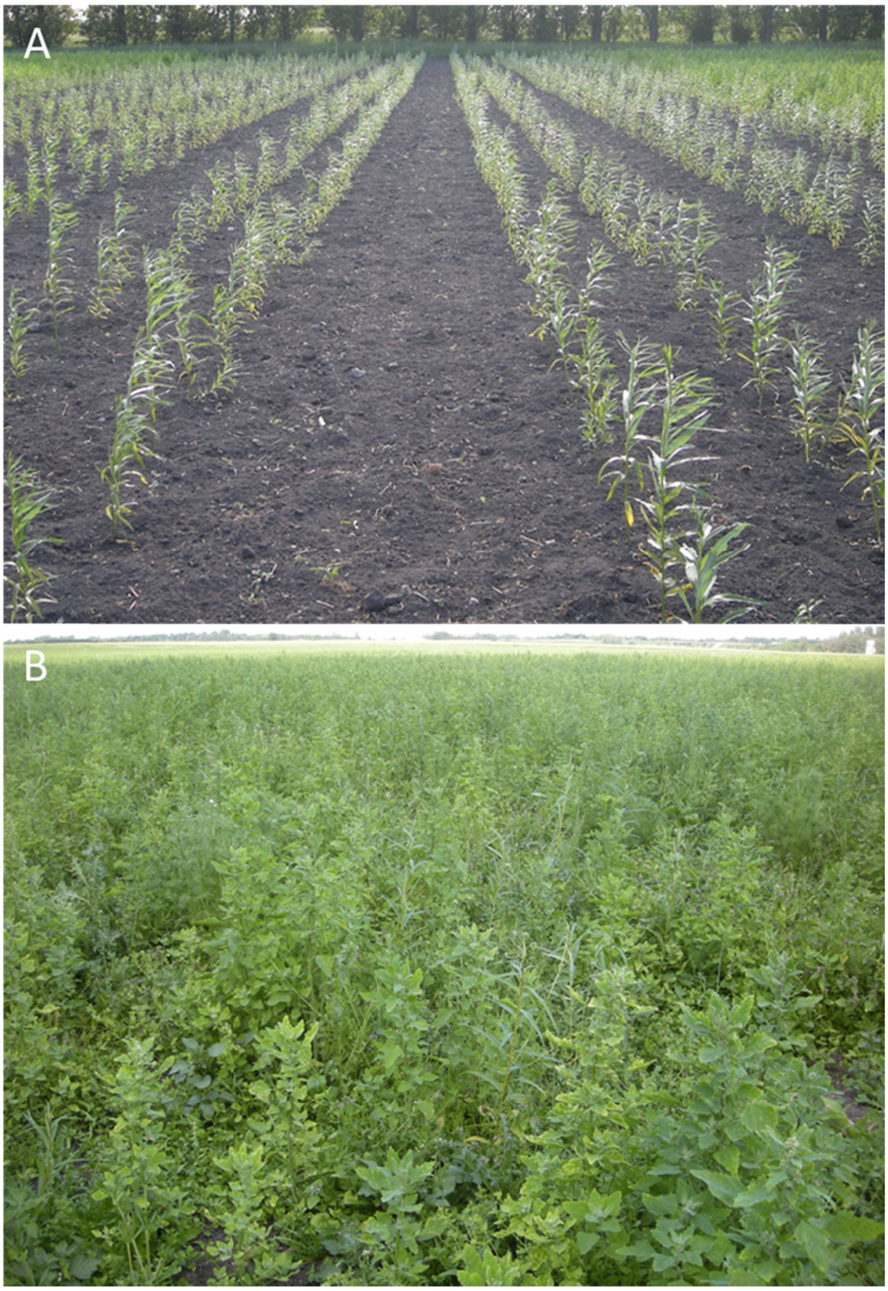

Figure 1. Images of a willow plantation 10 weeks after planting (site P). A) Plots with weeds removed mechanically and by repeated hand hoeing and B) plots with no weed control. Photo: I. Åhman.

3 Weed control

3.1 Weed control measures

Manual weed control has probably been performed as long as humans have been cultivating plants (Cobb & Reade, 2010). At present, farmers rely heavily on herbicides to control weeds (Cobb & Reade, 2010), but other curative control methods such as mechanical weeding and cultural methods such as cover crops are also used (Bàrberi, 2002). According to EU Directive 2009/128/EC (The European Parliament and the Council of the European Union, 2009) all professional growers in the European Union must follow the general principles of integrated pest management (IPM). These include use of non-chemical and preventative (*e.g.* crop rotation and competitive cultivars) measures while pesticides should only be used when other methods are insufficient. Since IPM combines different methods to control weeds, it has the potential to reduce the environmental impact and also reduce the selection pressure for resistance to herbicides (Harker & O'Donovan, 2013). The importance of finding alternative methods or combination of methods has also increased due to the fact that the number of herbicides permitted for use in the European Union is decreasing. Besides, no herbicide with a major new mode of action has been introduced on the market since 1990 (Duke, 2012).

3.2 Herbicides

Synthetic herbicides first appeared in the 1930s (Cobb & Reade, 2010). Control by herbicides is usually considered to be more efficient than that achieved by other weed control methods, since herbicides can be applied during a wider range of soil conditions and can easily control weeds within a crop row if they are selective. Moreover, the effects of herbicide treatment can persist for weeks in the soil, whereas *e.g.* a mechanical weed control measure can in fact favour further weed emergence, or damaged weeds can recover (Bàrberi, 2002). Besides being efficient, herbicides are usually also comparatively cheap to use. The following herbicides are permitted for use in Swedish willow plantations: Bacara (flurtamone and diflufenican), Matrigon 72 SG (clopyralid), Focus Ultra (cycloxydim), Kerb flo 400 (propyzamide) and Fenix (aclonifen) (Swedish Chemicals Agency, 2014). In the autumn prior to establishment and at the termination of a willow plantation the field is usually sprayed with Roundup (glyphosate).

3.3 Mechanical weeding

Weeds that grow between crop rows can in most cases be controlled sufficiently with mechanical weed control methods, such as row crop cultivators or rototillers, if the timing and the number of treatments are right (Upadhyaya & Blackshaw, 2007). Weeds within crop rows are more difficult to control mechanically. However, there are several intra-row mechanical methods. One is to harrow the whole field, *i.e.* both crop and weeds are treated. Another is to use torsion weeders, which use flexible tines that are tilted towards each other and uproot weeds near the crop (Fig. 2). A third method is finger weeders (Fig. 2), which have rubber fingers that grip from the side around the plant and thereby uproot weeds within the row (Van der Weide *et al.*, 2008; Upadhyaya & Blackshaw, 2007). Both torsion weeders and finger weeders can easily be mounted on an inter-row cultivator and have been shown to weed effectively in several row crops (Ascard & Fogelberg, 2008; Upadhyaya & Blackshaw, 2007). However, the result of the mechanical intra-row methods is highly dependent on the timing and on the crop plants being larger and/or better anchored than the weeds (Van der Weide *et al.*, 2008).

The present Swedish recommendation is to use a combination of herbicides and mechanical weeding during the establishment of a willow plantation (Swedish Board of Agriculture, 2012). However, only a few previous studies have investigated the efficiency of mechanical weed control methods in willow SRC. One of these studies was performed in the beginning of the 1990s and concluded that mechanical intra-row weeding had to be developed for willow SRC, since weeds in the row competed strongly with the willow plants (Danfors, 1991). To our knowledge no such development has taken place.

Figure 2. A) Torsion weeder and B) finger weeder. Photo: J. Ascard.

3.4 Cover crops

The term *cover crop* usually refers to plants that are grown for other reasons than as a cash crop (Upadhyaya & Blackshaw, 2007). They can be grown together with the main crop during the season, sometimes referred to as a living cover crop (Upadhyaya & Blackshaw, 2007) or living mulch (Hartwig & Ammon, 2002), or in rotations during times when no main crop is growing (Upadhyaya & Blackshaw, 2007). If grown in between two main crops, the cover crop is commonly killed before the next main crop is sown or planted (Hartwig & Ammon, 2002).

One reason to grow cover crops is that they suppress weeds. The weed suppressing effect is achieved by rapid occupation of areas that would otherwise be occupied by weeds. Consequently, cover crops compete with the emerging and growing weeds for resources. Besides competition for resources both living cover crops and cover crop residues have been shown to inhibit weed seed germination and weed establishment (Upadhyaya & Blackshaw, 2007; Teasdale & Daughtry, 1993). However, the cover crop residues have a lower suppressive effect than a living cover crop. Other positive effects of cover crops are reduction of water runoff and soil erosion, improved soil structure and water-holding capacity, and addition of organic matter (Hartwig & Ammon, 2002). Furthermore, if the cover crop is a legume, nitrogen can be fixed from the atmosphere, which may reduce the need for nitrogen fertiliser.

Several studies have shown that main crops also suffer from competition with living cover crops (Hiltbrunner *et al.*, 2007; Malik *et al.*, 2001) and that cover crop residues can suppress main crop growth (Westgate *et al.*, 2005).

Studies conducted with willow SRC and different species of cover crops also show this. In a study with living cover crops conducted in the USA, white clover (*Trifolium repens* L.) and buckwheat (*Fagopyrum esculentum* Moench), sown in conjunction with willow planting, proved to significantly decrease the production of willow compared with treatments involving hand-weeding or spraying with herbicides (Lawrence Smart, pers. comm. 2014). Furthermore, rye (*Secale cereale* L.), planted in the year prior to willow planting and killed in the following spring has been shown not to result in acceptable weed control due to poorer willow growth than with other weed control strategies (Volk, 2002). Adiele & Volk (2011) found that white clover sown approximately one month before willow cuttings were planted was able to suppress weeds, but also hampered the willow plants severely. Hence, even though there are many positive effects of using cover crops, they add complexity to the agroecosystem that may be difficult to predict and manage.

4 Assessment of aboveground willow biomass

Willow SRC is normally harvested after 3-4 growing seasons and reliable assessments of the annual production of standing biomass without interfering with further stand development are important for scientific studies. Likewise, farmers and farm advisors might want to estimate willow production in order to decide on timing of harvest or continued management inputs. The assessment methods used in these situations are commonly referred to as *non-destructive*, whereas assessment methods that harvest the entire area or a subarea are referred to as *destructive* methods. The non-destructive methods are usually based on measurements of the diameter of either all shoots in a certain area or a sample of shoots (Sevel *et al.*, 2012). These measurements are converted to shoot biomass by using allometric relationships between the measured parameters and shoot weight (Arevalo *et al.*, 2007; Nordh & Verwijst, 2004; Verwijst & Telenius, 1999). Although these are referred to as non-destructive methods, some shoots need to be harvested to determine the shoot allometry.

Studies have shown that the allometric relations for willow are affected by site, species, age and clone (Arevalo *et al.*, 2007; Verwijst & Telenius, 1999; Telenius & Verwijst, 1995) and if these parameters are not considered they might lead to considerable biomass estimation errors for certain stands and consequently bias the results.

Biomass estimations obtained from non-destructive methods have been found to deviate from those obtained from destructive methods (Sevel *et al.*, 2012; Nordh & Verwijst, 2004). Choice of sampling procedure, definition of living shoots and differences between harvest cutting heights have been suggested as causes for these differences. Hence, there are many uncertainties regarding the biomass estimation methods for willow SRC and therefore further studies that investigate the causes for these differences are needed (Sevel *et al.*, 2012). The magnitude of differences in estimates resulting from different methods may also vary between clones (Arevalo *et al.*, 2007; Telenius & Verwijst, 1995). This indicates that some assumptions implicitly made by using a certain method cannot be generalised to clones. However, thus far no comprehensive study has been performed to investigate the clone-specific characteristics underlying these differences.

5 Objectives of the study

Willow SRC is known to be sensitive to weed competition during the establishment phase and the present Swedish recommendation when establishing a willow plantation is to use herbicides in combination with mechanical weed control measures. The primary objective in this thesis was to determine the possibility to further improve the environmental profile of willow SRC by omitting the use of herbicides during establishment. If genetic variation in the competitive ability of willow SRC in relation to weeds could be found, this would be an incentive for breeding even more weed competitive cultivars. Therefore one study in this thesis investigated whether 10 commercial cultivars and two breeding clones differed in their ability to compete with weeds and whether this ability was affected by cutting back the first-year shoots. Another study compared the efficiency and economic returns on cover crops and mechanical weed control methods with those of the present weed control practice. To account for clonal differences in response to these control measures, two different willow clones were compared in that study.

New willow cultivars are continually being released, but yield data obtained under Swedish conditions are sparse. A second objective in this thesis was therefore to assess the productivity of recently released cultivars in Sweden. In a field study, shoot biomass yield of 10 commercial clones (four recently released and six older) was estimated for the first harvest cycle, during which a strict weeding regime had been applied.

While destructive annual biomass estimations of a growing willow crop may be useful, they can be expensive due to the large size of the components in comparison with conventional agricultural crops and they can influence growth of subsequent seasons. This can be addressed by the use of non-destructive methods. However, estimates obtained with non-destructive and destructive methods have been shown to differ and the magnitude of these differences is reported to depend on clone. Another objective in this thesis was to investigate why these differences arise. This was done by testing whether the assumptions underlying destructive and non-destructive protocols are valid for six different willow clones.

Specific objectives of the studies reported in Papers I-IV were to:

- Evaluate the weed competitive ability of 12 different willow clones (Paper I and II)

- Evaluate the effects of cutting back the first-year shoots on growth of willow clones during the first harvest cycle when cultivated under severe weed pressure (Paper II).

- Evaluate the effects of different weed control measures on biomass production by two different biomass willow clones during the first harvest cycle (Paper III)

- Analyse the expected economic returns on willow biomass production under different weed control measures extrapolated to the entire life span of the plantation (Paper III).

- Estimate the shoot biomass yield of 10 commercial willow clones subjected to strict weed control during the first harvest cycle (Paper II)

- Investigate why estimates of above-ground willow biomass from destructive and non-destructive protocols differ (Paper IV)

6 Material and Methods

6.1 Sites

All field trials were conducted near Campus Alnarp of the Swedish University of Agricultural Sciences in southern Sweden. Three different sites (designated J, P and S) were used in this project. The sites differed in soil properties (Table 1), weed flora and weed pressure (Papers I and II). However, since the sites were less than 1.5 km apart, the climate conditions were approximately similar. All plantations were surrounded by a 90 cm high fence to prevent damage by wild animals. Prior to the studies, the experimental fields were managed conventionally with a six-year crop rotation.

Table 1. *Details of field trial sites*

Characteristics	Site		
	J	P	S
Latitude	55°38′49″N	55°38′60″N	55°39′34″N
Longitude	13°4′21″E	13°4′44″E	13°5′35″E
Soil pH	6.9	7.6	6.7
Organic matter (%)	2.8	19.6	2.8
Clay (%)	14.0	22.0	15.0
Silt (%)	20.0	43.5	31.0
Sand (%)	63.2	14.8	51.2
Preceding crop	Sugar beet	Rye	Barley

6.2 Experimental setups

The field trials described in Papers I and II were arranged in a strip-plot design with three treatments (‘Weeded’, ‘Unweeded’ and ‘Unweeded-no cutback’), and 10 cultivars in four blocks at all three sites, while at site S two additional breeding clones were added. Within each block, clones and treatments were randomised to rows and columns, respectively. In Paper I the 'Unweeded-no cutback' treatment was not included in the analyses. Data for Paper IV were obtained from the 'Weeded' treatment at site S.

Paper III is based on a trial that was laid out in a complete randomised block design with five weed control treatments and two commercial willow clones (Gudrun and Tordis), with for replicates. The trial was located at site J, next to one of the trials described above.

For all trials, the plot size was 7 m x 9 m and each plot comprised 80 plants. The plants in each plot were arranged in four double rows (1.5 m between double rows and 0.75 m between rows within double rows), with 10 plants in each row, resulting in a plant density of approximately 13,000 plants ha^{-1}. Assessments were made in central net plots to avoid border interactions. The size of the central net plots was varied, mainly due to observed interactions. At least one plant outside the net plots was considered as border.

6.3 Plant material

All cultivars and breeding clones used in the trials were from Lantmännen Lantbruk's breeding programme (Table 2). The cuttings, approximately 18 cm long, were supplied by professional nurseries and were planted in mid-April 2010 (Papers I, II and IV) and 2011 (Paper III). All cuttings had been stored for a maximum of 3 months at approximately -4 ºC by the time of planting.

6.4 Willow and weed assessments

The willow biomass was estimated either destructively or non-destructively by determining an allometric relationship between shoot diameter and shoot dry weight (Papers I-IV). The aboveground weed biomass was estimated during the establishment year using a hand-held multispectral radiometer (Papers I and III), and during subsequent seasons by cutting and weighing weeds after drying (Paper III). The weed flora was assessed by placing a frame at three or four locations within each plot (Papers I-III). In Papers II and III, the total ground cover and the ground cover of each weed species were recorded inside the frame, while only the five most common weed species were recorded in Paper I. The average weed height was also assessed within each frame in Paper II.

Table 2. *Willow (Salix) clones studied in this thesis and their genetic background*

Clone	Genetic background
Gudrun	*S. dasyclados*[1]
Karin	*S. dasyclados*[1], *S. schwerinii, S. viminalis*
Klara	*S. dasyclados*[1], *S. schwerinii, S. viminalis*
Linnea	*S. schwerinii, S. viminalis, S. eriocephala, S. triandra*
Lisa	*S. schwerinii, S. viminalis*
Stina	*S. aegyptiaca, S. schwerinii, S. viminalis, S. lanceolata*
Sven	*S. schwerinii, S. viminalis*
SW Inger	*S. triandra, S. viminalis*
Tora	*S. schwerinii, S. viminalis*
Tordis	*S. schwerinii, S. viminalis*
98[2]	
58[2]	

[1]Sometimes referred to as *S. burjatica*; [2]Breeding clones. Only planted at site S. Genetic background not available. Table taken from Paper I.

7 Results and discussion

7.1 Effects of weeds on willow clones during the first harvest cycle

Comparing weeded and unweeded plots, growth of all willow clones included in this study was severely hampered by weeds during the first harvest cycle (Papers I and II; Fig. 3). The growth reduction after the establishment year was over 90%, irrespective of clone and site, regardless of whether the growth reduction was calculated as mean plant shoot dry weight of living plants (Paper I) or mean total shoot dry weight per unit area (Paper II). These findings confirm claims in earlier studies that willow is very sensitive to weed competition during the establishment phase (Sage, 1999; Clay & Dixon, 1995; Labrecque *et al.*, 1994). Only one site (site P) showed clonal differences in growth reduction after the establishment year (Papers I and II). Cultivars Tora and Klara had the lowest growth reductions at this site, but there was still 90.6% and 90.8% lower willow plant shoot biomass, respectively, in unweeded plots of these clones than in weeded plots (Paper I). The result from this study showing only small differences in weed competitive ability between willow clones during establishment phase was reinforced by results from an indoor study with willow material representing a wider genetic range grown in competition with either a grass or an herb (Fig. 4; unpublished data).

Weeds not only affected the growth of the willow plants, but also the plant mortality rates during the first growing season. The mean plant mortality in the weeded treatment was less than 1%, whereas the mean mortality in the unweeded treatment varied between 2.7 and 37.4% depending on site (Paper I). Lack of water due to a dry period during the summer, in combination with differences in water-holding capacity of the soils, might explain most of the differences between sites. Furthermore, site differences in weed pressure and damage by browsing small mammals might also have influenced the results. As with the growth reduction effect, clonal differences in willow plant mortality were only found at site P after the first growing season (Paper I). In contrast to these results, no other study investigating the effect of weeds on willow establishment has found any increased plant mortality after the first growing season due to weeds (Volk, 2002; Clay & Dixon, 1995).

The willow biomass was negatively correlated with the amount of weeds during the first season at all three sites (Paper I). Similarly, Sage (1999) found a negative correlation between willow growth and weed biomass, in that case with one-year-old shoots on two-year-old willow stools.

Figure 3. (Left) Willow plots thoroughly weeded and (right) unweeded plots. Photo taken five months after planting at the site S (which had least mean growth reduction). Photo: J. Albertsson.

Over time, the overall willow growth reduction decreased from 93.5% in the establishment year to 68.3% after two years of regrowth at site S, whereas no significant decrease was observed at the other sites (Paper II). The much lower cumulative plant mortality in the unweeded treatment after the first harvest cycle (9.8 %) at site S compared with the other sites (site J 56.2%; site P 57.3%) might explain why a decrease in growth reduction was only found at this site. Clonal differences in growth reduction were found at two of the sites after the first harvest cycle (Paper II). The clones Stina and SW Inger were among the lowest in growth reduction at all sites. Furthermore, these clones actually had higher production of willow shoot biomass in the unweeded treatment than in the weeded treatment at site S when only the incremental growth during the third season was considered. However, the low growth reduction of these two clones can be partly explained by the fact that neither was among the best in terms of willow shoot biomass production when grown without weeds.

Figure 4. Willow clones with a wide genetic background cultivated together with an herb in an indoor weed competition study (unpublished data). Photo: J. Albertsson.

The occurrence of weeds affected the number of willow plants damaged by voles. In the autumn before the end of the first harvest cycle, there was no plant damage in the weeded treatment at any site. However, in the unweeded treatment, between 6 and 21% (depending on site) of the plants that were alive that season were damaged by voles (unpublished data). The fact that damage was only found in the unweeded treatment might be explained by vole habitat requirements. Studies have shown that vole populations are favoured by continuous ground cover that consists of litter and/or green plant material (Hansson, 1977). Hence, the unweeded treatment represents an excellent habitat for voles.

From the establishment year until the end of the first harvest cycle, there was a general shift from annual to perennial weed species in the 'Unweeded' treatment at all three sites. During the establishment year fat-hen (*Chenopodium album* L.) was common at all sites, whereas scentless mayweed (*Tripleurospermum inodorum* (L.) Sch. Bip), black bindweed (*Fallopia convolvulus* (L.) A Löve) and cleavers (*Galium aparine* L.) were common in at least two of the three sites (Paper I). During the second growing season, perennials such as creeping thistle (*Cirsium arvense* (L.) Scop) and grasses began to invade the plantations (Paper II). However, *T. inodorum* dominated at two of the sites, while another annual, chamomile (*Matricaria chamomilla* L.), dominated at the third. Despite these differences in weed flora between sites during the first two growing seasons, more than 60% of the ground was covered by *C. arvense* at all three sites in the third season (Paper II). There were no significant differences between clones in terms of total weed cover or average weed height at any site during the first harvest cycle.

Similarly, Gustafsson (1988) found that many annuals germinated during the first year of willow cultivation, whereas perennials became more common in older stands. Moreover, although that study was carried out in a field that had been used for grazing prior to willow planting, and not arable farming as in the present work, *C. arvense* became the dominant species four years after willow establishment.

7.2 Effects of cutting back the first-year shoots

Cutback of first-year shoots has been an agronomic practice in Sweden, despite the fact that there is apparently no scientific evidence that this increases willow biomass production. In fact, the few studies that have been performed show that production is either negatively affected or unaffected by this practice (Larsen, 2014; Verwijst & Nordh, 2010; Volk, 2002). Likewise, Paper II show that none of the clones tested at any of the sites had significantly higher willow shoot biomass in the treatment where cutback had been performed compared with the treatment where it had been omitted (Paper II). Indeed for certain clone and site combinations the production after the first harvest cycle was more than 6 t ha^{-1} DM higher in the treatment where no cutback had been performed, even though there was severe weed pressure. The magnitude of the differences between the two treatments was found to differ between clones at sites P and S as determined by ANOVA. However, the *post hoc* test could only distinguish between the clones at site S, where Klara was more negatively affected by cutback than Gudrun. When the two treatments were compared per site, sites S and P had significantly lower production in the 'Unweeded' than in the 'Unweeded-no cutback' treatment, while the production at site J did not differ between treatments (Paper II). The non-significant effect at site J might be attributed to the generally low production for both treatments at this site compared with the other sites. The significant effect at sites S and P was maintained even when the biomass that was produced and cut back during the first season was added. At site P, the cutback not only affected plant growth negatively but also increased plant mortality (Paper II). Thus, besides being unnecessary, at certain locations cutback might have a negative effect on willow shoot production during the following seasons when performed under severe weed pressure. Since our study was performed under unweeded conditions, it complements the three other studies cited above, all of which were performed when weed control measures had been applied.

7.3 Effects of different weed control measures on growth and economic viability of two willow cultivars

The recommended practice when establishing a willow plantation is to use a combination of herbicides and mechanical weeding (Swedish Board of Agriculture, 2012; Abrahamson *et al.*, 2002). However, to further improve the good environmental profile of willow SRC and to follow the general principles of IPM, it is desirable to omit the use of herbicides during establishment. Paper III therefore compared the weeding efficiency of the recommended practice, treatment 'HRC' (see below), with four non-chemical treatment strategies (Table 3).

Table 3. *Measures applied during the first and second growing season for treatments 'HRC' (herbicides and row crop cultivator), 'RC' (row crop cultivator), 'RCT' (row crop cultivator with torsion weeder), 'CC' (cover crop) and 'CCC' (cut cover crop)*

Treatment	Measures
HRC	One application of herbicide two days after planting + one run with a row crop cultivator in the first season and two runs in the second season.
RC	Three runs with a row crop cultivator in the first season and three in the second season.
RCT	Three runs with a row crop cultivator with torsion weeder in the first season and three in the second season.
CC	Cover crop (a combination of Persian clover and white clover) sown two days before willow planting.
CCC	Same as for 'CC' but the cover crop (and the weeds) were cut three times in the first season and once in the second season.

To account for possible cultivar differences in response to the weeding strategies, two willow cultivars, Gudrun and Tordis, which differ in growth rhythm and leaf morphology were included in the study.

No interaction between clone and treatment was found for willow shoot biomass yield or plant mortality (Paper III). After the first harvest cycle (two-year shoots on three-year stools) the ‘RCT’ treatment gave significantly higher willow shoot biomass production than the ‘RC’ treatment, which in turn gave significantly higher production than the two cover crop treatments (Paper III). However, the recommended practice (treatment ‘HRC’) gave the highest production of all (Paper III; Fig. 5). Willow plant mortality was related to clone, since Tordis had higher plant mortality than Gudrun after the first harvest cycle. This result contradicts findings in the other field trials performed (Papers I and II). The probable cause was that the cuttings of Tordis used in this trial (Paper III) were of poor quality. No differences in plant mortality were found between the ‘HRC’ treatment and the two mechanical treatments (‘RC’ and ‘RCT’) but the two cover crop treatments (‘CC’ and ‘CCC’) had significantly higher plant mortality than the others (Paper III). In all three seasons, there were no significant differences between ‘HRC’ and ‘RCT’ in terms of weed aboveground biomass.

Biomass production in the six subsequent harvest cycles was estimated in order to calculate the expected annual economic returns during the whole life time of the plantation for all cultivar and weed control strategy combinations. In these calculations, a wood chip price of 190 SEK per MWh was assumed. The results showed that all combinations gave a positive annual economic return, with Tordis and treatment ‘HRC’ giving the highest profit (831 SEK ha^{-1}) and Gudrun and treatment ‘CCC’ the lowest (247 SEK ha^{-1}). The profitability of the treatments decreased in the order HRC > RCT > RC > CC > CCC for both clones. The calculations also showed that the economic return on a willow plantation is very sensitive to decrease in wood chip prices, while a substantial increase in weeding costs has only a minor effect (Paper III).

The results from Paper III indicate that a row crop cultivator combined with torsion weeders (treatment ‘RCT’) might be a good option if herbicides are to be omitted during the establishment phase of a willow SRC plantation.

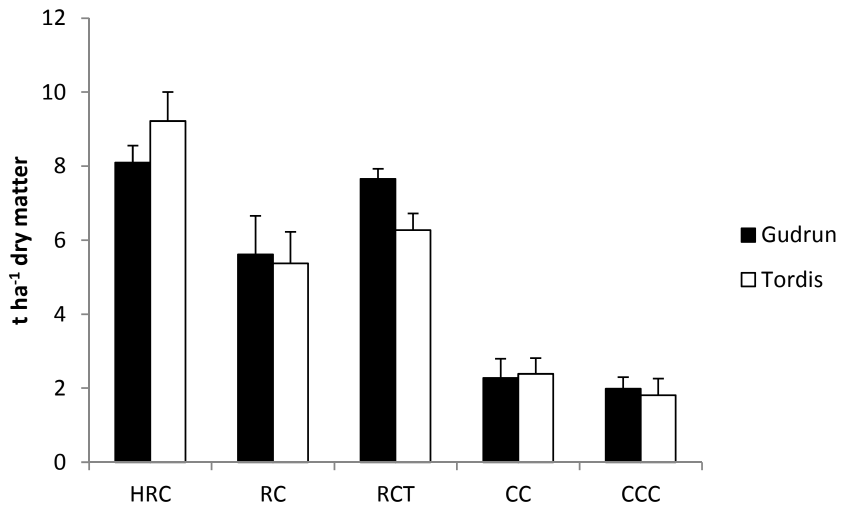

Figure 5. Annual mean willow shoot biomass yield after the first harvest cycle (establishment year excluded) for five weed control strategies (HRC, RC, RCT, CC and CCC; see Table 3 for explanation) and two willow clones (Gudrun, Tordis). Error bars show SE.

7.4 Willow shoot biomass production following strict weed control

After the first growing season, the clone Linnea ranked highest in terms of willow shoot biomass production at all three experimental sites and it had significantly higher production than several of the other clones in the ‘Weeded’ treatment (Paper I). However, this high production rate compared with the other clones was not maintained in subsequent seasons (Paper II; Fig. 6).

According to former agronomic practice, the willow shoots were cut back after the first growing season. Hence, the shoots were two years old at the end of the third season when destructive harvesting was performed. Interactions between site and clone were identified but irrespective of these interactions, Sven and Tordis ranked among the highest in biomass production, whereas Karin ranked among the lowest at all sites after the first harvest (Paper II; Fig. 6). Similarly, Tordis performed well at all five locations in a Danish study where eight different clones were compared after the first three-year harvest cycle (Larsen *et al.*, 2014). In another Danish study Sven, had the highest average annual biomass production when 25 different commercial plantations were evaluated (Nord-Larsen *et al.*, 2014). However, even though Sven and Tordis ranked highly in our study, they did not produce significantly more biomass than the more recently released clones Klara and Linnea at any of the sites (Paper II).

There was a tendency for lower production at site P, with Tordis as the only exception (Fig. 6). The high soil pH at this site (Table 1) might be related to that site P is suboptimal for willow SRC, as evidenced by necrotic and yellowing leaves.

The annual production at site J for weeded plots of Gudrun was 11.5 t ha^{-1} DM and for Tordis 13.8 t ha^{-1} DM. However, in the trial with five different weed control measures (Paper III) the annual production of these two cultivars was just 8.1 and 9.2 t ha^{-1} DM, respectively, in the treatment 'HRC', in which the weeds were controlled according to conventional practice. The 'HRC' trial was planted, grown and harvested one year after the other trial, but conditions for willow growth were, if anything, more favourable during the establishment year for 'HRC' and hence do not explain its lower yield level. However, even though the two trials were located close to each other, their soil characteristics differed slightly and thus might have influenced willow biomass production. Furthermore, the weed control intensity differed in the two trials, which might also explain part of the differences between yield levels.

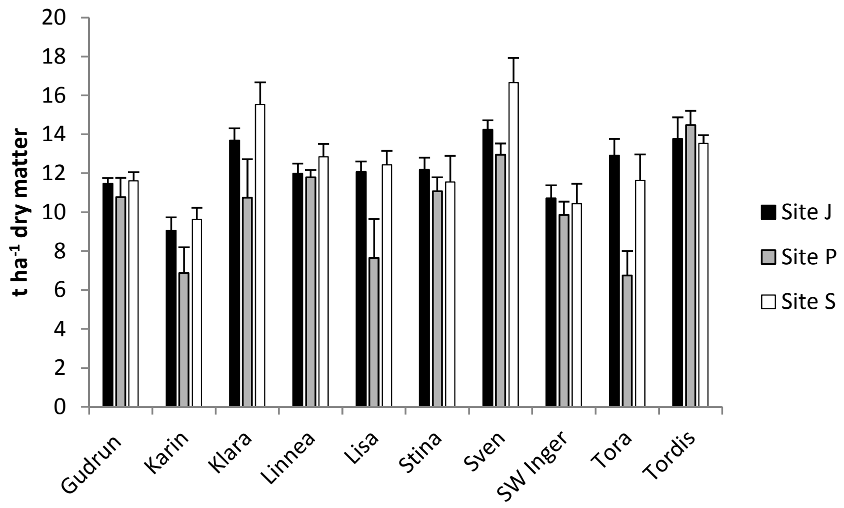

Figure 6. Annual mean willow shoot biomass yield of 10 commercial clones at sites J, P and S after the first harvest cycle (establishment year excluded). Error bars show SE.

7.5 Assumptions made in protocols for biomass estimation of short-rotation willow

Several studies have shown that destructive and non-destructive yield estimations differ in willow SRC (Sevel *et al.*, 2012; Arevalo *et al.*, 2007; Nordh & Verwijst, 2004) and that the magnitude of these differences might vary by clone (Arevalo *et al.*, 2007; Telenius & Verwijst, 1995). Therefore assumptions that might influence the results of biomass estimation methods were tested in Paper IV. The results showed that various assumptions regarding dry matter content (DMC) were violated for certain clones, but valid for others (Table 4). Consequently, any assumptions made should preferably be tested for each clone or at least be clearly stated, in order to enable comparisons between data using different biomass estimation methods.

Table 4. *Test results (Rejected = R; Not rejected = NR) of dry matter content (DMC) assumptions for six different willow clones.*

Assumption	Clone					
	Gudrun	Karin	Linnea	Sven	Tora	Tordis
DMC of the entire shoot does not vary systematically with shoot size.	R	**NR**	R	R	R	R
DMC values of different diameter size fractions within shoots do not vary systematically.	R	**NR**	R	R	**NR**	R
DMC of the balance point[a] does not differ systematically from whole shoot DMC.	R	**NR**	**NR**	R	**NR**	R
DMC does not change over time.	R	R	R	R	**NR**	R

[a] The point of the shoot where the fresh weight of the apical and basal parts of the shoot are equal.

In addition to the assumptions regarding DMC, stub height was measured after the shoots had been harvested either by hand or machine. It was found that the stub height of the machine-harvested shoots was on average 7.6 cm greater than that of the manually harvested shoots and that this difference was not related to clone (Paper IV). The higher stubs left by the harvesting machine represented on average 4.5% of the standing biomass. Hence, stub height differences related to harvesting method should be taken into account when performing yield estimations.

The findings in Paper IV highlight important factors for obtaining accurate biomass estimates. Not all of these were considered in Papers I-III and hence may have influenced the results of these papers. However, in most cases yield estimates used for comparisons were obtained with the same method. Moreover, assumptions regarding DMC were stated in Papers II and III, giving the reader the possibility to take these into account, *e.g.* when comparing data. Shoot cut height might have influenced the results from site J and P in Paper II since shoots at the first harvest were cut manually in the 'Unweeded' treatment, while shoots in the 'Weeded' treatment was cut using a harvester. However, since Paper IV showed that manually cut shoots tend to be cut at a lower height, the result in Paper II would, if anything, underestimate the effect of weeds at these sites.

8 Conclusions

This thesis showed that there are only small differences between willow clones in terms of their ability to compete with weeds when measured as willow growth reduction and plant mortality after the first harvest. All willow clones were in fact severely hampered by weeds and, depending on site, the mean growth reduction ranged between 68.3% and 94.3% and the mean cumulative plant mortality in the unweeded treatment between 9.8% and 57.3%. The plant mortality in the weeded treatment was approximately 1% regardless of site. Consequently, choice of clone, at least from among the currently available commercial stock, will probably have limited effect on weed control in willow SRC. Furthermore, the results indicate that breeding for competitive ability is probably not a feasible way to improve the environmental profile of willow SRC, since there were only slight differences in weed competitiveness between clones. The results confirmed previous findings that weed control measures should be applied during the first growing season to ensure proper establishment of a willow plantation.

The biomass production of willow plants under severe weed pressure was either negatively affected or not affected by cutting back the first-year shoots. The magnitude of the differences between the two treatments was only affected by clone to a small extent. In addition, at one of the three sites this practice increased plant mortality. Hence, the results indicate that cutting back the first-year shoots does not increase the ability of willow plants to compete with weeds and may in fact decrease it. Other studies have found similar results in weeded willow plantations. Consequently, the combined results from this thesis and other studies suggest that the first-year shoots should be left uncut as long as they are not preventing other management actions.

The study with five different weed control strategies indicated that it is possible to establish an agriculturally and economically viable willow SRC plantation without the use of herbicides. The non-chemical strategy that gave the highest biomass yield after the first harvest cycle and highest annual economic return was use of a row crop cultivator combined with a torsion weeder. However, more trials are needed to optimise this strategy for willow SRC production, *e.g.* identifying the optimal distance between the tines of the torsion weeder and optimising the timing and number of treatments. The results presented here also need to be validated at other sites and when the first-year shoots are not cut back. Neither of the cover crop strategies tested performed well and both gave lower willow biomass yield, higher plant mortality and lower annual economic returns than the other strategies. These results suggest that the practice of using a cover crop as a weed control method when establishing willow plantations needs to be further developed, *e.g.* by finding more suitable cover crop species and optimising the sowing time. There were no interactions between weed control strategy and cultivar for willow shoot biomass yield or willow mortality. Hence, the results indicate that neither of the cultivars tested (Gudrun, Tordis) is more suitable for combining with a certain weed control strategy. They also indicate that an increase in weed control costs has only a minor effect on the annual economic return if extrapolated over the entire expected life span of the plantation. Thus, weed control measures during the establishment phase should not be omitted due to fear of economic losses.

Interactions were found between clones and sites regarding willow shoot biomass production when grown under nearly weed-free conditions after the first harvest cycle. Irrespectively of these interactions, Sven and Tordis were among the highest and Karin among the lowest ranked cultivars at all three sites. From this study it can be concluded that the more recent cultivars (Lisa, Klara, Linnea and Stina) do not yield more than the highest-yielding older cultivars, at least not in southern Sweden during the first harvest cycle. However, it is important that a range of cultivars is used when establishing new willow plantations to reduce the risk of resistance to pests and diseases being overcome and to exploit potential differences between cultivars in response to abiotic stresses.

Basic assumptions made with regard to physical structure and dry matter content that are implicitly made when using a certain biomass estimation method were proven to be partly valid for some of the cultivars tested but not for others. It was shown that stub height should be considered when comparing different estimation methods. The results obtained explain some of the differences between destructive and non-destructive biomass estimation methods reported in other studies and may be used to further improve aboveground biomass estimates in willow SRC.

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