Long Term Changes in Stand Structure and Biomass Production in Short Rotation Willow Coppice

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Abstract

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Short rotation willow coppice (SRWC) is a recently commercialised agricultural crop in Sweden, producing biomass for energy. The expected lifespan of a SRWC plantation is more than 20 years, or at least 5 harvests. Consequently, understanding of long term stand development in relation to management, plant material and site characteristics is of great importance.

The focus of this thesis is on SRWC biomass production during later cutting cycles. Long term development and dynamics have been studied during three cutting cycles by means of annual census of individual stools, scaled up to stand level. Methods for non-destructive biomass assessment, by means of allometric relations, have been developed and validated for different clones. A method for predicting willow shoot growth in field trials, under different nutrient and water conditions, based on characteristics found in pot-grown plants under corresponding conditions, has also been investigated.

The best non-destructive method for assessing shoot weight of clones with bow-shaped and branching stems was found to be shoot dry weight related to the sum of the cross sectional areas of all shoots. In straight, un-branched clones, the measuring height could be elevated to 105 cm above stem base without loosing precision. A comparison of a destructive and a non-destructive method, applied on 12 different clones, showed a mean deviation of 2.5%. Stool mortality during the 1st cutting cycle was non-density dependent. Biomass production increased in the 2nd cutting cycle but high density dependent stool mortality at the end of the 2nd cutting cycle negatively influenced the production in the 3rd cutting cycle, which was lower than both the 1st and 2nd cutting cycle. A stool size hierarchy was established early and prevailed through all cutting cycles. Stool mortality occurred mainly among small stools. In the beginning of the 4th cutting cycle, biomass production stabilised due to compensatory growth of the remaining stools. Total leaf area and total nitrogen pool of pot-grown plants were good clone-specific characters for predicting shoot biomass growth in the field during the first cutting cycle and may be used for shortening the time needed to characterise new clones.

The results suggest that sustainability in SRWC systems is enhanced by matching clone and site and adapting fertilisation and harvest timing to actual stand development.

Keywords: Allometry, cutting cycle, fertilisation, harvest, leaf area, mortality, nitrogen pool, Salix, shoot, size hierarchy, stand dynamics, stool, Sweden.

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To my late father and my mother

Contents

Appendix

Paper I-IV

The present thesis is based on the following papers, which will be referred to by their Roman numbers:

I. Verwijst, T. and **Nordh, N-E.** 1992. Non-destructive estimation of biomass of *Salix dasyclados*. *Bioresource Technology* 41: 59-63.

II. **Nordh, N-E.** and Verwijst, T. 2004. Above-ground biomass assessments and first cutting cycle production in willow (*Salix* sp.) coppice – a comparison between destructive and non-destructive methods. *Biomass and Bioenergy* 27: 1-8.

III. Weih, M. and **Nordh, N-E.** 2005. Determinants of biomass production in hybrid willows and prediction of field performance from pot studies. *Tree Physiology 25*: 1197-1206.

IV. **Nordh, N-E.** and Verwijst, T. 2005. Biomass production and population dynamics of 12 willow (*Salix*) clones grown in three short rotations during 14 years (manuscript).

Paper I – III are reproduced with permission of the journals concerned.

Introduction

Background

The research and development concerning short rotation willow coppice (SRWC) in Sweden was initiated in the 1960s and has been going on continuously for almost four decades (Statens Energiverk, 1985). The R&D has covered a variety of topics e.g. plant anatomy (Sennerby-Forsse, 1986a) and plant physiology (Weih, 2001), damage due to pathogens (Ramstedt, 1999; Cambours *et al*., 2005) insects (Björkman *et al*., 2000) and abiotic factors (von Fircks, 1992), plant genetics and breeding (Larsson, 1998; Rönnberg-Wästljung & Gullberg, 1999), development of the techniques used for the commercial crop (Danfors, 1992), stand development and dynamics, and above ground biomass production (Verwijst, 1991; Willebrand & Verwijst, 1993), root dynamics (Rytter & Rytter, 1998), use of water and nutrients (Ericsson, 1994; Lindroth & Ciencala, 1996; Weih & Nordh, 2002), fertilisation (Alriksson *et al*., 1997), heavy metal uptake (Klang-Westin & Perttu, 2002), phytoremediation (Aronsson & Perttu, 2001; Mirck *et al*., 2005). Much of this knowledge has also been successively published in guides and manuals on how to grow and manage SRWC (Sennerby-Forsse, 1986b; Ledin et al., 1994; Danfors *et al*., 1998).

The driving forces behind the interest for SRWC in Sweden have shifted over time. Initially, in the 1960s, focus was on providing bulk material for the paper and pulp industry. Following the oil crisis in the early 1970s, the focus shifted towards research on SRWC as a domestic, renewable and CO_2 neutral biomass source for energy. Later on, rural employment and alternative use of abandoned agricultural land were additional motives for continuous R&D. In recent years, much attention has been paid to numerous positive environmental applications of SRWC such as playing a role in municipal wastewater treatment systems, restoration and prevention of leakage of drainage water from waste deposits as well as uptake of heavy metals from contaminated arable soils.

The R&D was accompanied by a commercialisation of SRWC on agricultural land that started in the late 1980s. The fastest expansion took place during 1990-96 when the planted area increased almost exponentially and reached about 15,000 ha (Rosenqvist *et al*., 2000). In 1991, energy and environmental taxes on fossil fuels increased markedly making biofuels more competitive and between 1991 and 1996, subsidies for establishing of SRWC were substantial and covered most of the cost, if not all, for site preparation, plant material and planting. The financial support was however unconditional, i.e. there was no service in return asked from the grower - in terms of weed control and fertilisation, necessary management measures as shown by R&D - to receive the subsidies. As a consequence, many plantations were poorly or not at all managed and hence the yield in these plantations was often very low (Jonsson, 1995). After 1996, the financial support decreased and there was a period of political uncertainty both at a national

Swedish level and at European Union level whether or not SRWC should be subsidised as an agricultural crop. As a result, the planted area levelled off at around 15,000 ha, i.e., poor plantations were removed at the same rate as new plantations were established. At present, SRWC is often regarded as an agricultural crop and the subsidies have been conditioned to adequate management of the crop.

From a biological and agronomic point of view the developed system can be considered as a success since the yields are increasing and the system is economically competitive with other crops used by the farmers. From a commercial and political point of view, the system can be considered as a failure because large scale implementation is lacking. The 15,000 ha of SRWC established so far contributes 0.1 to 0.2 TWh of the 406 TWh consumed annually in Sweden (Energimyndigheten, 2005). Large scale implementation has not been carried out for a number of reasons. While most technical barriers to large scale implementation in Sweden have been solved many non-technical barriers are prevailing and hamper SRWC expansion (Alker *et al*., 2005). One important barrier is the lack of experience with the production system during its later stages, i.e. after repeated harvests, giving rise to a number of questions about the long term production levels and thereby, the economic sustainability of the system.

The major topic of this thesis is biomass production in SRWC systems during later cutting cycles. To perform long term census data, accurate biomass estimations were crucial for the work and consequently, methodological issues are addressed (Papers I and II). Dealing with a new crop with a partial unknown genetic base, issues related to intraspecific variation between willow clones and clone selection are also addressed (Paper III). A major emphasis has been put on the population dynamics of willow stands to capture the processes that determine productivity in the long term (Paper IV).

The biological basis of willow cultivation (SRWC) in Sweden

Willows (*Salix* spp.), a genus of more than 300 species and numerous hybrids (Meikle, 1984) are pioneer species (FAO, 1979; Verwijst, 2001) adapted to occupy disturbed habitats and many of the species are characterised by a fast juvenile growth. Like several other broadleaved tree species (*Populus* sp., *Alnus* sp., *Eucalyptus* sp.), willows have an ability to tolerate repeated disturbances and after being coppiced, new shoots sprout from the stump, forming a stool (Sennerby-Forsse *et al*., 1992). Many willows can also be vegetatively propagated and planted as clones by stem cuttings. These characteristics are of main interest when cultivating SRWC. By applying short harvest intervals, referred to as cutting cycles of 3-5 years, shoots are kept in a juvenile stage with high growth rate and hence, biomass yield is optimised.

Willows have been used and cultivated through history (Stott, 1992), e.g. by the Romans (Cato, 234-149 B.C.), but willow growing for biomass purposes is a novel concept and consequently the potential for improving the plant material by breeding is large (Stettler *et al*., 1992). Willow breeding in Sweden mainly aims to obtain plant material with characteristics that best match existing agricultural practice, including high growth rate, frost hardiness, resistance to pests and diseases, and stool morphology and shape (Larsson, 1998).

According to Mead (2005, p. 250) "Actual stand productivity, at any time on a given site, is determined by how well trees capture resources". However, a growing plant may allocate its acquired resources in many different ways to its several components (e.g. roots, shoots, branches and leaves) and to respiratory processes. By keeping the stand juvenile by means of short cutting cycles, it is possible to minimise the respiratory cost, thereby maximising the net primary production, i.e. the difference between gross production and stand respiration (Kira & Shidei, 1967). Differential resource allocation (Fig. 1) is reflected in the wide variety of shapes that stools may have, and even in a single species we may find differences in shapes between clones (Johansson & Melin, 1994). Differences in allocation pattern usually have both an environmental and a genetic background. It also should be noted that management measures - actually being man-made modifications of site and/or climate - such as fertilisation and irrigation, may lead to differential resource allocation and as such may complicate biomass estimations in experimental design; for a given regression model, describing the relation between stem weight and diameter, stands may display clone- and site specific parameters. In practice, this means that allometric relations may be clone and/or environment specific, and that stand-specific equations should be established.

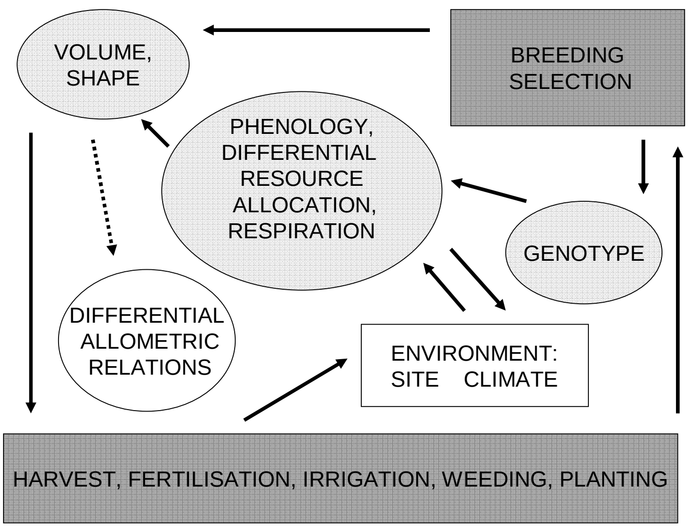

Figure 1. The functioning of SRWC systems in relation to management, consisting of harvest, fertilisation, irrigation, weeding and planting.

SRWC management includes a wide range of measures. A major management measure consists of the choice of site and clones. Increased knowledge of clone characteristics, e.g. the use of nutrients and water (Paper III) will improve the possibilities in the future to better match clones to specific site conditions. Sites exposed to frost during the growing season are not suitable for SRWC, but by selecting clones with a site-adapted phenology the risk of production losses due to frost damage can be reduced.

One common characteristic for a pioneer species is a low competitive ability for light which makes weed control a very important management measure to improve growth, especially during the establishment phase. Stool growth conditions can be further improved by fertilisation and irrigation which also can change the ratio between roots and shoot (Ericsson, 1995) by increasing the allocation to above ground stool parts. SRWC stands are densely planted (1.5 to 2.0 stools m^{-2}) and if adequate management actions that improve individual stool performance are applied it will have consequences for the development at stand level. By increasing the growth rate of individual stools, competition between stools will be intensified faster and eventually, stools will start to die. If stool mortality is high, there is a risk of decreasing stand biomass production in the long term (Verwijst, 1996). The intense competition between stools in a SRWC system can, however, be reset by harvesting. Consequently, timing of harvest, i.e., changing the length of the cutting cycle in relation to standing biomass, is also an important management measure to get high and sustainable biomass production in SRWC.

The commercial growing system

SRWC in Sweden is a commercialised and fully mechanised agricultural cropping system producing biomass primarily for energy use. The plantations are established with stem cuttings made from one-year old shoots that are harvested during shoot dormancy and stored at -2 to -4 °C until planting, preferably done in late April to early June. The autumn before establishing the crop, a systemic herbicide, glyphosate, is applied to remove perennial weeds and the soil is ploughed. Just before planting in spring, the site is harrowed. The current planting design used is a double-row system with altering inter-row distances of 0.75 m and 1.5 m and a spacing of 0.6 m between cuttings within the rows, giving a planting density of about 15,000 cuttings ha^{-1} (Danfors *et al*., 1998). The planting machine, which plants three double-rows at a time, cuts the shoots into 15 to 20 cm long cuttings and pushes them into the soil. During the establishment year, mechanical weed treatment may be needed on repeated occasions. If the stand is successfully established additional weed control is seldom needed. After the first growing season, the shoots are usually coppiced during winter to encourage the sprouting of more shoots the following season.

Fertilisation starts the year after establishment and the recommended application during the first cutting cycle is an average of about 70 kg N ha^{-1} $year^{-1}$, the main part applied in year 3 and 4 (Ledin *et al*., 1994). Recommended fertilisation during the later cutting cycles are an average amount of 60 to 80 kg N ha^{-1} $year^{-1}$ which corresponds to the amount of nitrogen that is removed from the system at harvest (Ledin *et al*., 1994).

SRWC plantations are harvested every 3 to 5 year and harvest is done during winter, when the leaves have been shed, the plants are dormant and the ground is usually frozen. The harvester simultaneously cuts the shoots, feeds them into a chipper, chips the wood into chips and blows them into a container. The containers are transported by lorry to a nearby end-user, mostly a municipal district heating plant, were the wood chips are burnt fresh. In a good plantation the yield may be 7 to 10 t DM ha^{-1} $year^{-1}$ corresponding to about 30 to 45 MWh of energy. The energy ratio, i.e. the amount of energy taken out of the system in relation to energy input, can be as high as 20 (Börjesson, 1996). A cutting cycle ends with harvest, and as the expected lifespan or rotation period of a commercial SRWC is about 25 years (Ledin, 1996), 6 to 7 harvests can be taken before ending the plantation.

Apart from biomass production, willow plantations can be established and utilised for several environmental applications (Perttu, 1998; Aronsson & Perttu, 2001) often referred to as phytoremediation. This includes irrigation with municipal waste water (Aronsson & Perttu, 2001), uptake and removal of heavy metals from contaminated soils (Klang-Westin & Perttu, 2002), treating of landfill leachate (Dimitriou et al., 2006) etc. Many commercial SRWC plantations are also fertilised with sludge from municipal wastewater treatment plants (Dimitriou & Aronsson, 2004).

General aim and specific hypotheses addressed

As SRWC is an agriculture crop, expensive to establish and expected to last for more than 20 years, sustainable biomass production is crucial for the profitability. The major aim of this thesis is to assess the population dynamics and to understand the long term performance of SRWC, especially during the later cutting cycles, in relation to site characteristics and different management measures.

The growth and development of a set of individual stools of different clones were followed annually and biomass production was calculated and scaled up to stand level. To be able to do this, non-destructive biomass estimation methods, rather than destructive methods, had to be used to avoid interfering with stand development. By applying both a non-destructive and a destructive method of measuring biomass on the same set of individual stools, a controlled comparison of the two methods was done with the hypothesis that there would be no difference between the methods.

Most clones used for SRWC have straight, un-branched shoots and upright growth, but some clones may have curved shoots and exhibit irregular branching. In these cases the non-destructive method has to be modified to give an accurate estimation of the shoot biomass. One such modified method is also presented in this thesis.

Large scale field trials to test long term performance of different clones under various environmental conditions are expensive, labour intensive and time consuming. Therefore, simplification and shortening of the testing procedure of new clones would be of large benefit. Here, a method to predict standing shoot biomass of 3-year-old willows grown in a field trial, based on the growth of pot grown plants after one season, is described. The hypotheses were that there are clone-specific relationships between certain growth traits such as leaf area and shoot biomass production and that these are similar in pot- and field-grown plants.

When pursuing general and more specific aims the ambition was always to try to derive knowledge that could be used in practical management performance.

Materials & Methods

This section gives a brief description of the materials and methods and the aims for the appended papers. For a more detailed description the reader is referred to the corresponding paper.

Paper I

The study was carried out 1988 on a *Salix dasyclados* clone – Swedish clone number 77075 (Ager *et al*., 1986) - displaying a growth form with very bow-shaped and branching stems, planted 1986 at a density of 20,000 cuttings ha^{-1} in a 0.4 ha commercial plantation about 30 km south of Örebro, Sweden (59°04´N, 14°54´E). Sampling of 50 randomly selected stems from 50 individual stools was done in autumn after leaf fall. A stem was defined as a collection of plant parts connected at 5 cm or higher above soil surface (Paper I, Fig. 1). The stems and their branching shoots were marked in the field at 5, 25 and 55 cm height above soil surface and then cut at 5 cm above soil surface. Afterwards all shoots were measured on length, diameter at 50 cm from the base, and diameter at the three heights marked in the field. The stems with their branching shoots were divided into three sections corresponding to the field marks and oven-dry weight was determined separately for each section. Stem weight was then related to several different dimensional variables.

The aim of the study was to develop a non-destructive biomass measurement method for clones that display a growth form and a branching pattern different from the usual straight un-branched growth of most clones used for SRWC.

Paper II

The study was performed during the first 4-year cutting cycle in a willow clonal trial established in 1990 near Västerås, Sweden (59°37´N, 16°40´E). The trial was

manually planted with cuttings in a double- row design at a density of 20,000 cuttings ha^{-1} and included 12 clones, one clone of *Salix dasyclados* and 11 clones of *S. viminalis*, in monoclonal plots, 10 m x 10 m in size, and four replications. The management consisted of chemical and mechanical weed control and fertilisation with solid fertiliser, corresponding to in total 285 kg N ha^{-1} during 4 years. The trial was harvested in March 1994.
Measurements consisted of stool survival and above ground living woody biomass of individual stools scaled up to production per unit area. Two different biomass measurements methods were used on the same set of individual stools:

1. A non-destructive method where stem diameter was measured at 55 cm above shoot base on all living shoots per stool. Shoot dry weight (W_s) was calculated using the clone- and age-specific allometric relationship between W_s and stem diameter at given height (D_h), described in Eq. 1:

$$W_s = b \cdot D_h^c \qquad \text{Eq. 1}$$

and all W_s was summed up to individual stool dry weights. The parameters b and c were estimated from a destructive sample of 30 shoots per clone, stratified according to diameter. The diameters of the sampled shoots were measured at 55, 85 and 105 cm above shoot base and the shoots were cut at 5 cm above shoot base and weighed after drying. Regression analysis was done using an iterative least square method, SYSTAT/NONLIN (Wilkinson, 1990) and the parameters b and c were determined for each clone and measurement height.

2. A destructive method by which all living shoots per stool were harvested and the individual stool fresh weight was weighed in the field. The dry matter content (*dmc*) for each clone was determined from a sample of 10 stem pieces per clone.

The aims of the study were firstly to validate the accuracy of the non-destructive method in comparison to the destructive method. Secondly, the influence of shoot shape on the allometric relationship between stem diameter at three different measuring-heights and shoot dry weight was investigated. Finally, survival and biomass production of 12 willow clones were assessed.

Paper III

This study was carried out during the 1st 3-year cutting cycle in three field trials established 2001 in Sweden. Two of the trials, differing in soil characteristics, were located at Ultuna (clay) and Pustnäs (sandy loam) near Uppsala (59°49´N, 17°40´E) and the third trial at a drier site (sand) near Stenstugu, Gotland (57°36´N, 18°27´E). Six to nine commercial clones, previously characterized for growth characteristics (Weih & Nordh, 2002), were included in the trials and planted in a commercial double-row system at a density of about 18,000 cuttings ha^{-1}. The trials at Ultuna and Pustnäs were divided into four plots and to each plot one of the following treatments were applied: no irrigation and no fertilisation (W_0F_0); no irrigation and fertilisation (W_0F_+); irrigation and no fertilisation (W_+F_0); and irrigation and fertilisation (W_+F_+). The trial at Stenstugu included only one plot with no irrigation and no fertilisation. Measurements included annual assessments of plant survival, shoot production and weed cover. Assessment of total leaf area and biomass as well as total nitrogen contents of leaves and shoots was done in the trial at Pustnäs in 2003.

The aims of this study were to predict shoot biomass of field-grown stools after three years growth based on the growth of pot-grown plants after one growing season (Weih & Nordh, 2002) by investigating if the same clone-specific relationships between growth traits (leaf area and biomass production) found in the pot studies also could be found in the field trials.

Paper IV

This study was performed in the same willow clonal trial located near Västerås, Sweden (59°37´N, 16°40´E) described in Paper II, and covers the period from 1990 to 2003 corresponding to 3.5 cutting cycles. During this period the trial was fertilised on nine occasions (in total 852 kg N ha^{-1}) and harvested three times by a commercial harvester. The cutting cycle length was four years. Measurements of stool and shoot survival and above ground living woody biomass of individual stools were done annually for each clone and standing biomass production per unit area was calculated. Biomass was measured with two different but accordant methods (Paper II). Standing biomass of dead wood was measured destructively before harvest in the end of the 2^{nd} and 3^{rd} cutting cycle.

The aims of the study were to assess biomass production and stand dynamics during several cutting cycles by means of annual measurements of individual plant performance, scaled up to stand level. Stand development was evaluated in relation to climate and fertilisation and management measures for a sustainable production were discussed.

Results and discussion

This thesis shows that biomass production in SRWC systems is reflected by stand development, which partly can be controlled to enhance biomass production in the longer term. While production in SRWC systems can be described as the product of stool density and biomass increment per stool, there is an interaction between those components that needs to be accounted for, realising that there is a limit to the capacity of individual stools to grow and compensate for the death of neighbouring stools.

Changes in resource capturing and in allocation patterns in developing stands go along with changes in allometric relations in plant parts, thereby urging for time- and site-specific biomass estimation procedures (Telenius & Verwijst, 1995). Furthermore, there are differences in growth and allocation patterns between clones, and clone-site interactions are also important components of final biomass production (Weih & Nordh, 2002).

The biological basis of the practical management of a SRWC system deals with optimising the net capturing and conversion of solar radiation into harvestable biomass through the process of photosynthesis. While the energy efficiency in natural ecosystems ranges from 0.1 to 0.5 % (Odum, 1971), the efficiency in managed systems with coppiced broadleaved trees like willow reaches the efficiency of many agricultural crops (Cannell, 1989). This is largely due to high allocation to above ground parts and the relatively low respiration cost of juvenile tissue.

In the following section of the thesis, methodological aspects of biomass estimation will be presented and discussed (Paper I and II) and finally, long term stand development and its implications for practical management will be presented (Paper III and IV).

Methodology

Non-destructive biomass assessment methods in SRWC plantations commonly relate dry weight of the shoot to stem diameter at 50 cm above harvest level (Nilsson, 1981; Verwijst, 1991). This method applies well to willow clones that display an erect physiognomy but does not fit the growth form of the *S. dasyclados* clone 77075 (Paper I) where the above ground allocation pattern is reflected in bow-shaped stems with many branches that often show apical dominance. The best performing method for clone 77075 was when the shoot dry weight was related to the sum of the cross sectional areas of all shoots (both the main stem and the branches) intercepted at 55 cm distance from the stem base (Paper I, Fig. 1, L55). A linear regression model, $W = a(AREA)$, where W is the shoot dry weight and a is the regression coefficient, could be used to fit the data (adj r^2 = 0.989).

Another shoot shape characteristic that may differ between *S. dasyclados* and *S. viminalis* clones is stem tapering, i.e. how fast the stem diameter is decreasing with increasing shoot height. Large stem taper will make the stem diameter measurements more sensitive to deviations from a given measurement level. This was observed at Brunnby (Paper II), where clone 81090 - the only *S. dasyclados* in the trial and with slightly bow-shaped shoots - showed a more pronounced tapering than the *S. viminalis* clones between 85 and 105 cm above shoot base (Nordh, 2001). When comparing the correlations of non-linear regressions between stem diameter measured at three different heights above shoot base (55, 85 and 105 cm) and shoot dry weight, clone 81090 had the highest correlation at

55 cm (adj $r^2 = 0.992$) while all the other clones had best correlations at 85 or 105 cm (Paper II, tab. 2). In general, however, the non-linear regressions showed god fit for all three measuring heights (adj $r^2 \geq 0.961$) showing that in a 4-year-old stand it is possible to elevate the point of measure to at least 105 cm above shoot base without loosing precision and thereby also improve working ergonomics.

A large part of the woody biomass in a willow shoot is found in the shoot base and hence, if harvest level is increased a few centimetres the biomass harvested is reduced by several percent (Hytönen *et al*., 1987; Telenius & Verwijst, 1995). For clones that have shoots with pronounced tapering and/or are bow-shaped close to soil surface, the fraction of biomass located close to the ground is even larger. Clone 77075 (Paper I) had about 41% of the biomass located below 55 cm above the soil surface and consequently, small variations in harvest levels will have a large impact on harvest outcome. Additional harvest losses may occur as bow-shaped shoots are often dropped in the field as they are difficult to grip and feed into the chipper. Since 1987, when the studied plantation was established, clone 77075 and other clones with similar morphologies have been taken out of the commercial selection used for SRWC. In current commercial practice, stool morphology, i.e. erect growth, is an important selection criteria when breeding willow (Larsson, 1998) but as willows are often used as a multipurpose crop (Abrahamson *et al*., 1998; Verwijst, 2001), clones may be selected and grown because of other useful characteristics.

Processes that influence long term stand development in SRWC systems can be understood in greater detail if they can be studied by annual measurements on individual stools. To do this without interfering with plant growth and stand development, biomass measurement methods with limited destructive sampling are needed. Such methods have been used and described previously (Nilsson,1982; Hytönen *et al*., 1987; Verwijst & Telenius 1999; Paper I). The comparison between the non-destructive method and the destructive method showed a good coincidence between the methods for all clones where the mean deviation was 2.5% and the largest difference found was a 7.1% underestimation of stool weight when using the non-destructive method (Paper II, Tab. 3). This suggests that the precision of the non-destructive biomass measurement method is high and can be used in mature commercial SRWC stands to facilitate decisions on harvest timing. Commercial SRWC stands may exhibit large spatial within-field variation in growth and, therefore, the procedures of sampling stools to measure and assess stool survival are not as straightforward as in controlled experimental plots. This was studied by Telenius & Verwijst (1995) and they found that sampling of stools and assessment of stool survival was preferably done along row sections rather than on individual stools.

The differences in shoot allometry both between clones and years found in the studies (Paper I and II) indicate that there are also clone differences in resource allocation which influence the volume and shape of shoots (Fig. 1).

Biomass production and dynamics

The production per unit area during the establishment phase of a plant population is to a large extent depending on plant density. When plant density is low, the production is directly proportional to the density and described by a linear relationship often referred to as 'yield-density effect' (Harper, 1977). However, the denser the initial spacing, and as time passes and plants grow bigger, the plants will start to compete and the yield at given site conditions will eventually become independent of plant density. This was described by Kira *et al*. (1953) as the 'law of constant final yield' and has also been observed when comparing mature SRWC plantations planted at different densities (Willebrand & Verwijst, 1993).

SRWC systems planted with about 15,000 to 20,000 cuttings ha^{-1} are usually depicted as dense plantations, but, during the initial year in the first cutting cycle, before the bare cuttings have developed roots and shoots, the stand is characterised by a sparse and far from closed canopy. In this stage much of the incoming radiation reaches the ground floor and consequently, weed control is crucial.

During the first cutting cycle at Brunnby the mean annual increment per unit area increased every year (Paper IV, Fig.1), shoot mortality was low (Paper IV Fig. 3) and, except for the establishment year, the stool mortality was also very low (Paper I, Tab 6) indicating that there was no or only low competition between stools. The standing woody biomass at the end of the 1st cutting cycle was correlated to survival ($p < 0.001$) and production gained 3 t DM ha^{-1} for each 10 % increase in survival. The mortality during the establishment year was almost exclusively observed as cuttings that never started to grow, and this shows the importance of good establishment to reach high yield in the 1st cutting cycle. There are several plausible explanations why some cuttings did not sprout, i.e. variations in micro-site conditions, poor cutting quality due to inadequate storage or differences in cutting size, but none of these were investigated at Brunnby. Rossi (1991; 1999) showed that for both poplar and willow the survival and growth were improved by increased cutting length and Burgess *et al*. (1990) found better growth and survival of willows due to both longer and thicker cuttings. All cuttings planted at Brunnby were 20 cm long but the thickness varied from the commercially recommended minimum diameter of 8 mm to about 20 mm.

In the 2nd cutting cycle the mean annual increment per unit area peaked in the 2nd year and declined thereafter. The final mean yield, including standing dead wood, was about 34 % higher than in the 1st cutting cycle which is in accordance with the findings of Hofmann-Schielle *et al*. (1999) and Labrecque & Teodorescu (2003). The annual relative stool mortality increased in the two last years of the 2nd cutting cycle and stool mortality occurred mainly among smaller plants while large plants had higher survival rate. This can be shown by sorting stools in size classes according to initial weight in the end of the 2nd year of the 1st cutting cycle and follow the survival in each size class during 3 cutting cycles (Fig. 2).

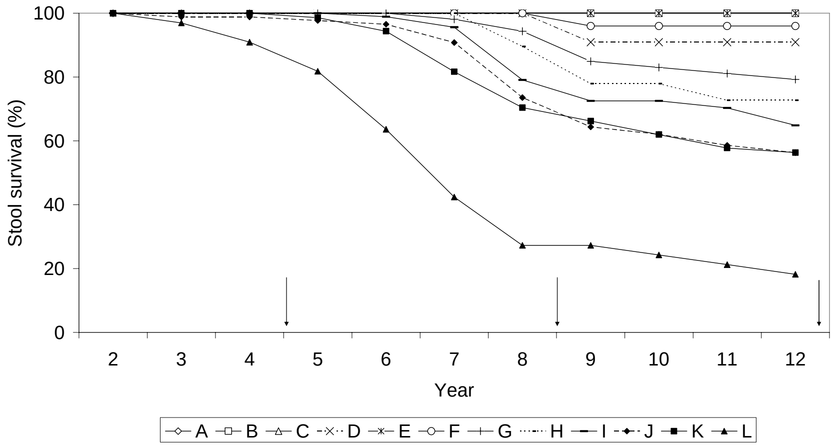

Figure 2. Stool survival during 3 cutting cycles (12 years) in relation to initial stool dry weight (g) in year 2. A sample of in total 470 stools from 12 clones was sorted according to weight in classes of 100 g. The letters A to L correspond in decreasing order to the following initial stool size classes: A = 1199 to 1100 g; ...; L = 99 to < 0 g. The number of stools in each size class ranged from 2 (A) to 91 (I). At the end of the 3rd cutting cycle 309 stools had survived and number of surviving stools in each size class ranged from 2 (A) to 6 (I). The arrows indicate harvest (Nordh, unpublished data).

The size development of the surviving stools in the 12 size classes during 3 cutting cycles shows that the ranking in size is more or less the same over time (Fig. 3). Hence, a stool size hierarchy is already present in the second year and this hierarchy prevails over time also when the above ground biomass is removed by harvest (Fig. 3). Weiner & Thomas (1986), showed for a range of different plant species that plant size hierarchies develops early. This was also observed by Verwijst (1996) who hypothesised that the root reserves were in proportion to above ground stool size. Although no biomass measurement was made until the 2nd year of the 1st cutting cycle it is likely that the stool size hierarchy was established already during the planting year. The combined observations of low cutting vigour and the rapidly developed stool size hierarchy, emphasises the importance of the establishment phase for the long term stand development, and that the use of homogenous, high quality cuttings along with proper site preparations are means to achieve good establishment and hence a solid foundation for future stand development.

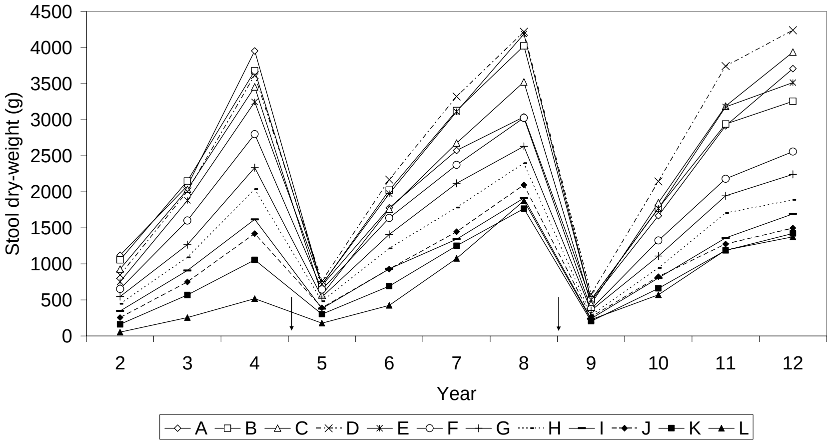

Figure 3. Stool weight development during 3 cutting cycles (12 years) in relation to initial stool dry weight (g) in year 2. The arrows indicate harvest. For further explanations, see Fig. 2 (Nordh, unpublished data).

The accentuated stool mortality in the later half of the 2nd cutting cycle seems to be density dependent (Paper IV, Fig 4) and it can be assumed that this mortality could have been avoided or at least postponed if harvest had been carried out after three years instead of four. This expectation is partly confirmed by the performance of another SRWC trial, planted 1994 on a clay soil in Ultuna near Uppsala, 80 km east of Brunnby. This clone trial has a different set of clones than in Brunnby but the same design and stool density, and a similar fertilisation regime as in Brunnby. The trial was coppiced the year after establishment and thereafter harvested on a 3-year cutting cycle. In Fig. 4, a comparison of mean accumulated biomass and mean stool survival in the two trials has been made (Nordh, unpublished data). After the first 10 years the accumulated biomass is about the same in the two trials but the stool survival pattern differs. The trial harvested every fourth year has a very rapid and large decrease in stool survival in the end of the 2nd cutting cycle while the trial harvested every third year exhibits slower stool mortality evenly distributed over time. After 10 years, the difference in survival is close to 15 percentage units and the higher stool density in the trial harvested every third year gives better prerequisites for a continued sustainable biomass production. This comparison strengthens the assumption that by adapting the cutting cycle length stool survival may be improved.

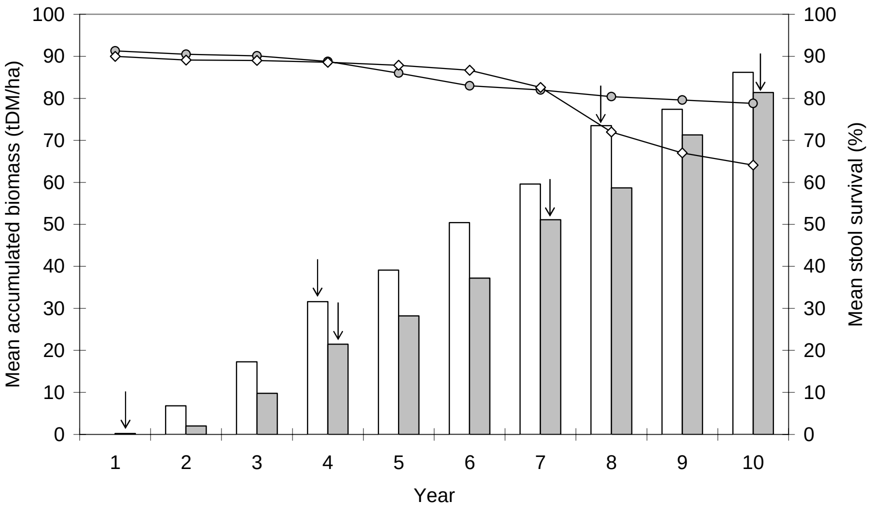

Figure 4. Comparison of biomass accumulation and survival in stands with 4-year cutting cycle (white bars and ◇) and 3-year cutting cycle (grey bars and ●). The stand of the 4-year cutting cycle consisted of 12 clones established in 1990 at Brunnby, near Västerås. The stand of a 3-year cutting cycle consisted of 16 clones established in 1994 at Ultuna, near Uppsala. Accumulated biomass includes both living and dead aboveground wood. Arrows indicate harvest (Nordh, unpublished data).

The low biomass production in the 3rd cutting cycle at Brunnby was also partly caused by the high stool mortality. In comparison to the 2nd cutting cycle the mean stool weight of living woody biomass decreased 11 % in the 3rd cutting cycle while the mean standing living woody biomass per unit area decreased as much as 28 % (Paper IV). However, after two years in the 4th cutting cycle, the mean stool weight had increased 34 % and the mean standing biomass increased 15 % in relation to the corresponding year in the 3rd cutting cycle. This indicates that the remaining stools were not able to fully compensate for their dead neighbours during the 3rd cutting cycle but in the 4th cutting cycle the biomass production seems to stabilise as individual stools are growing bigger by occupying available space caused by the decrease in stool density. In addition, the growth of remaining stools could also be further enhanced by fertilising if water is not a limiting factor (Paper IV, Fig. 6).

The general trends of mean stool mortality and mean biomass production per unit area as described above were valid for all clones although significant effects of clone, year and their interaction on biomass production were found (Paper IV).

Clone-specific characteristics were also found when trying to predict field performance - measured as shoot biomass production - of a number of clones based on their performance in a pot trial (Paper III). The results show that total leaf area and total N pool of plants grown in pots can be used for predicting shoot biomass growth in the field. The studies were performed in a non-coppiced stand, during the first 3-year cutting cycle only, which restricts the predictive power of the method. As shoot biomass yield tends to increase in the 2nd cutting cycle (Paper IV), the applicability of the method for long term performance of willow clones, needs to be further tested by relating characters from pot studies to clone field performance during later cutting cycles. This view is supported by the shifts in ranking between clones and years found in Paper IV. Another limitation of the method is that the relationships were found to be clone-specific, meaning that predictions on field performance of a certain clone can only be made by studying potted plants of the same clone. Also in this study (Paper III) the biomass production was influenced by fertilisation but not by irrigation.

The accumulated above ground woody biomass production of the different clones during the 3.5 cutting cycles at Brunnby ranged from 95 to 133 t DM ha^{-1} (Paper IV). Assuming that the energy content of willow is about 4.5 MWh per t DM (Danfors *et al*., 1998), the biomass yield is equivalent to about 430 to 600 MWh ha^{-1}. The clones included in the trial come from an early selection and are no longer part of the current selection of commercial clones, but still, several of the clones have produced biomass at levels that exceeds the yield levels used for profitability calculations by Agrobränsle AB (2005), i.e., 22 t DM ha^{-1} in the 1st harvest and 28 t DM ha^{-1} in the 2nd and following harvests (Paper IV, Tab.3). The ongoing Swedish willow breeding program has regularly introduced new improved and high-yielding willow hybrid clones on the market (Larsson, 1998) that are likely to increase the yield in SRWC plantations if proper clone-site matching can be achieved. Weih (2001) tested the performance of a natural clone and an improved hybrid clone under different fertilisation and irrigation regimes in a pot study and found that the hybrid was more sensitive to nutrient and water stress than the natural clone. The natural clone turned out to be a "generalist", performing better than the hybrid when low rates of fertiliser and water were supplied while the hybrid clone performed as a "specialist" and grew better than the natural clone at high rates of water and fertiliser. This shows that the relative performance of clones may be dependent on choice of site. As the study on long term dynamics of 12 clones was performed only at a single site (Paper IV), one may raise the question of site-specificity of the results. As there are virtually unlimited combinations of clones, sites and cultural practices (Host *et al*., 1996), model development instead of experimental field testing, has been proposed to screen possible alternatives. Given the commercial development SRWC in Sweden, an interesting option would be to amalgamate clone and site specific information into a database. Analyses of such data greatly would enhance the possibility of suitable clone-site matching in commercial practice. This also would allow for precision farming (Godwin *et al*., 2003). One important issue to address is whether clones selected for SRWC plantations, that are expected to prevail at least for 20 to 25 years, should be clones that perform well under a wide range of site conditions or if clones that are highly specialised should be used.

Irrespective of the clone-site matching issue, the results of this thesis suggest that – given the temporal variations in radiation and precipitation among years – a flexible management should be developed, which adapts harvest timing and fertilisation to actual stand development.

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