The potential contribution of a short-rotation willow plantation to mitigate climate change

Lenny van Bussel

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Summary

Due to several environmental problems and their possible solutions, renewable energy is gaining more and more interest nowadays. The Dutch government has ambitious objectives in the field of renewable energy. Substitution of fossil fuels by willow biomass, an example of renewable energy, may mitigate climate change. However to know the potential contribution of a short-rotation *Salix* plantation to mitigate climate change, production numbers and the emissions related to several management activities have to be determined. This study aims to enlarge the knowledge on this subject.

The production numbers of above-ground woody biomass and stand characteristics of three *Salix* varieties planted at several initial densities (13,675 – 22,222 plants ha^{-1}) were assessed in this study. Shoots in their first and second growing season were measured. Biomass assessments were based on a harvest method, a destructive method, and on allometric relationships between shoot dry weight and shoot diameter, a non-destructive method. To assess the non-destructive method, biomass estimations were carried out with help of both methods and compared with each other. Planting density and aging of the shoots influence the number of shoots per plant and the average diameter per shoot. A higher planting density results in less but thicker shoots per plant; the same is noticed for aging of the shoots. One variety is performing poor under Dutch conditions, indicated by a low average plant weight, and a low number and mainly thin shoots per plant. Under Dutch conditions production numbers were found in a range of 5.62 – 15.62 t DM ha^{-1} yr^{-1}. A higher planting density results in higher production numbers. The biomass production during the two growing seasons is approximately the same. The results suggest that production numbers under Dutch conditions correspond with production numbers in regions with the same climatic conditions. In comparison with regions with extremer climatic conditions, production numbers under Dutch conditions are 150 – 300 % higher. The non-destructive method is a reliable manner to measure production numbers. The method is less time consuming and is therefore a good alternative for measuring productivity of commercial plantation.

This study assumes a 15 years lifespan of a short-rotation *Salix* plantation under Dutch conditions, consisting of 1 year of site preparation and 7 harvest cycles of 2 years. During the lifespan several management activities have to be carried out, resulting in emissions of greenhouse gases. Leaf litter may be a source of greenhouse gases as well. On the other hand, carbon sequestration in the soil may offset the effects of those emissions. This study evaluates the energy and greenhouse gas balance of a short-rotation *Salix* plantation during its lifespan. Literature research was carried out to find numbers concerning energy use during management activities and greenhouse gases emissions. A model was applied to calculate possible amounts of carbon sequestered in the soil under a *Salix* plantation. To be able to sum up the effects of the different greenhouse gases and the offset potential of the carbon sequestration, all numbers

were converted to CO_2 eqv ha^{-1}. The production of 1 GJ was used as a functional unit to compare emissions from a *Salix* plantation and a coal-fuelled power plant. Two management activities, namely production and transport of fertiliser and harvesting, emit almost three-quarter of the total amount of greenhouse gases. In comparison with a coal-fuelled power plant the amount of emitted greenhouse gases by a *Salix* plantation is low, approximately 5 % of the amount of emissions in case 1 GJ is produced by utilising coal. The amount of carbon sequestrated in the soil may offset the effect of the emitted greenhouse gases totally, but only if biomass production levels are high enough. To produce 20 GJ of biomass energy an input of 1 GJ of fossil fuel is needed.

This study indicates that short-rotation *Salix* plantations under Dutch conditions may produce considerable amounts of biomass with help of low fossil energy inputs and results in little greenhouse gas emissions. However, the total amount of biomass produced in the Netherlands highly depends on the amount of available land for growing *Salix* crops. This is still an uncertain factor, calling for more research.

Preface and acknowledgement

It has been the consideration of our wonderful atmosphere in its various relations to human life, and to all life, which has compelled me to this cry for the children and for outraged humanity. Will no body of humane men and women band themselves together, and take no rest till this crying evil is abolished, and with it nine-tenths of all the other evils that now afflict us? Let everything give way to this. […] Let this be our claim: Pure air and pure water for every inhabitant of the British Isles. Vote for no one who says "It can't be done." Vote only for those who declare "It shall be done."

Alfred Russel Wallace, *Man's Place in the Universe*, 1903

As this quotation of Alfred Russel Wallace indicates, even in 1903 people were already concerned with the problem climate change and how to solve it. In previous parts of my study I have studied the effects of climate change on ecosystems. However, I was also curious not only for the effects of climate change, but also for possible solutions. With this MSc-thesis I have tried to contribute to the knowledge climate change mitigation.

I would like to thank a few people. First of all I would like to thank my both supervisors, Leen Kuiper and Frits Mohren. They have given me valuable ideas and very relevant comments on my work. Also I would like to thank my mother Nellie and sister Anke for their help with the fieldwork! It was really nice to have you there in Flevoland during those snowy and rainy days. Hans Jansen also deserves a “thank you” because of his very helpful assistance with some of the statistical problems. And even from Sweden I gained some valuable comments of Theo Verwijst, thank you as well! Last but not least I would like to thank my fellow students and friends, for the pleasant breaks during the long days in “Lumen” and their support.

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1. Biomass production in the Netherlands of three willow (Salix) clones grown under different management strategies

Abstract

The production numbers of above-ground woody biomass and stand characteristics of three willow (*Salix*) varieties planted at several initial densities (13,675 – 22,222 plants ha^{-1}) were assessed in this study. Shoots in their first and second growing season were measured. Biomass assessments were based on a harvest method, a destructive method, and on allometric relationships between shoot dry weight and shoot diameter, a non-destructive method. To assess the non-destructive method, biomass estimations were carried out with help of both methods and compared with each other. Planting density and aging of the shoots influence the number of shoots per plant and the average diameter per shoot. A higher planting density results in less but thicker shoots per plant; the same is noticed for aging of the shoots. One variety was performing poor under Dutch conditions, indicated by a low average plant weight, and a low number and mainly thin shoots per plant. Production numbers in a range of 5.62 – 15.62 t DM ha^{-1} yr^{-1} under Dutch conditions was found. A higher planting density results in higher production numbers. The biomass production is approximately the same during the two growing seasons. The results suggest that production numbers under Dutch conditions correspond with production numbers in regions with the same climatic conditions. In comparison with regions with extremer conditions, production numbers under Dutch conditions are 150 – 300 % higher. The non-destructive method is a reliable manner to measure production numbers. The method is less time consuming and is therefore a good alternative for measuring productivity of commercial plantation.

Keywords: Short rotation forestry, *Salix*, planting density, biomass production, the Netherlands

1.1. Introduction

Due to several environmental problems, especially climate change, renewable energy is gaining more and more interest nowadays. Renewable energy is defined by the IPCC as: “Energy sources that are, within a short timeframe relative to the earth’s natural cycles, sustainable, and include non-carbon technologies such as solar energy, hydropower, and wind, as well as carbon neutral technologies such as biomass” (IPCC, 2001a). The use of renewable energy can help to mitigate climate change. Mitigation is defined as: “An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases” (IPCC, 2001a).

The Dutch government has ambitious objectives in the field of renewable energy: in 2020 the contribution of renewable energy to the total energy production has to be 10% (Ministerie van Economische Zaken, 2005). According to the objectives, in 2020 the contribution of bio-energy has to be 120 PJ yr^{-1}, which corresponds to about 40% of the total renewable energy target. Part will be generated with help of bio-energy resources, among others dedicated energy crops grown in the Netherlands, sometimes called “energy farming”. Energy crops can be classified in woody crops and grasses (Londo, 2002). This research will concentrate on a woody crop, namely *Salix* in short rotation forestry. To be able to know how much *Salix* in short rotation forestry can contribute to the objectives of the Dutch government it is necessary to know how much biomass can be produced by this crop under Dutch conditions.

According to Mitchell and Ford-Robertson (1992 p. xiii) “Short rotation forestry is used to describe a wide range of silvicultural regimes, from 1-year cutting cycles of poplar and willow grown under so-called “wood grass” regimes, to 20-year rotations of southern pines”. Short rotation forestry makes use of fast growing trees (Weih, 2004), which have the ability to resprout after harvest or damage. This resprout-ability is a natural survival mechanism, probably developed in response to fire, drought and other periodical stress factors (Sennerby-Forsse et al., 1992; Cannell, 2004; Harmer, 2004).

Several crops have this resprout-ability and are fast growing, thus can be used in short rotation forestry. Those crops originate from a clone of forest community types, from boreal to tropical, examples are: *Alnus, Eucalyptus, Platanus, Populus, Robinia,* and *Salix* (Hinckley et al., 1992). In this research the focus will be on *Salix* crops. *Salix* was chosen because this crop is among others well adjusted to the Dutch growth conditions (Gigler et al., 1999; Londo, 2002) and it has a long history in the Netherlands (Schepers et al., 1992).

Salix belongs to the family Salicacea. Characteristics of this family are a wide, natural distribution range, wood that is suitable for energy production because of its uniform texture, high initial growth, a short life span, easy reproduction by vegetative means (stem cuttings), relative early flowering, and the ability to resprout vigorously (Weih, 2004).

Salix is currently not commercially cultivated as an energy crop in the Netherlands, thus ‘normal’ yield figures cannot be derived from field data to determine the mitigation potential (Londo, 2002). Especially production levels of newly developed clones under Dutch conditions are not known. Neither known are the effects of different management regimes, such as establishment techniques and spacing (Mitchell and Ford-Robertson, 1992; Makeschin, 1999; Nordh, 2005), on the production of biomass of those newly developed clones.

The objective of this research is to assess biomass production and stand characteristics of three different clones (Jorr, Loden, and Tora), with 1 and 2 year old shoots. Also biomass production of those three clones with three different planting densities (13,675 to 22,222 plants ha^{-1}) will be compared. To make biomass estimations of *Salix* plantations in future easier and less destructive, allometric relationships, between shoot dry weight and shoot diameter, will be established for the different clones and planting densities.

1.2. Material and Methods

1.2.1. Site description

The *Salix* plantations used in this study are located on three different sites in Flevoland, the Netherlands, near Lelystad, all sites were established in 2000 (see Table 1 and Figure 1 for more details). Three different clones, three different planting densities and two different shoot ages were compared. The measurements were carried out in March 2006, because until then the *Salix* plants were in their dormancy phase, and thus in their first growing season (personal communication, L. Kuiper[1]). See Figure 1 for the position of the sites

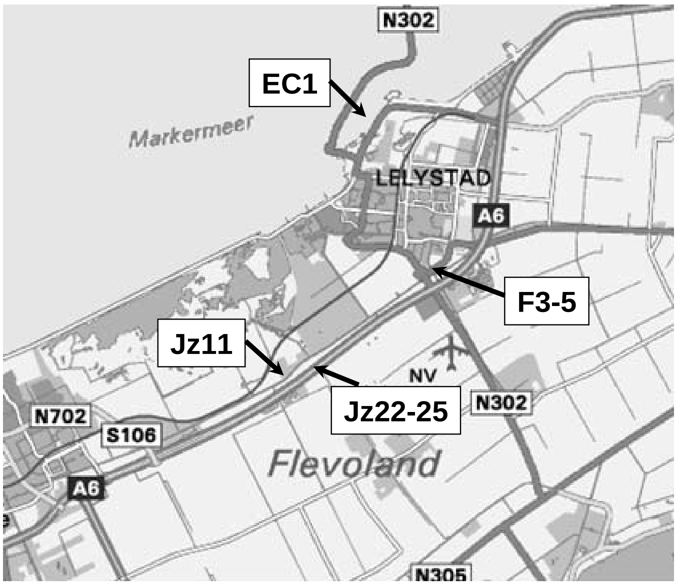

Figure 1 Locations of the sites

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[1] Dr. Ir. L. C. Kuiper, Stichting Probos
P.O. Box, 6700 AG Wageningen, the Netherlands (February 2006)

Table 1 Description of different plots

Plot name	***Salix* variety**	**Plant density (plants ha^{-1})**	**Total area (ha)**	**Coppiced in end of**	**Cutting cycle**	**Growing season**
EC1 plot 1	Jorr	22,222	0.5	2002 and 2004	3	1
EC1 plot 2	Tora	22,222	0.5	2002 and 2004	3	1
EC1 plot 3	Loden	22,222	0.5	2002 and 2004	3	1
EC1 plot 4	Jorr	17,778	0.5	2002 and 2004	3	1
EC1 plot 5	Tora	17,778	0.5	2002 and 2004	3	1
EC1 plot 6	Loden	17,778	0.5	2002 and 2004	3	1
EC1 plot 7	Jorr	13,675	0.5	2002 and 2004	3	1
EC1 plot 8	Tora	13,675	0.5	2002 and 2004	3	1
EC1 plot 9	Loden	13,675	0.5	2002 and 2004	3	1
F3-5 right side	Jorr	17,778	2.75	2002 and 2004	3	1
JZ11 plot 1	Jorr	17,778	3.63	2003 and 2005	2	2
JZ11 plot 2	Tora	17,778	3.52	2003 and 2005	2	2
JZ22-25	Jorr & Tora	17,778	2.36	2003 and 2005	2	2

The planting design of the different plots is a double-row system with alternating distances of 75 and 150 cm, and a variable spacing of 40, 50 and 65 cm between the plants. Plot JZ22-25 contains two *Salix* clones; those clones are mixed per row.
The experimental design of the different plots hinders the execution of any repetitions, thus the outcomes of this research will only indicate a tendency of biomass production under different treatments (no statistical evidence can be given). See Figure 2 for more details about the experimental design of the sites.

Another problem concerning the experimental design is the non-randomly distribution of the different treatments. Some clones experience more edge effects than other clones. This problem was solved partly by measuring only trees in the central plots, but a systematic error because of the non-random distribution of the treatments cannot be avoided. This should be taking into account with the interpretation of the conclusions.

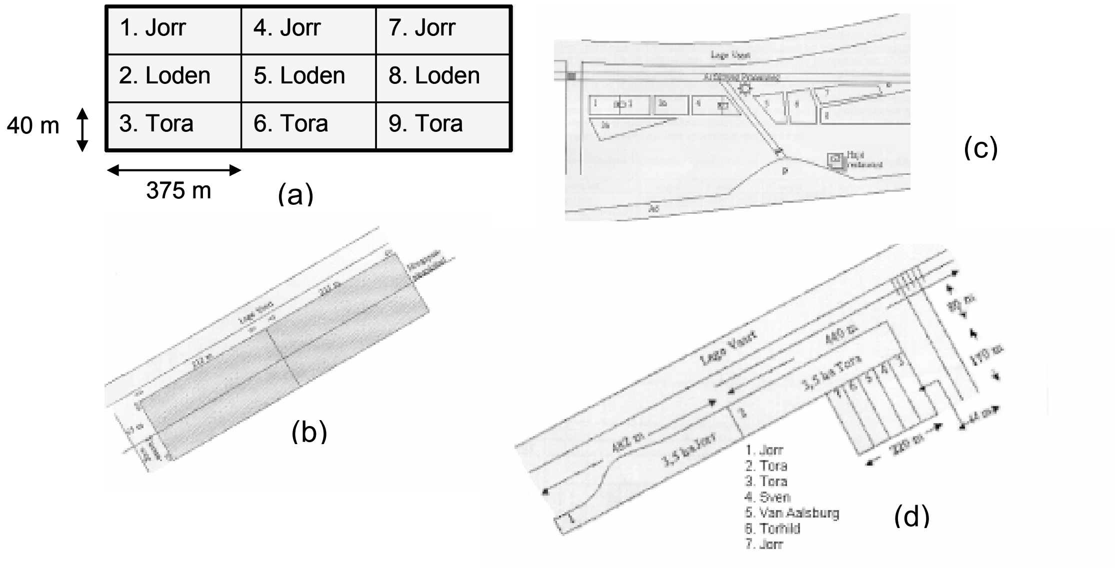

Figure 2 Experimental designs of EC1 (a), F3-5 (b), JZ22-25 (c) and JZ11 (d)

1.2.2. Measurements and assessments

The most straightforward procedure to determine the standing living woody biomass is harvesting (Nordh and Verwijst, 2004), which is a destructive method. Due to previously carried out management on some plots, the harvest of the shoots, it was not possible to carry out the harvest method on all plots. As a result, the harvest method was not applicable and non-destructive measurements were carried out.

Standing living woody biomass in *Salix* plantations depends on the number of plants present and biomass per plant (Nordh, 2005). The number of plants changes in time due to mortality, thus mortality should be taken in consideration if biomass is calculated.
The number of shoots per ha can be calculated with help of the average number of shoots per plant and the number of plants per ha present; this is necessary for the non-destructive method. Biomass per plant can be expressed in different ways as well, depending on the measuring method. The most straightforward way to determine biomass per plant is to weight the whole woody part of a plant. This quantity is used in the destructive method. Another way to calculate biomass per plant is to measure the number of shoots per plant, diameter of the shoots, and the shoot diameter distribution. These quantities are used in the non-destructive method.

If standing living woody biomass is mentioned in this study, only above-ground biomass is meant.

1.2.2.1. Destructive measurements

In order to prevent edge effects, destructive measurements were done in central plots, each central plot containing 72 plants. In each plot two central plots were constructed (see Table 2 and Figure 3).

Table 2 Design of central plots

Initial planting design (plants/ha)	Design of central plot
22,222	6.75 m * 4.80 m
17,778	6.75 m * 6.00 m
13,675	6.75 m * 7.80 m

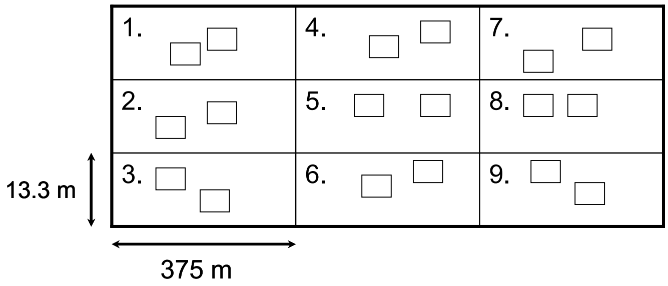

Figure 3 Schematic overview of central plots in site EC1

The second central plot was created to gain more reliable results concerning plant mortality, individual plant weight, and number of shoots per plant.

First the number of living plants (L, [-]) in the two central plots was counted. With help of this number the proportion of surviving plants (S, [-]) in the plot was calculated:

$$S = L / 72 \qquad \text{(eq. 1)}$$

The proportion of surviving plants per plot was calculated as an average of the proportions of surviving plants in the two central plots.

Second, biomass measurements were carried out on 10 living plants, which were randomly chosen from the central plots. To construct a diameter probability distribution, the diameter at shoot base (D_s, [cm]) of each shoot was measured. The number of shoots per plant was counted as well.

After this, all living shoots of those 10 plants were cut at shoot base and individual plant fresh weight (FW_{plant}, [kg]) was determined in the field by weighing the shoots of one plant together, using a balance with an accuracy of 100 g. This was also carried out for 10 more plants, randomly chosen from the other central plot. The number of shoots per plant of those 10 plants was counted as well. Together with the results of the other central plot the average number of shoots per plant (AN_{shoot}, [-]) was calculated.

Some numbers had to be converted from fresh weights into dry weights. This was done with help of the dry matter content (dmc, [g DW/g FW]. The dry matter content was calculated with help of 10 stem pieces per plot. Those stem pieces of approximately 40 cm were cut from 10 randomly chosen shoots per plot; it was avoided to use the upper or lowest parts of the shoots.

The sample fresh weight of each stem piece (FW_{stem_piece}, [kg]) was measured in the laboratory using a balance with an accuracy of 0.01 g. After weighting the stem pieces were cut, put in paper bags and dried at 85°C for at least 72 h until a constant oven dry weight was achieved. After drying, dry weight (DW_{stem_piece}, [kg]) was measured, using a balance with an accuracy of 0.01 g. The dry matter content (dmc, [g DW/g FW]) was calculated, using the following equation:

$$dmc = (\sum DW_{stem\_piece} / FW_{stem\_piece}) / n \qquad \text{(eq. 2)}$$

where n = number of stem pieces (10).

Standing living woody biomass per ha in dry matter [kg DM ha^{-1}] was calculated with help of:

$$B = (\sum FW_{plant} / n) * dmc * S * C \qquad \text{(eq. 3)}$$

where FW_{plant} [kg] is fresh weight of an individual plant, n is number of measured plants, dmc [g DW/g FW] is the dry matter content, S [-] is proportion of surviving plants (eq. 1), and C [plants ha^{-1}] is the number of cuttings per hectare.
Production per ha per year in dry matter [kg DM ha^{-1} yr^{-1}] was gained by dividing B by the age of the shoots.
This method is derived from Nordh and Verwijst (2004).

Production numbers of woody biomass per ha in dry matter (B, [kg DM ha^{-1} yr^{-1}]) were calculated with help of:

$$P = B / \text{age of shoots} \qquad \text{(eq. 4)}$$

1.2.2.2. Non-destructive measurements

To be able to calculate production numbers of woody biomass on a non-destructive manner, an allometric relationship between shoot dry weight (DW_{shoot}) and diameter at shoot base (D_{shoot}) is necessary:

$$DW_{shoot} = b * (D_{shoot})^c \qquad \text{(eq. 5)}$$

where b and c are parameters related to clone, age and management.

To find that relationship, the diameters of 30 living and undamaged shoots, cut from the central plots, were measured at shoot base to the nearest mm (D_s, [cm]). Shoots were taken per clone,

per plant density, and per shoot age, they were taken stratified according to a range of diameters.
The fresh weight of each shoot (FW_{shoot}, [kg]) was measured to nearest 0.1 g in the laboratory. To be able to find the dry weight of each shoot the average dry matter content (dmc, [g DW/g FW]) of 10 stem pieces per plot was determined. The procedure stated above was followed.
With help of the individual fresh weight of the shoot and the dry matter content of the shoot, the individual dry weight per shoot (DW_{shoot}, [kg]) could be calculated:

$$DW_{shoot} = FW_{shoot} * dmc \qquad \text{(eq. 6)}$$

As stated above, on any plots some management was already applied. This management included the harvest of all shoots and in some cases removing the harvested shoots. Because of this, no allometric relationship could be established from JZ11 plot 2 and JZ22-25. In spite of the management, the proportion of surviving plants (S, [-]), the average number of shoots per plant (AN_{shoot}, [-]) and the number of cuttings per hectare (C, [plants ha^{-1}]) could be find of JZ11 plot 2 and JZ22-25.
On plot JZ11 plot 1 the same management was applied, but the shoots were not taken away, so an allometric relationship could be established from this plot.
With help of the allometric relationship of the two year old shoots of clone Tora, an estimation could be made of the standing living woody biomass of JZ11 plot 2 and JZ22-25 in case of no harvest.

To calculate the standing living woody biomass per hectare (B, [kg DM ha^{-1}]) on a non-destructive manner, the following steps were followed:

1. The proportion of surviving plants (S, [-]), the average number of shoots per plant (AN_{shoot}, [-]) and the number of cuttings per hectare (C, [plants ha^{-1}]) were determined (see above).
2. The diameter at shoot base was measured of 10 (in case of 1 year old shoots) or 30 (in case 2 year old shoots) randomly chosen plants. With help of the results the probability of each diameter was determined (pD_{shoot_x}).
   Of each diameter the corresponding weight of the shoot was calculated with help of
   $DW_{shoot\_x} = b * (pD_{shoot\_x})^c$ (eq. 7).
3. Finally the following formula was used to find the standing living woody biomass:
   $B = (C * S * AN_{shoot}) * \sum_{x = i \ldots r} (pD_{shoot\_x} * DW_{shoot\_x})$ (eq. 8)

Production numbers of woody biomass per ha in dry matter (B, [kg DM ha^{-1} yr^{-1}]) were calculated with help of:

$$P = B / \text{age of shoots} \qquad \text{(eq. 4)}$$

This method was partly derived from Nordh and Verwijst (2004).

1.2.3. Data analysis

To find significant differences between the different plots in number of shoots per plant or per ha, average diameter, and average dry weight per plant, first a test of normality was carried out on the specific data. If the data was normally distributed an One-Way Anova test was carried out to test for significant differences between different plots. If the data were not normally distributed transformation of the data was applied. If even after transformation, normality could not be adopted, the Kruskal-Wallis test was used to test for significant differences between different plots.

If the One-Way Anova or Kruskal-Wallis test indicated significant differences between the plots, a test of homogeneity of variance was carried out. If the homogeneity of variance could be adopted a Scheffé test was carried out to find specific differences between different plots. If homogeneity of variance could not be adopted, the data was transformed to see if homogeneity of variance could be adopted afterward. If not, the Games-Howell test was used to test for specific significant differences between different plots (Field, 2005).

First all the plots were tested together, to detect significant differences. In addition to find an effect of planting density of clonal use, more comparisons were carried out. To find the effect of planting density, comparisons were carried out with changing planting density per clone. To find the effect of clonal use, comparisons were carried out with different clones with the same planting density.

To detect significant differences between diameter distributions of the different plots, the diameters were divided in different classes of approximately 3 mm. A Chi-Square test was carried out to find eventually significant differences (Field, 2005).

With help of the computer-program SPSS the clone and density specific values of parameters of b and c of the allometric relationships could be found.

To test for significant differences between the allometric relationships, dummy variables were used. With help of a backward iteration and the confidence intervals it could be tested which relationships belong to one group and the specific allometric relationship of each group could be established.

All statistics were computed by using SPSS software package.

1.3. Results

First the results of the tests carried out with all the data together will be shown. Next the results of the tests with specific emphasis on clonal or planting density are shown.

1.3.1. Number of shoots per plant and per ha

Of all plants, the number of shoots per plant ranges from 4.20 ± 1.54 to 15.20 ± 3.38 shoots/plant. See Table 4 for specific data per plot.

The numbers of shoots per plant were significantly different between the different plots (Kruskal-Wallis test; H(12) = 180.11, p < .01). Homogeneity of variances could adopted after log-transformation, (F(12, 289) = 1.449, *ns*). Significant differences (Scheffé test; p < .05) were found between four plots (all plots with 2 year old shoots and Tora; 22,222 plants ha^{-1}) and the rest of the plots.

Biomass production levels are more affected by the total number of living shoots ha^{-1} than by the number of shoots per plant, because mortality is included in the total number of living shoots ha^{-1}. Figure 4 gives the number of living shoots ha^{-1}. The density of living shoots/ha ranges from $225 \cdot 10^3 \pm 18 \cdot 10^3$ to $60 \cdot 10^3 \pm 4 \cdot 10^3$ living shoots/ha, if all plots are considered.
The same significant differences were found (Kruskal-Wallis test; H(12) = 158.046, p < .01), with the exception of the plot with Tora; 22,222 plants ha^{-1}. This plot is less different from the other plots if total number of living shoots ha^{-1} is considered in stead of living shoots per plant.
The total number of shoots per ha per plot is approximately reduced by 50% after the second growing season.

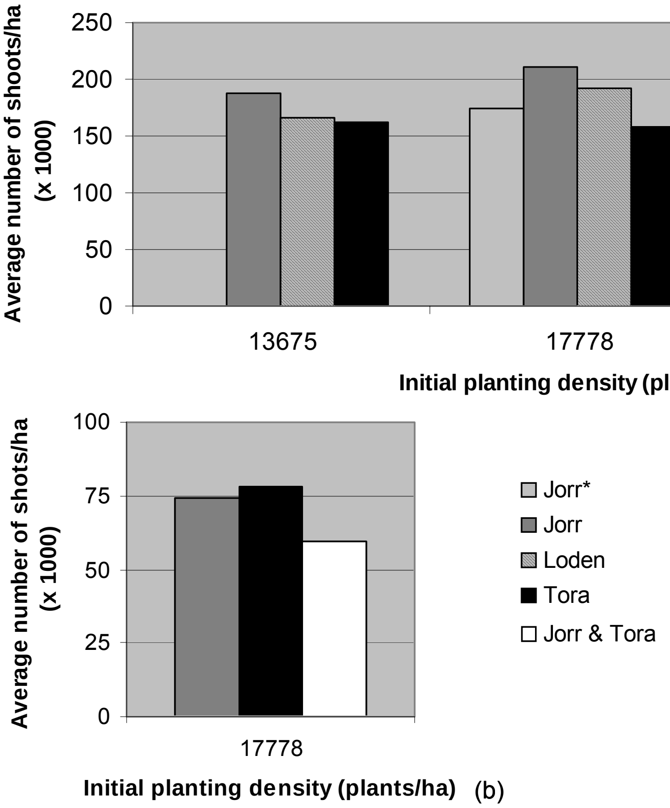

Figure 4 Number of living shoots ha^{-1} per plot (located on F3-5) (a) shows the number of living shoots ha^{-1} for 1 year old shoots; (b) shows the number of living shoots ha^{-1} for 2 year old shoots*

1.3.2. Average diameter of the shoot per plant

Of all plots, the average shoot diameter per plot ranges from 1.03 ± 0.02 to 2.62 ± 1.08 cm per plot. See Table 4 for specific data per plot.

The average diameter of the shoots per plant is significantly different between the different plots (Kruskal-Wallis test; H(12) = 686.316, $p < .001$). Significant differences (Games-Howell test; $p < .05$) were found between 1 year old shoots and 2 year old shoots. The average diameter of 2 year old shoots is significant thicker than the average diameter of 1 year old shoots ($p = .000$). Also it was found that the average diameter of plots with Tora (17,778 and 13,675 plants ha^{-1}) is significantly different from the rest. Those diameters are significantly smaller than the diameters in the other plots. One plot (Loden; 22,222 plants ha^{-1}) has significant thicker shoots than the other plots with 1 year old shoots.

The diameter distribution of the different plots was investigated also. A Chi-Square test was carried out to test for significant differences. This test indicated substantial significant differences. Nevertheless, no clear trend could be detected; almost all plots differ significantly from each other, but not in a consistent pattern.

1.3.3. Average dry weight per plant

Off all plants the average shoot diameter per plot ranges from 0.360 ± 0.182 to 0.965 ± 0.479 kg per plot. See Table 4 for specific data per plot.

The average dry weights per plant were significantly different between the different plots (Kruskal-Wallis test; H(9) = 79.19, $p < .01$). Homogeneity of variances could adopted after log-transformation, (F(9 ,177) = .777, *ns*). Significant differences (Scheffé test; $p < .05$) were found between plots with Tora and the rest of the plots. Exception is the plot with Jorr; 22,222 plants ha^{-1}. Plants of Tora, with all planting densities, and plots with Jorr with 22,222 plants ha^{-1} are significant lighter than the plants of the other plots.

1.3.4. Results of test for an effect of planting density or clonal use

To find the possible effect of planting density or clonal use on shoots/plant, shoots ha^{-1}, average shoot diameter, and dry weight per plant the plots had to be separated. In Table 3a and 3b the significant differences ($p<.05$) are indicated between the different plots. The plots printed in italics indicated the, tallest, most, heaviest etc. variety per plot.

Table 3a Significant differences with respect to clonal use

	Test for significant differences between varieties	
Shoots per plant	*Jorr and Loden with 22,222*	Tora with 22,222
Shoots per ha	*Jorr and Loden with 22,222*	Tora with 22,222
	Jorr with 17,778	Tora with 17,778
Average diameter	*Loden with 22,222*	Jorr and Tora with 22,222
	Jorr and Loden with 17,778	Tora with 17,778
	Loden with 13,675	Jorr and Tora with 13,675
Dry weight per plant	*Jorr and Loden with 22,222*	Tora with 22,222
	Jorr and Loden with 17,778	Tora with 17,778
	Jorr and Loden with 13,675	Tora with 13,675

Table 3b Significant differences with respect to planting density

	Test for differences between planting densities	
Shoots per plant	*Jorr with 17,778 and 13,675*	Jorr with 22,222
	Tora with 17,778 and 13,675	Tora with 22,222
Shoots per ha	*Loden with 22,222*	Loden with 13,675
Average diameter	*Jorr with 17,778*	Jorr with 13,675
	Loden with 22,222	Loden with 17,778 and 13,675
	Tora with 22,222	Tora with 17,778 and 13,675
Dry weight per plant	*Jorr with 17,778*	Jorr with 22,222

Table 4 Characteristics per plot

Plot name	***Salix* variety**	**Plant density (plants/ha)**	**Age of shoots (yr)**	**Number of Shoots (# plant^{-1})**		**Density of living shoots (# ha^{-1})**		**Diameter per shoot (cm)**	
				Mean	**S.D.**	**Mean**	**S.D.**	**Mean**	**S.D.**
EC1 plot 1	Jorr	22,222	1	9.75	3.49	201498	16139	1.275	0.4258
EC1 plot 2	Loden	22,222	1	11.30	3.98	225998	17776	1.540	0.4479
EC1 plot 3	Tora	22,222	1	5.80	2.31	119865	10665	1.330	0.5516
EC1 plot 4	Jorr	17,778	1	13.25	4.13	212003	14769	1.411	0.4615
EC1 plot 5	Loden	17,778	1	11.80	3.98	192998	14561	1.058	0.3970
EC1 plot 6	Tora	17,778	1	11.20	4.54	157300	14250	1.029	0.0240
EC1 plot 7	Jorr	13,675	1	15.20	3.38	187074	9305	1.138	0.3421
EC1 plot 8	Loden	13,675	1	14.15	5.82	166411	15317	1.342	0.3539
EC1 plot 9	Tora	13,675	1	12.90	4.54	162295	12775	1.035	0.3509
F3-5 right-side	Jorr	17,778	1	10.95	5.55	175202	19851	1.438	0.4023
JZ 11 plot 1	Jorr	17,778	2	5.07	1.86	74762	4999	2.391	1.0237
JZ 11 plot 2	Tora	17,778	2	5.33	2.25	78697	6059	2.217	1.0067
JZ 22-25	Jorr & Tora	17,778	2	4.20	1.54	59734	4000	2.617	1.0807

Plot name	***Salix* variety**	**Plant density (plants/ha)**	**Age of shoots (yr)**	**Dry weight per plant (kg)**		**Length of highest shoot (m)**	
				Mean	**S.D.**	**Mean**	**S.D.**
EC1 plot 1	Jorr	22,222	1	0.620	0.2118	2.95	0.35
EC1 plot 2	Loden	22,222	1	0.780	0.2913	2.59	0.29
EC1 plot 3	Tora	22,222	1	0.360	0.1818	2.56	0.59
EC1 plot 4	Jorr	17,778	1	0.850	0.2743	2.61	0.21
EC1 plot 5	Loden	17,778	1	0.810	0.2972	3.14	0.31
EC1 plot 6	Tora	17,778	1	0.420	0.1642	2.51	0.30
EC1 plot 7	Jorr	13,675	1	0.742	0.2694	2.68	0.17
EC1 plot 8	Loden	13,675	1	0.768	0.2647	2.54	0.08
EC1 plot 9	Tora	13,675	1	0.385	0.1694	2.26	0.55
F3-5 right-side	Jorr	17,778	1	0.965	0.4793	3.57	0.23

1.3.5. Biomass production & allometric relationships

As an example, Figure 5 shows the non-linear regression between the dry weight and diameter of shoots for EC1 plot 1.

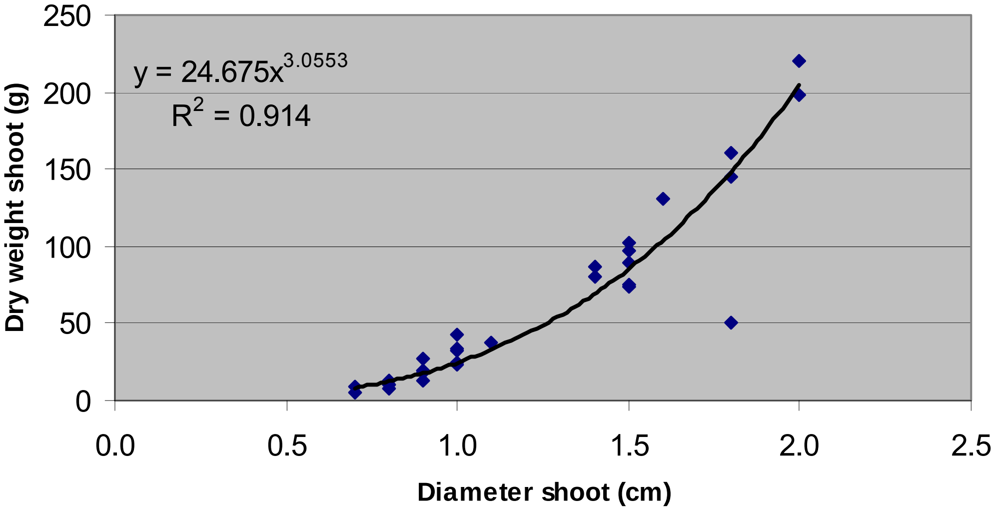

Figure 5 The non-linear regression between dry weight and diameter of shoots for plot EC1

In Table 5 the results of the non-linear regression can be found; this includes the estimation of the parameter values, the R^2, and the division in groups with the same allometric relationship.

Table 5 Specific allometric relationships per plot, relating shoot dry weight to stem diameter: parameter estimates and R2; Dry weight shoot = $b\ D^c$

Plot name	*Salix* variety	Plant density (plants ha^{-1})	Age of shoots (yr)	b	c	R^2	Group
EC1 plot 1	Jorr	22,222	1	24.667	3.056	0.914	1
EC1 plot 4	Jorr	17,778	1	21.048	3.491	0.867	1
EC1 plot 7	Jorr	13,675	1	22.664	3.407	0.939	1
JZ 11 plot 2	Tora	17,778	2	21.474	2.890	0.988	1
EC1 plot 2	Loden	22,222	1	20.606	2.609	0.972	2
EC1 plot 5	Loden	17,778	1	20.045	2.707	0.958	2
EC1 plot 8	Loden	13,675	1	16.873	3.067	0.965	2
EC1 plot 6	Tora	17,778	1	16.470	3.314	0.927	2
EC1 plot 9	Tora	13,675	1	16.823	3.402	0.931	2
EC1 plot 3	Tora	22,222	1	24.084	2.796	0.934	3
F3-5 right-side	Jorr	17,778	1	23.169	2.777	0.955	3
F3-5 left-side	Jorr	17,778	1	20.618	2.886	0.860	3

After a more specific analysis it could be concluded that some allometric relationships were significant not different from each other, although others are. See Table 5 for the different groups (1 to 3). The value of b was kept constant, so only the value of c differs between the different groups.

The allometric relationship per group is:

Group 1 Dry weight shoot = $26.152 * D^{2.733}$
Group 2 Dry weight shoot = $26.152 * D^{2.243}$
Group 3 Dry weight shoot = $26.152 * D^{2.594}$
With Dry weight shoot in grams and D is diameter in cm.

A comparison was made between the different measurements methods (harvest method, non-destructive method with specific allometric relationships, and non-destructive method with general allometric relationships). It is assumed that the destructive measurement method gives the most exact outcomes, so the differences in standing living woody biomass between the destructive and the other two methods were calculated and indicated in Table 6. With help of these results it can be concluded that although the general regression method gives a slightly overestimation of the results, it predicts the results rather correct.

Table 6 Differences in standing living woody biomass between different methods; relative to results of harvest method

Plot	Specific regression method (%)	General regression method (%)
Jorr; 22,222 plants ha^{-1}; 1 year old	-13.67	-5.47
Loden; 22,222 plants ha^{-1}; 1 year old	-0.68	-3.86
Tora; 22,222 plants ha^{-1}; 1 year old	-5.97	-3.36
Jorr; 17,778 plants ha^{-1}; 1 year old	-60.44	-29.25
Loden; 17,778 plants ha^{-1}; 1 year old	22.66	19.15
Tora; 17,778 plants ha^{-1}; 1 year old	19.49	5.41
Jorr; 13,675 plants ha^{-1}; 1 year old	-2.01	5.59
Loden; 13,675 plants ha^{-1}; 1 year old	5.91	-2.32
Tora; 13,675 plants ha^{-1}; 1 year old	14.95	-2.43
Jorr; 17,778 plants ha^{-1}; 1 year old	14.93	12.74

For the non-destructive method it is necessary to have a good estimation of the shoot diameter range. The measuring of the diameters is a time consuming activity, especially in plots with 1 year old shoots because of the high amount of shoots.

To test for the necessary number of sampled plants with 1 year old shoots, a Chi-Square test was carried out. The diameter distribution of 20 plants was compared with the diameter distribution of 10 plants. The test was carried out five times, not once the test indicated significant differences between the diameter range of 10 and 20 plants.

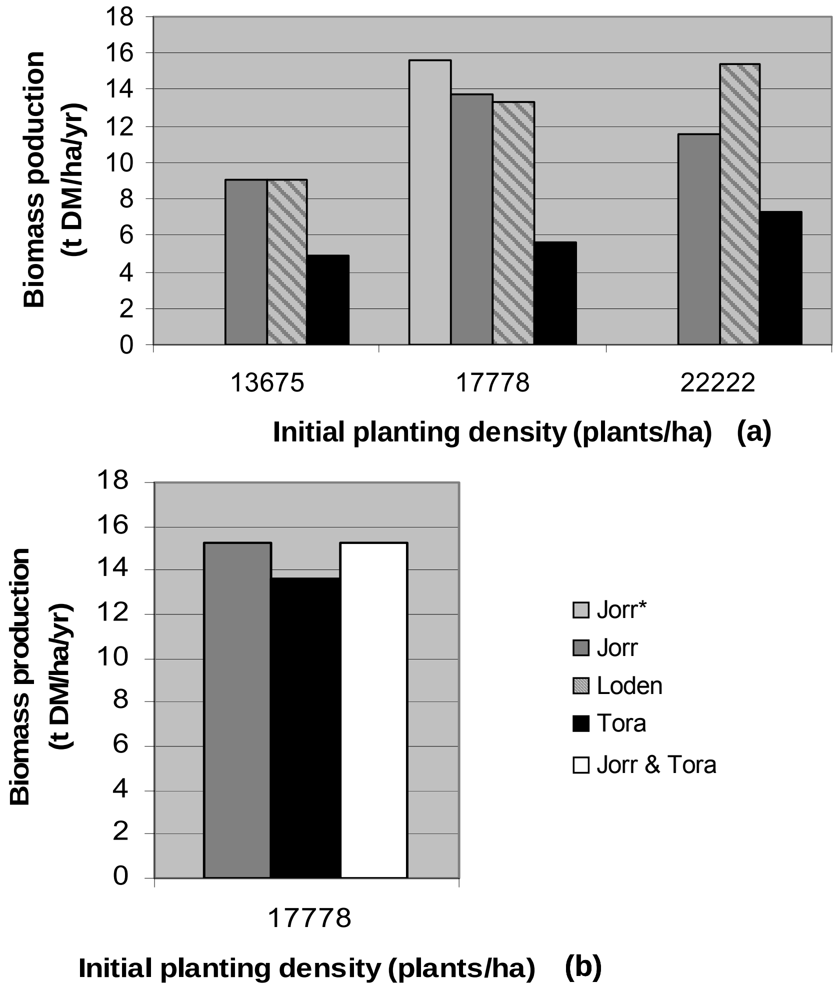

Figure 6 The standing living woody biomass (t DM ha^{-1}) per plot; (a) shows the number of living shoots ha^{-1} for 1 year old shoots; (b) shows the number of living shoots ha^{-1} for 2 year old shoots

In Figure 6 the production numbers for plots with 1 and 2 year old shoots are shown. The production numbers woody biomass of 1 year old shoots varied from 5.62 to 15.62 t DM ha^{-1} yr^{-1}, and production numbers of approximately 15 t DM ha^{-1} yr^{-1} were measured for 2 year old shoots.

Standing living woody biomass in case of 1 year old shoots was determined by a destructive harvest method. Standing living woody biomass in case of 2 year old shoots was determined with help of the non-destructive method. The allometric relationship of group 1 was applied to determine the production of Jorr and Jorr & Tora. This allometric relationship was chosen because it represents the biomass production for 2 year old shoots.
In Appendix 1 several Tables and box-plots are shown. In those tables and box-plots more detailed information can be found about all significance differences ($p < .05$) of the above stated analyses.

1.4. Discussion

The objective of this research was to assess biomass production and stand characteristics of three different clones (Jorr, Loden, and Tora), with 1 and 2 year old shoots. Also biomass production and stand characteristics of those three clones with three different planting densities (13,675 to 22,222 plants ha^{-1}) were compared.

The results of this study show differences in several aspects between the different clones and planting density, and the combination of those two management strategies. Conclusions were drawn based on the effect of the combination of clonal use and planting density. This was done, because clones can respond different to for example planting density, the so-called clone-by-spacing interaction (Kopp et al., 1997). Conclusions were drawn as well concerning the effect of clonal use or planting density separately.

If the production woody biomass ha^{-1} yr^{-1} for all plots is compared, rather larger differences in production numbers between the different plots appear. A clear trend can be seen with regard to the planting density, a higher planting density gives a higher standing living woody biomass.

An explanation for higher biomass production in plots with higher planting densities may be the effect of competition between weeds and *Salix* plants. A high planting density results in a rapid stand closure. A closed stand uses light efficiently and causes shade on the ground, this results in an effective weed control which promotes biomass production.

Research carried out in Sweden by Bergkvist and Ledin (1998) also found a strong dependence of plant density of biomass yield. They found that a higher plant density than $2 \cdot 10^4$ ha^{-1} did not result in a significant higher yield. Lowest biomass production was found in the plots with lowest plant density ($4.4 \cdot 10^3$ plants ha^{-1}).

Only planting density also affects the number of shoots per plant and thickness per shoots. Some results implicate the trend that if plants are planted with higher densities, less shoots are produced per plant, but the produced shoots are thicker. This conclusion is confirmed by research carried out by Kopp et al (1997).

Not only planting density, but the utilisation of specific clones results in differences in biomass production. The clone Tora produces less biomass ha^{-1} yr^{-1} than the other clones do; Loden produces slightly more than Jorr. If the production numbers in the second growing season are assessed, the difference between Jorr and Tora is much smaller. The poor performance of Tora is also expressed in the low amount and small diameter of the shoots.

If a comparison is made between average woody biomass production numbers after one and after two growing seasons, it is observed that the production is approximately the same after both growing seasons. Thus, aging of the shoots does not have large influences on biomass production.

As stated in the method part, production of woody biomass in *Salix* plantations depends on the amount of present plants and biomass per plant (Nordh, 2005).
To explain the differences in production numbers between the different plots, the following aspects will be looked at: number of shoots ha^{-1} and average shoot diameter.
If the aspects clonal use and planting density are compared at the same time all plots with 2 year old shoots have significantly less shoots ha^{-1} than the other plots (except for Tora; 22,222 plants ha^{-1}). Thus it can be concluded that especially the age of the shoots has a significant effect on the number of shoots ha^{-1}.
Nordh and Verwijst (2006) also found a decreasing shoot density with age. They found between $2 \cdot 10^5$ and $3 \cdot 10^5$ shoots ha^{-1} for the 1 year old shoots and between $1.5 \cdot 10^5$ and $2 \cdot 10^5$ shoots ha^{-1} for the 2 year old shoots, with an initial density of $2 \cdot 10^4$ plants ha^{-1}. However, their research was based on measuring the same plants for two subsequent years instead of measuring plants on two different plots during the same years.

Aging also influence the average diameter of the shoots. After the second growing season the average diameter of the shoots is significantly thicker than after the first growing season, which was the expected result. Thus it can be concluded that although 2 year old shoots have less shoots, their biomass production is compensated because of thicker shoots.

The poor performance of Tora in only the first growing season is striking. As stated in the method part, the different plots of site EC1 were not randomly spread. The plots with Tora were situated on the edge of the site, next to a ditch. Nordh (2005) has shown that the relative performance of clones may dependent on choice of site. This may explain the worse performance of Tora, and indicates that the design of the sites failed to prevent possible site effects.
In Table 7 production numbers are given which were gained in other countries under different management regimes.

Table 7 Production numbers in different countries under different management regimes

Country	Production numbers (t DM ha^{-1} yr^{-1})
The Netherlands (this study)	5.62 – 15.62 t DM ha^{-1} yr^{-1} (different clones, planting densities, no fertilizer applied)
Central Sweden (Weih and Nordh, 2005)	5.4 – 11.9 t DM ha^{-1} yr^{-1} (same clones used as in this study, fertilizer applied)
Southern Canada (Labrecque and Teodorescu, 2005)	6.21 – 16.90 t DM ha^{-1} yr^{-1} (no fertilizer applied)
The Netherlands (Kuiper, 2003)	8 - 10.7 t DM ha^{-1} yr^{-1} (different clones and fertilisation regimes)
United Kingdom (Grogan and Matthews, 2002)	6 – 18 t DM ha^{-1} yr (no information about fertilizer application)
Central and south Finland (Tahvanainen and Rytkonen, 1999)	4.75 t DM ha^{-1} yr (fertilizer applied)
Southernmost Finland (Tahvanainen and Rytkonen, 1999)	10 t DM ha^{-1} yr (fertilizer applied)
United States of America (central New York State) (Kopp et al., 2001)	10 – 16 t DM ha^{-1} yr (different clones, fertilisation applied) 10 – 14 t DM ha^{-1} yr (different clones, no fertilizer applied)

The research carried out by Weih and Nordh (2005) was based on the same clones as this study. The difference between the both studies is the age of the roots. The roots of the plants used in this research are older than the roots of the Swedish research. Nordh (2005) found increasing standing biomass in following cutting cycles, and with and more developed roots. This result is confirmed by Sennerby-Forsse et al (1992).
With help of this knowledge it can be concluded that the differences between the yields would probably be smaller if production was measured of plants with the same root age. The results can be different as well because different response of the clones to Swedish and Dutch conditions (Sennerby-Forsse et al., 1992).

The production numbers of this study correspond with production numbers of countries with approximately the same climatic conditions (southern Canada, United Kingdom, and central New York State). In comparison with countries with a hasher climate (Sweden and Finland) the production numbers measured in the research are considerably higher (approximately 150 – 300 % higher).

Recommendations

- A single clone community is supposed to have a great risk for disease selection and rapid epidemics (Ramstedt, 1999). So although this research indicates that certain clones produce higher amount of biomass, it is recommended to plant a mixture of different *Salix* varieties in one plantation. Nevertheless, it should be avoided to plant Tora on a Dutch plantation because of its low production capacity.
- An increase of biomass production with higher planting densities was shown with help of this study. Nevertheless, the fewer trees that have to be planted, the cheaper it will be to grow *Salix* as an energy crop and the sooner it will be competitive with other land uses.

Research should be carried out to find the optimal planting density, in terms of cots and production numbers.

– Further research should be carried out on *Salix* plants with older roots and plants which grow in longer cutting cycles under Dutch conditions. Other research indicates rather larger differences in biomass production between different cutting cycles, for example in Sweden (Nordh, 2005). But the effects of older roots and longer cutting cycles under Dutch conditions are still unknown.

  Also important is to measure the diameters of the shoots after the third growing season. Because of the maximal diameter a harvest machine can handle, 60 to 70 mm (Nordh and Dimitriou, 2003), although those diameters are not reached in Sweden during three year cutting cycles, it is possible those diameters will be reached under Dutch conditions.
– For a sustainable biomass production it is not only important to have high productivity, but it is also important to maintain that level of high productivity and to maintain soil fertility. Application of fertilisers is one possibility to maintain high production levels and soil fertility. However, application of fertilisers should be understood and tested very well, since excessive applications will waste money and resources, and maybe results in harmful effects on the environment. On the other hand, application of insufficient nutrients will lead to soil degradation and losses in crop productivity (Mitchell and Ford-Robertson, 1992; Cannell, 2004; Weih, 2004).

2. Life Cycle Assessment of a Dutch short-rotation willow (Salix) plantation

Abstract

The utilization of energy crops for energy generation is considered as a possible way to mitigate climate change; mainly due to the substitute of fossil fuels by biomass. As a result of several management activities greenhouse gases are emitted during the 15 years lifespan of a *Salix* plantation. Leaf litter may be a source of greenhouse gases as well. On the other hand, carbon sequestration in the soil may offset the effects of those emissions. This study evaluates the energy and greenhouse gas balance of a short-rotation *Salix* plantation during its lifespan. Literature research was carried out to find related numbers concerning energy use and greenhouse gases. A model was applied to calculate possible amounts of carbon sequestered in the soil under a *Salix* plantation. The production of 1 GJ was used as a functional unit to compare emissions from a *Salix* plantation and a coal-fuelled power plant. In comparison with a coal-fuelled power plant the amount of emitted greenhouse gases by a *Salix* plantation is low, approximately 5 % of the amount of emissions if 1 GJ is produced by utilising coal. The amount of carbon sequestrated in the soil may offset the effect of the emitted greenhouse gases totally, but only if biomass production levels are high enough. To produce 20 GJ of biomass energy an input of 1 GJ of fossil fuel is needed. This study indicates that short-rotation *Salix* plantations under Dutch conditions may produce considerable amounts of biomass with help of low fossil energy inputs and results in little greenhouse gas emissions.

Keywords: Short rotation forestry, *Salix*, Life Cycle Assessment, Greenhouse gas emissions, the Netherlands

2.1. Introduction

Due to several environmental problems, especially climate change, renewable energy is gaining more and more interest nowadays. Renewable energy is defined by the IPCC as: “Energy sources that are, within a short timeframe relative to the earth’s natural cycles, sustainable, and include non-carbon technologies such as solar energy, hydropower, and wind, as well as carbon neutral technologies such as biomass (IPCC, 2001a)”.

The Dutch government has ambitious objectives in the field of renewable energy: in 2020 the contribution of renewable energy to the total energy production has to be 10% (Ministerie van Economische Zaken, 2005). According to the objectives, in 2020 the contribution of bio-energy has to be 120 PJ yr^{-1}, which corresponds to about 40% of the total renewable energy target. Part will be generated with help of bio-energy resources, among others dedicated energy crops grown in the Netherlands, sometimes called “energy farming”.

Energy crops can be classified in woody crops and grasses (Londo, 2002). This report concentrates on a woody crop, namely *Salix* in short rotation forestry. *Salix* was chosen because this crop is well adjusted to the Dutch growth conditions (Gigler et al., 1999; Londo, 2002) and it has a long history in the Netherlands (Schepers et al., 1992).

A *Salix* plantation is commonly established with stem cuttings. The cuttings easily develop roots when planted as a 'bare stick'. After establishment of the root system, a coppice method is normally applied. If a tree is coppiced, it is cut down at the base of the trunk; the part that remains is called stump. After coppice new multiple shoots emerge from the stump. The original cutting, the shoots, and the roots together form a unit often called stool (Sennerby-Forsse et al., 1992).
Typical rotations lengths for a *Salix* plantation are 2-4 years and the lifespan of the stools is expected to be 10-20 years, depending on growth conditions. After those 10-20 years the yield starts to decline and the plantation has to be replaced (uprooted). Thus, in total 5-7 cutting cycles are possible, depending on the rotation length and growth conditions (Harmer, 2004). The trees are usually planted on agricultural and on degraded forest land, usually in high-densities (Cannell, 2004; Weih, 2004).
With every harvest of the biomass, nutrients are removed from the site. To prevent soil degradation and losses in crop productivity, application of nutrients is necessary, especially in the long term (Mitchell and Ford-Robertson, 1992; Cannell, 2004; Weih, 2004; Rebelo de Mira and Kroeze, 2006).

A major advantage of biomass as energy source is its carbon neutrality with respect to the atmosphere. This means that the amount of CO_2 emitted during the utilizing of the biomass energy is the same as the amount of CO_2 absorbed during the growth of the biomass crop (Leemans et al., 1996; Heller et al., 2003). Because of this no net increase of atmospheric CO_2 is caused, in contrast to the utilisation of fossil fuels for energy generating.
However, due to several necessary management activities (for example tractor operation during planting and harvesting, fertilizer and irrigation application etc) some CO_2 is emitted to the atmosphere. So although the utilisation of the *Salix* crop does not result in increased CO_2 concentrations in the atmosphere, the whole system does. Not only CO_2 but also other greenhouse gases such as N_2O are emitted due to management activities.
Biomass of *Salix* may be used to substitute fossil fuels. The mitigation potential of a *Salix* plantation is based on this principle, but also the emissions due to the management should be taken into account, only then a fair picture of the mitigation potential of a *Salix* plantation can be established.
Short rotation forestry is also able to improve soil quality and to enhance nutrient cycling. This may result in additional sequestration of carbon in the soil, creating a sink for CO_2 (Neergaard et al., 2002; Lemus and Lal, 2005). This sink can offset the negative effect of the emitted greenhouse gases due to the management of the *Salix* plantations.
Research was carried out to estimate the emissions due to management of *Salix* plantations, also several energy analysis were carried out for *Salix* plantations (Börjesson, 1996b, 1996a; Heller et al., 2003; Lettens et al., 2003). However, no specific research is carried out for Dutch conditions.

From the above it is clear that the question to what extent Dutch *Salix* plantations contribute to the mitigation of climate change, taking into account all aspects, is not yet answered. Thus the aim of this research is to roughly evaluate the balance of the greenhouse gases CO_2 and N_2O of a *Salix* plantation under Dutch conditions. The evaluation energy input : output ratio is included as well.
The emissions of greenhouse gases due to management practices, fertilisation application, and leaf litter are included, as well as the amount of carbon sequestrated under a *Salix* plantation. This balance is calculated for two different *Salix* clones: Jorr and Tora, which grew in mono-cultures. To find the mitigation potential of a *Salix* plantation, the outcomes are compared with CO_2 emissions of a coal-fuelled power plant.

2.2. Material and Methods

2.2.1. Life Cycle Assessment

According to Van den Berg et al (1995) the definition of a Life Cycle Assessment is: "A systematic way to evaluate the environmental impact of products or activities by following a "cradle-to-grave" approach. This approach implies the identification and quantification of emissions and material and energy consumptions which affect the environment at all stages of the entire product life cycle". See for example the report of Seppälä (1998), which describes the environmental impacts of the management of forest resources and related industries in Finland.

The object of this LCA is a short rotation *Salix* coppice stand of one ha. It is not aimed to carry out a complete LCA, but only to concentrate on the environmental theme 'Climate change'. Two important greenhouse gases for this environmental theme: CO_2 and N_2O were considered. CO_2 is an important greenhouse gas in this respect, because it is emitted during *Salix* cultivation in considerable amounts. N_2O is important because it is emitted a lot by fertilized soils (Rebelo de Mira and Kroeze, 2006) and it has a high Global Warming Potential (see below). To find the mitigation potential of *Salix* in the Netherlands, a power plant fuelled with coal will be used as a reference system.

To be able to sum up the effects of the different greenhouse gases, global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) are used. Global Warming Potential of a gas (GWP) is defined as: "An index, describing the radiative characteristics of well mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide" (IPCC, 2001b). In the case of this research the specific time interval is 100 years. The GWP of CO_2 = 1 and the GWP of N_2O GWP = 296 (i.e. the effect of 1 kg N_2O equals the effect of 296 kg CO_2) (IPCC, 2001b).

In some studies kg C eqv have been used instead of kg CO_2 eqv. However, normally kg CO_2 eqv are used in LCAs. Conversions have been made with help of 44/12 kg C = 1 kg CO_2; this conversion has also been applied to express carbon sequestration in kg CO_2 eqv (Witvliet and Kuiper, 2000; Rebelo de Mira and Kroeze, 2006).

2.2.2. System description

In Figure 7 all management activities for a short rotation *Salix* coppice stand are systematic shown, including the boundary of the Life Cycle Assessment.
This research assumes 1 year of site preparation, coppicing after the first year of growth, a 2 year cutting cycle and removing of the willow stools after 7 cutting cycles. So in total the time-line is 15 years. See Table 2 for the contribution or diminution of the different aspects.

Data related to emissions due to fuel and oil consumption by the operation of tractors and agricultural implements were taken from literature. Data were from Lettens (2003) and Börjesson (2006). The data found in these reports was recalculated to greenhouse gas emissions (t CO_2 eqv ha^{-1}) per management activity and energy requirements (MJ ha^{-1}) per management activity. The level of management activities was not the same in both researches. However, average numbers for each management activity applied in this research were calculated based on both reports.

The total amount of greenhouse gas emissions and energy requirements per life cycle of the *Salix* plantation have been calculated by multiplying the emissions and energy requirements per management activity with the number of times the management activity is executed during the lifespan of the *Salix* plantation.

Table 8 The effect of the different aspects during the growth of a Salix plantation; a plus sign indicates that the aspect contributes to the environmental theme climate change a minus sign indicates a diminution

	Contribution (+) or diminution (-) to environmental theme climate change
Emissions due to management activities	**+**
Soil emissions due to fertilisation	**+**
Emissions from leaf litter	**+**
Carbon sequestration in the soil	**-**

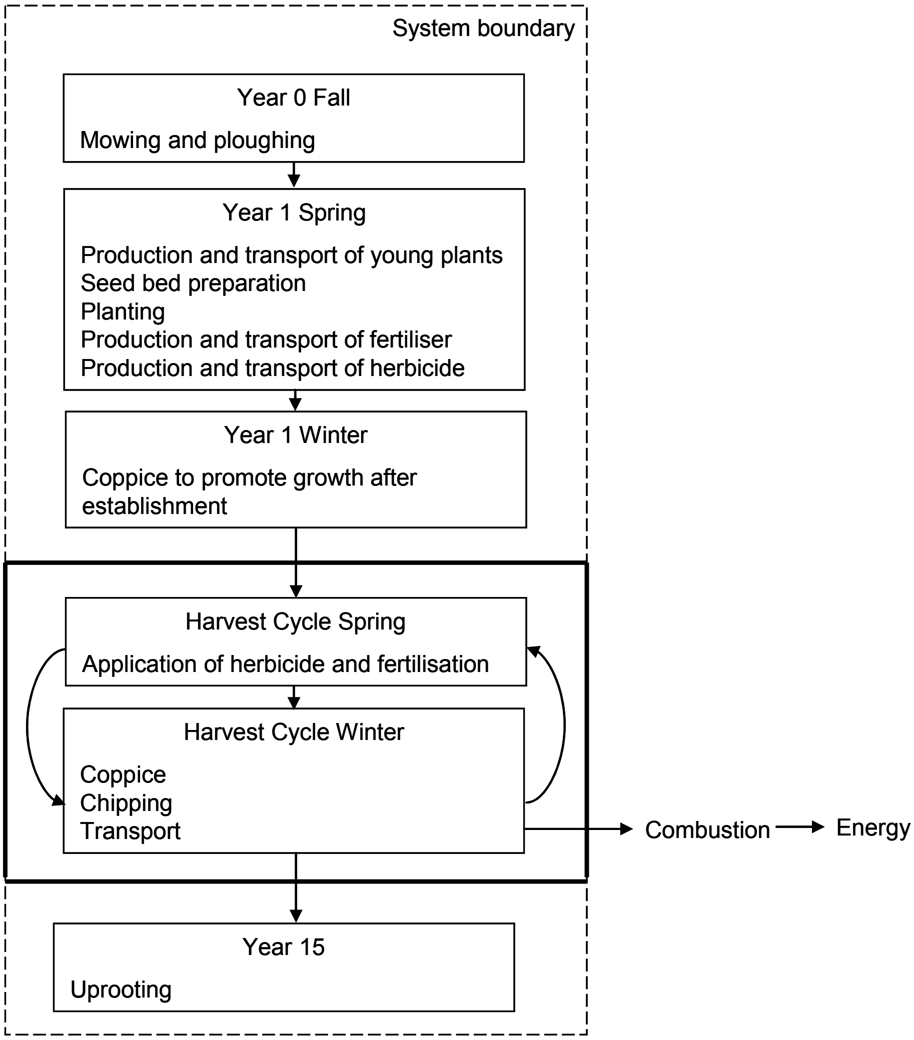

Figure 7 Schematic overview of necessary activities to cultivate Salix. After the first 2 years the crop enters the 2 year harvest cycle that is repeated 7 times. The last harvest is succeeded with uprooting of the site.

2.2.3. Soil emissions

If biomass is harvested, nutrients are removed from the site. This removal will result in loss of soil fertility, causing losses in production. To maintain high production numbers it is necessary to apply fertilisation (Mitchell and Ford-Robertson, 1992; Cannell, 2004; Weih, 2004). In this research an application of 100 kg N ha^{-1} per harvest cycle is assumed, because it is a common applied amount (Rebelo de Mira and Kroeze, 2006).

Fertilised soils are considered the most important sources of N_2O. N_2O emissions can be divided in direct and indirect emissions. Direct emissions are a result of enhanced N_2O formation by bacterial processes (nitrification and denitrification) at the fertilised site. The indirect emissions take place at remote sites (terrestrial or aquatic) and result from nitrification and denitrification of nitrogen that is transported from the fertilised sites by leaching, runoff or volatilisation and consecutive deposition. Formation of N_2O is determined by the amount of applied fertilisation and factors such as temperature, pH, and soil moisture content (Heller et al., 2003; Rebelo de Mira and Kroeze, 2006). However, no specific soil data of the sites in this research were available, thus it was assumed that the conditions of the sites resemble the conditions in the research by Rebelo de Mira and Kroeze (2006).

The growth rates in the plots used in this study did not included the application of fertilization and irrigation; nevertheless, high biomass production numbers were measured (see below, Table 12). This is due to the high nutrient availability of the soil (Ente et al., 1965), caused by high nitrogen deposition and previous management. Extra application of fertilisation to these sites will probably result in higher competition, so it is unlikely that yields will be higher if fertilisation and/or irrigation is applied (Mitchell and Ford-Robertson, 1992; personal communication Verwijst, 2006[1]).
Nevertheless, this high nutrient availability will not last if harvest keeps going on, fertilisation will be necessary on the long term. To be able to make fair comparisons with other studies and because it supposed that fertilisation application is necessary on the longer term, it is assumed in this research that 100 kg N ha^{-1} yr^{-1}, which is a common applied amount (Rebelo de Mira and Kroeze, 2006), is applied from the beginning.

Calculation of soil emissions was based on Rebelo de Mira and Kroeze (2006), who calculated emissions as a function of the amount of fertiliser, soil, and standard emissions factors from the IPCC Guidelines.

Another source of N_2O may be the leaf litter that is produced every year. Most of the time nutrients released during the decomposition of the leaf litter remain within the system and become available for subsequent tree growth. However, it is also possible that some leaves decompose under anaerobic circumstances (denitrification), and in that case N_2O can be released. Decomposition is under most circumstances aerobic, but in this research also the potential emissions of anaerobic decomposition were included, to indicate its potential contribution.
This was done based on the results of research by Heller et al. (2003), for this research a linear relationship was assumed between the amount of leaf litter and N_2O emissions. A leaf N content of 1.5 % was assumed.

2.2.4. Carbon sequestration

A simple mass balance of the major ecosystem pools and fluxes of carbon in a short rotation forestry stand was used to calculate the carbon sequestration under a *Salix* plantation. This mass balance is based on the data from Grogan and Matthews (2002). The equations (although some are adapted) and the values of the decay rates originate from this article. See for more detail Van Bussel (2005).

It is assumed that carbon in the stand in distributed over the biomass and the soil. The carbon in the biomass part is divided into three different fractions: leaves, shoots and roots.

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The carbon in the soil is divided into two parts: the fresh organic matter (FOM) pool, with a fast decay rate, and the humic soil carbon (HUM) pool, with a slow decay rate. Figure 8 gives the schematic overview of the model. Table 9 gives the most important parameters of the model and their accompanying values.

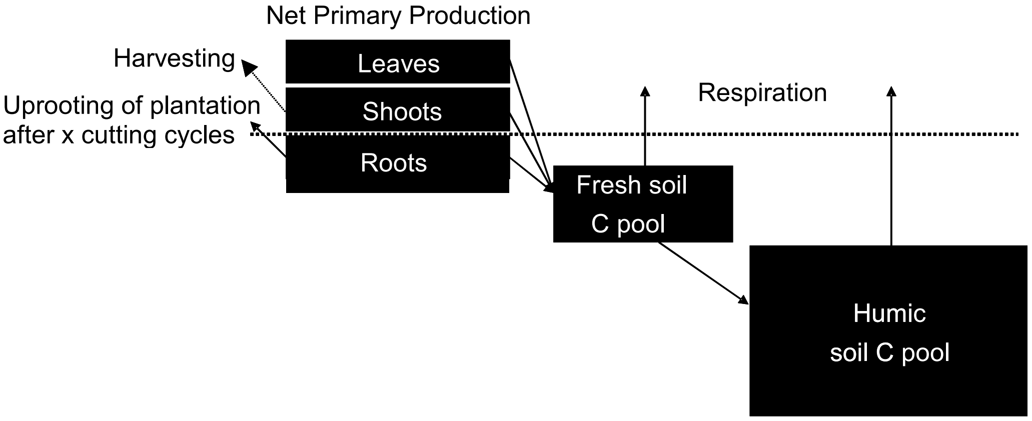

Figure 8 Schematic overview of the different pools and carbon fluxes in a Salix stand (after Grogan, 2002)

Table 9 Most important parameters of the model, including their values

Parameter	Value of parameter
the carbon content of the dry matter of all *Salix* compounds (f_c)	0.46 g C g DM^{-1}
the rate constant of the fresh organic pool (k_{FOM})	0.7860 yr^{-1}
the rate constant of the humic soil carbon pool (k_{HUM})	0.0031 yr^{-1}
Initial carbon content of the soil	41860 kg C ha^{-1}

The structural/woody root biomass is the most import biomass part for carbon sequestration. Data on structural/woody root biomass in short rotation forestry are limited (Heller et al., 2003). From previously research it could be concluded that especially during the first cutting cycle carbon is allocated to the structural/woody root biomass (Weih and Nordh, 2005). Data about successive cutting cycles is lacking, but is it expected that the structural/woody root biomass increases after the first cutting cycle. The assumption was made that after the first cutting cycle, structural/woody root biomass increases with 5% each year.

Likely, carbon allocation to the rest of the biomass differs between cutting cycles as well. However, only specific data is available on carbon allocation patterns during the first cutting cycle. Therefore it is assumed that the carbon allocation pattern did not change during the different cutting cycles, except for the *structural/woody root biomass*. It is also assumed that the carbon allocation pattern of two Salix clones is the same in both the Netherlands and Sweden. See Van Bussel (2005) for more details about carbon allocation patterns and the growth of roots.

2.2.5. Above-ground woody biomass production

The production levels for the different *Salix* clones were based on data gained from a field trial in Flevoland, the Netherlands, near Lelystad (see previous chapter). See Table 10 for more details about the field trails. The plants are planted in 2000.

Table 10 Description of different plots

Plot name	*Salix* variety	Plant density (plants ha^{-1})	Total area (ha)	Coppiced in end of	Cutting cycle	Growing season
EC1 plot 4	Jorr	17,778	0.5	2002 and 2004	3	1
EC1 plot 5	Loden	17,778	0.5	2002 and 2004	3	1
EC1 plot 6	Tora	17,778	0.5	2002 and 2004	3	1
JZ11 plot 1	Jorr	17,778	3.63	2003 and 2005	2	2
JZ11 plot 2	Tora	17,778	3.52	2003 and 2005	2	2

To carry out the LCA a series of 7 cutting cycles was considered. Successive rotations may exhibit additional growth because the root system has already developed (Heller et al., 2003; Nordh, 2005). With help of previous research carried out by Nordh and Verwijst (personal communication 2005[1]) estimations could be made regarding production numbers in successive rotations; i.e. they computed factors that indicate the change in production between different cutting cycles. Together with the measured data in Flevoland, which were data of the second and third cutting cycle, the production numbers of the first two cutting cycles were estimated. It was supposed that the production numbers remain the same after the third cutting cycle.

2.3. Results

2.3.1. Greenhouse gases emissions due to management

In Table 11 the necessary amounts of fossil fuel energy (GJ ha^{-1}) to execute a certain activity and greenhouse gas emissions per activity (t CO_2 eqv ha^{-1}) are shown. Some activities are carried out several times, and Table 11 shows the necessary amount of fossil fuel energy and greenhouse gas emissions during the 15 year lifespan of the *Salix* biomass crop.

In Figure 9 the breakdown by management activity concerning emissions of greenhouse gases is shown. Some activities (production and transport of herbicide, planting, harrowing, and seed bed preparation) contribute only little to the greenhouse gases emissions. On the other hand, two activities (production and transport of fertiliser and harvesting) cause more than 50 % of the emissions. The same is true for energy requirements.

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Table 11 Energy use and emissions due to management activities per activity and during the 15 year lifespan of willow biomass crop

Activity	**Number of times executed per 15 years**	**Fossil energy use (GJ ha^{-1} $activity^{-1}$)**	**GHG emission (t CO_2 eqv $activity^{-1}$)**	**Fossil energy use (GJ ha^{-1} 15 yr^{-1})**	**GHG emission (t CO_2 eqv 15 yr^{-1})**
Production and transport of young plants	1	4.99	0.47	4.99	0.47
Production and transport of fertilizer	1	67.55	4.43	67.55	4.43
Production and transport of herbicide	1	1.20	0.10	1.20	0.10
Seed bed preparation	1	0.33	0.03	0.33	0.03
Ploughing	1	1.35	0.11	1.35	0.11
Harrowing	1	0.70	0.05	0.70	0.05
Planting	1	1.11	0.09	1.11	0.09
Application of herbicide	8	0.26	0.02	2.08	0.16
Application of fertilization	7	0.84	0.07	5.89	0.48
Harvesting	8	5.95	0.48	47.57	3.84
Transport of *Salix* chips (30 km) by trucks	7	2.16	0.18	15.15	1.28
Termination of the culture	1	6.65	0.45	6.65	0.45
Sum				154.56	11.49

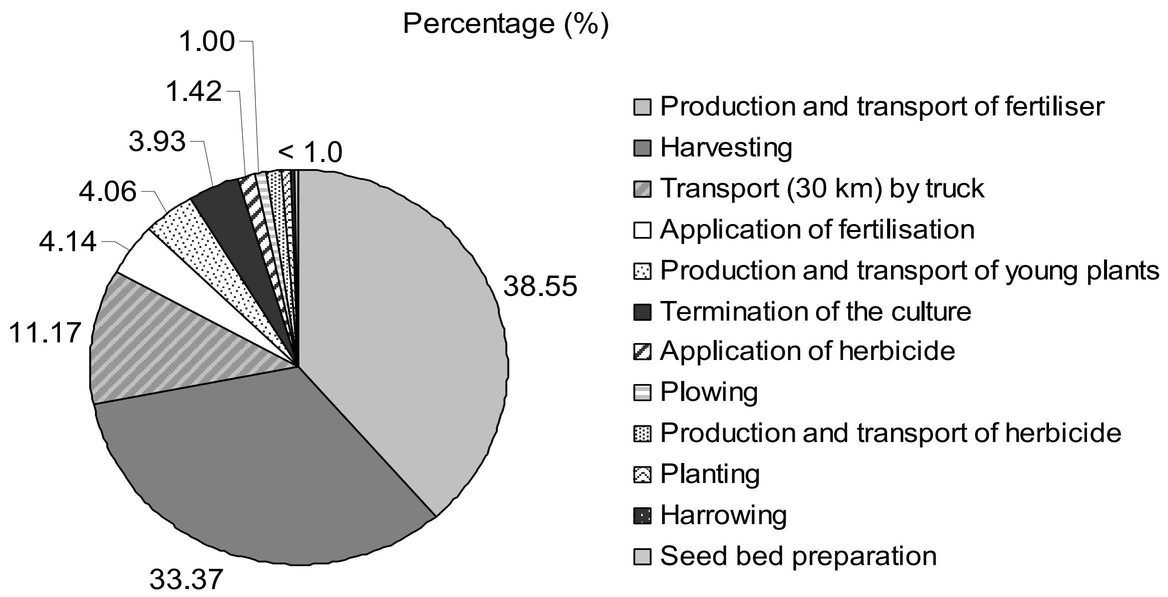


Figure 9 Breakdown of greenhouse gases emissions (percentages of total t CO2 eqv/ha during the whole lifespan of the Salix plantation

2.3.2. Soil emissions

Soil emissions are dependent on soil type and the amount of applied fertilisation. The soils in Flevoland are mineral soils (Ente et al., 1965). Rebelo de Mira and Kroeze (2006) assumed an emission of 37.2 kg N_2O ha^{-1} yr^{-1} if 100 kg N ha^{-1} yr^{-1}, is applied for mineral soils, assuming a production of 10 t DM ha^{-1} yr^{-1}. This equals an emission of 11 t CO_2 eqv ha^{-1}.

Heller et al. (2003) assumed a leaf litter production of 3.8 t ha^{-1} yr^{-1}, that amount emits in total 1.17 kg N_2O. If a linear relationship is assumed between the leaf litter production and N_2O emissions, an emission of 0.308 kg N_2O/t leaf litter can be assumed.
The *Salix* crops in Flevoland produce 3.371 t leaf litter ha^{-1} yr^{-1} (Jorr) and 1.801 t leaf litter ha^{-1} yr^{-1} (Tora). Thus during the lifespan Jorr produces 50.56 t leaf litter ha^{-1} and Tora produces 27.01 t leaf litter ha^{-1}. These amounts of leaf litter emit 15.57 kg N_2O ha^{-1} (Jorr) and 8.32 kg N_2O ha^{-1} (Tora). Converted to CO_2 eqv, leaf senescence gives an emission of 4.61 t CO_2 eqv ha^{-1} (Jorr) and 2.46 t CO_2 eqv ha^{-1} (Tora) during the whole lifespan of the plantation.

The addition of both numbers, emissions due to fertilisation and due to leaf litter, gives emissions of 15.61 t CO_2 eqv ha^{-1} for Jorr and 13.46 t CO_2 eqv ha^{-1} for Tora.

2.3.3. Production numbers during the whole lifespan

Table 12 shows the production numbers during the different cutting cycles for the two *Salix* clones.

In literature the following numbers for energy content of oven dry material of *Salix* chips were found: 19.8 GJ t DM^{-1} (Heller et al., 2003), 19.5 GJ t DM^{-1} (Börjesson, 1996b), 18 GJ t DM^{-1} (Lettens et al., 2003), 18.7 GJ t DM^{-1} (Börjesson, 2006). The average number of 18.5 GJ t DM^{-1} is used in this research. See Table 12 for the energy yield in GJ ha^{-1} after 15 years.

Table 12 Specific production per clone (t DM ha^{-1} yr^{-1}); and total production (t DM ha^{-1}) and total energy yield (GJ ha^{-1}) after 15 years

Cutting cycle	**Average biomass production (t DM ha^{-1} yr^{-1})**	
	Jorr	**Tora**
1	6.53	4.81
2	13.99	9.25
3 through 7	17.08	11.52
Total after 7 cutting cycles (t DM ha^{-1})	211.49 (= 3912.48 GJ ha^{-1})	143.34 (= 2551.86 GJ ha^{-1})

2.3.4. Carbon sequestration

The results of the carbon sequestration calculations are shown in Table 13; it is shown for a period of 15 years and a period of 100 years, for each variety. From the results it can be deduced that a higher production gives a higher carbon sequestration in the soil.

With help of the results it can be calculated that carbon sequestration equals 24.96 t CO_2 eqv ha^{-1} for Jorr and 7.60 t CO_2 eqv ha^{-1} for Tora after the lifespan of the *Salix* plantation.

Table 13 Carbon sequestration (t C ha^{-1}) and production (t C ha^{-1}) per Salix variety after 15 and 100 years

***Salix* varieties**	**Total production (t C ha^{-1})**	**Total decay (t C ha^{-1})**	**Total standing biomass (t C ha^{-1})**	**Soil carbon content in 0-50 cm soil (t C ha^{-1})**	**Extra carbon in soil (t C ha^{-1})**	**Extra carbon in soil (t CO_2 eqv/ ha)**
After 15 years						
Jorr	276.85	29.19	247.66	48.67	6.81	24.96
Tora	185.36	18.38	166.98	43.93	2.07	7.60
After 100 years						
Jorr	839.32	192.75	646.57	67.61	25.75	94.41
Tora	560.51	121.73	438.77	53.86	12.00	44.02

2.3.5. Overview

Table 14 gives an overview of the results. Due to carbon sequestration the atmospheric concentration of CO_2 are lowered, which results in a diminution of the contribution of a *Salix* plantation to climate change. That is why the numbers concerning carbon sequestration in Table 14 are indicated with a minus sign.

The amount of emitted greenhouse gases is indicated after 15 years (the lifespan of the *Salix* plantation). A *Salix* plantation of one ha produces a certain amount of biomass, which can be converted in a certain amount of energy (see Table 12). To make comparisons with a coal-fuelled power plant easier, the obtain energy is used to express the amount of greenhouse gases per 1 GJ obtained energy for biomass.

Table 14 Greenhouse gas emissions per ha over 7 rotations

	GHG emissions (t CO_2 eqv ha^{-1} 15 yr^{-1})		**Carbon sequestration (t CO_2 eqv^{-1} ha 15 yr^{-1})**	**Sum (t CO_2 eqv ha^{-1} 15 yr^{-1})**
***Salix* varieties**	**Management of *Salix* plantation**	**Soil emissions (fertilisation and leaf litter)**		
Jorr	11.49	15.61	-24.96	2.14
Tora	11.49	13.46	-7.60	17.35
	GHG emissions (kg CO_2 eqv GJ^{-1})		**Carbon sequestration (kg CO_2 eqv GJ^{-1})**	**Sum (kg CO_2 eqv GJ^{-1})**
***Salix* varieties**	**Management of *Salix* plantation**	**Soil emissions (fertilisation and leaf litter)**		
Jorr	2.94	3.99	-6.38	0.55
Tora	4.50	5.27	-2.98	6.79

The reference system in this research is a power plant fuelled with coal. The energy content of coal is on average 23.8 MJ kg^{-1}. To get 1 GJ the combustion of 42.02 kg coal is necessary, if a return of 100 % is assumed. This will result in an emission of 154 kg CO_2.

With help of the results it can be calculated that the energy obtained from a *Salix* plantation with average fertilisation application (100 kg N ha^{-1} yr^{-1}) is approximately 20 times higher than the energy utilised to grow the crop. The input/output ratio is slightly better for Jorr than for Tora, because Jorr produces slightly more biomass than Tora.

2.4. Discussion

The aim of this research was to roughly determine the greenhouse gas balance of a *Salix* plantation. Greenhouse gas emissions due to the management and fertilisation application of a *Salix* plantation under Dutch conditions were calculated, as well as the emissions due to leaf litter. The results of these calculations were compared with the potential of carbon sequestration in the soil. Two *Salix* varieties were compared, most important difference between those varieties are the production numbers.

In comparison with a coal-fuelled power plant the amount of emitted greenhouse gases by a *Salix* plantation is low. If *Salix* variety ‘Jorr’ is used, the amount of emitted greenhouse gases is 6.93 kg CO_2 eqv per produced GJ. Tora emits 9.77 kg CO_2 eqv per produced GJ. Carbon sequestration may offset the effect of the emissions due to several management activities. For Jorr the amount of carbon sequestration after 15 years is almost high enough to offset the effect of the emitted greenhouse gases totally. If carbon sequestration is counted, the utilization of Jorr results in the emission of 0.55 CO_2 eqv 1 GJ^{-1}. This corresponds to 0.4 % of the amount of greenhouse gases emitted by a coal-fuelled power plant to generate 1 GJ; the utilization of Tora results in the emission of 6.76 CO_2 eqv 1 GJ^{-1}. This corresponds to 4.4 % of the amount of greenhouse gases emitted by a coal-fuelled power plant to generate 1 GJ.

The energy input in comparison with the output of a *Salix* plantation is promising. The input/output ratio of energy is approximately 1 : 20.

From this research it can be concluded that the use of *Salix* biomass for energy generation is environmentally friendly with regard to global warming potential and the mitigation potential is rather extensive. As stated in the introduction the Dutch government has ambitious objectives in the field of renewable energy: in 2020 the contribution of bio-energy has to be 120 PJ yr^{-1}. Currently, the agricultural area in the Netherlands is 2.3 million ha. To satisfy the objectives of the Dutch government for bio-energy by only growing *Salix* crops, approximately 25 % of the total area of agricultural area in the Netherlands is necessary (assuming an average yield of 215 GJ ha^{-1} yr^{-1}).
The production of 120 PJ by coal-fuelled power plants results in emissions which equals 18.5 • 10^6 t CO_2 eqv. The production of 120 PJ with help of 25 % of the total Dutch agricultural area, results in emissions which equals only 0.440 • 10^6 t CO_2 eqv.

Recommendations
In comparison with other researches, the yields of *Salix* plantations per year are rather high in this research. Another difference is rotation length of only 2 years instead of 3 years. Higher yields are probably due to different growing conditions and clonal use (see previous chapter). In this study a rotation length of 2 years was assumed because of the available data. The disadvantage of a rotation length of only 2 years is that some management activities have to be executed more often, for example harvesting has to be done every 2 years instead of every 3 years. Other advantages of a 3 year rotation length are higher yields and higher carbon sequestration (Kuiper, 2003; Nordh, 2005).
However, from the other hand, during a 3 year rotation length more fertilisation and herbicide has to be produced and applied, resulting in increased emissions. As well the emissions from leaf litter will increase.
Research should be carried out to find production numbers after 3 growing seasons and the accompanying emissions. With help of those results it can be investigated what the effect will be of a longer rotation length on the greenhouse gas emissions, and thus on the climate change mitigation potential.

As stated in the introduction only a rough estimation of the balance of a *Salix* plantation was made. It is likely that during the lifespan of a *Salix* plantation technical improvements or developments will occur, for example more efficient tractors or agricultural implements will be developed, or coal combustion will be more efficient. No attempts were made in this research to include those technical improvements or developments. To gain a fair and complete understanding of the mitigation potential of *Salix* plantations, future developments have to be included in next analysis.

The breakdown of the greenhouse gas emissions due to the management activities has shown large contributions of only a few management activities. Research should be focused on the management activities that contribute substantial. With help of this research the decrease of the amount of emitted greenhouse gases can be done efficiently.

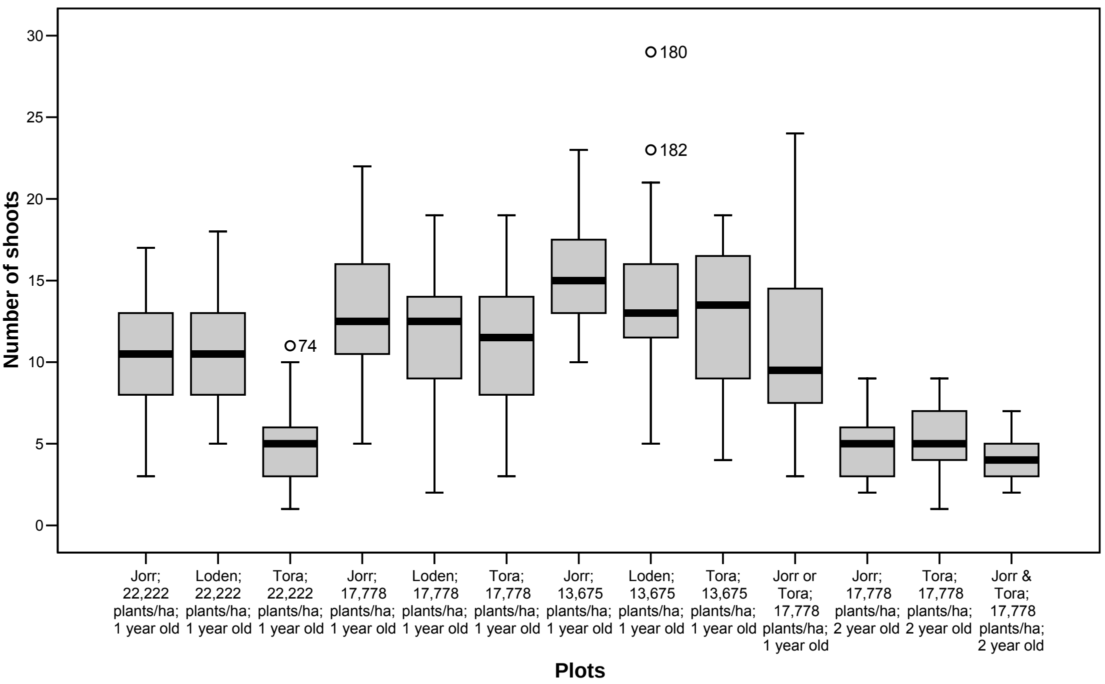
As stated above, to produce 120 PJ 25 % of the Dutch agricultural area is necessary. However, it is not know yet how much land is really available for short rotation forestry. Emphasis should be laid on research that determines the available land for short rotation forestry.

Appendix Detailed statistical results

Table 15 Significant differences between the number of shoots per plant in different plots

ns = no significant difference s = significant difference	Jorr; 22,222 plants/ha; 1 year old	Loden; 22,222 plants/ha; 1 year old	Tora; 22,222 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Loden; 17,778 plants/ha; 1 year old	Tora; 17,778 plants/ha; 1 year old	Jorr; 13,675 plants/ha; 1 year old	Loden; 13,675 plants/ha; 1 year old	Tora; 13,675 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old*	Jorr; 17,778 plants/ha; 2 year old	Tora; 17,778 plants/ha; 2 year old	Jorr & Tora; 17,778 plants/ha; 2 year old
Jorr; 22,222 plants/ha; 1 year old	-	ns	**s**	ns	ns	ns	ns	ns	ns	ns	**s**	**s**	**s**
Loden; 22,222 plants/ha; 1 year old	ns	-	**s**	ns	ns	ns	ns	ns	ns	ns	**s**	**s**	**s**
Tora; 22,222 plants/ha; 1 year old	**s**	**s**	-	**s**	**s**	**s**	**s**	**s**	**s**	**s**	ns	ns	ns
Jorr; 17,778 plants/ha; 1 year old	ns	ns	**s**	-	ns	ns	ns	ns	ns	ns	**s**	**s**	**s**
Loden; 17,778 plants/ha; 1 year old	ns	ns	**s**	ns	-	ns	ns	ns	ns	ns	**s**	**s**	**s**
Tora; 17,778 plants/ha; 1 year old	ns	ns	**s**	ns	ns	-	ns	ns	ns	ns	**s**	**s**	**s**
Jorr; 13,675 plants/ha; 1 year old	ns	ns	**s**	ns	ns	ns	-	ns	ns	ns	**s**	**s**	**s**
Loden; 13,675 plants/ha; 1 year old	ns	ns	**s**	ns	ns	ns	ns	-	ns	ns	**s**	**s**	**s**
Tora; 13,675 plants/ha; 1 year old	ns	ns	**s**	ns	ns	ns	ns	ns	-	ns	**s**	**s**	**s**
Jorr; 17,778 plants/ha; 1 year old*	ns	ns	**s**	ns	ns	ns	ns	ns	ns	-	**s**	**s**	**s**
Jorr; 17,778 plants/ha; 2 year old	**s**	**s**	ns	**s**	**s**	**s**	**s**	**s**	**s**	**s**	-	ns	ns
Tora; 17,778 plants/ha; 2 year old	**s**	**s**	ns	**s**	**s**	**s**	**s**	**s**	**s**	**s**	ns	-	ns
Jorr & Tora; 17,778 plants/ha; 2 year old	**s**	**s**	ns	**s**	**s**	**s**	**s**	**s**	**s**	**s**	ns	ns	-

Figure 10 Box-plot with number of shoots per plant per plot



A box-plot (also known as a box-and-whisker diagram) is a convenient way of graphically depicting the five-number summary, which consists of the smallest observation, lower quartile, median, upper quartile and largest observation (Field, 2005).

Table 16 Significant differences between the total number of shoots per ha in different plots

ns = no significant difference s = significant difference	Jorr; 22,222 plants/ha; 1 year old	Loden; 22,222 plants/ha; 1 year old	Tora; 22,222 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Loden; 17,778 plants/ha; 1 year old	Tora; 17,778 plants/ha; 1 year old	Jorr; 13,675 plants/ha; 1 year old	Loden; 13,675 plants/ha; 1 year old	Tora; 13,675 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old*	Jorr; 17,778 plants/ha; 2 year old	Tora; 17,778 plants/ha; 2 year old	Jorr & Tora; 17,778 plants/ha; 2 year old
Jorr; 22,222 plants/ha; 1 year old	-	ns	s	ns	ns	ns	ns	ns	ns	ns	s	s	s
Loden; 22,222 plants/ha; 1 year old	ns	-	s	ns	ns	ns	ns	ns	ns	ns	s	s	s
Tora; 22,222 plants/ha; 1 year old	s	s	-	s	s	ns	s	ns	ns	ns	ns	ns	s
Jorr; 17,778 plants/ha; 1 year old	ns	ns	s	-	ns	ns	ns	ns	ns	ns	s	s	s
Loden; 17,778 plants/ha; 1 year old	ns	ns	s	ns	-	ns	ns	ns	ns	ns	s	s	s
Tora; 17,778 plants/ha; 1 year old	ns	ns	ns	ns	ns	-	ns	ns	ns	ns	s	s	s
Jorr; 13,675 plants/ha; 1 year old	ns	ns	s	ns	ns	ns	-	ns	ns	ns	s	s	s
Loden; 13,675 plants/ha; 1 year old	ns	ns	ns	ns	ns	ns	ns	-	ns	ns	s	s	s
Tora; 13,675 plants/ha; 1 year old	ns	ns	ns	ns	ns	ns	ns	ns	-	ns	s	s	s
Jorr; 17,778 plants/ha; 1 year old*	ns	ns	ns	ns	ns	ns	ns	ns	ns	-	s	s	s
Jorr; 17,778 plants/ha; 2 year old	s	s	ns	s	s	s	s	s	s	s	-	ns	ns
Tora; 17,778 plants/ha; 2 year old	s	s	ns	s	s	s	s	s	s	s	ns	-	ns
Jorr & Tora; 17,778 plants/ha; 2 year old	s	s	s	s	s	s	s	s	s	s	ns	ns	-

Table 17 Significant differences between average diameter per shoot of different plots

ns = no significant difference s = significant difference	Jorr; 22,222 plants/ha; 1 year old	Loden; 22,222 plants/ha; 1 year old	Tora; 22,222 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Loden; 17,778 plants/ha; 1 year old	Tora; 17,778 plants/ha; 1 year old	Jorr; 13,675 plants/ha; 1 year old	Loden; 13,675 plants/ha; 1 year old	Tora; 13,675 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 2 year old	Tora; 17,778 plants/ha; 2 year old	Jorr & Tora; 17,778 plants/ha; 2 year old
Jorr; 22,222 plants/ha; 1 year old	-	**s**	ns	ns	ns	**s**	ns	ns	**s**	ns	**s**	**s**	**s**
Loden; 22,222 plants/ha; 1 year old	**s**	-	ns	ns	**s**	**s**	**s**	**s**	**s**	ns	**s**	**s**	**s**
Tora; 22,222 plants/ha; 1 year old	ns	ns	-	ns	ns	ns	ns	ns	**s**	ns	**s**	**s**	**s**
Jorr; 17,778 plants/ha; 1 year old	ns	ns	ns	-	ns	**s**	**s**	ns	**s**	ns	**s**	**s**	**s**
Loden; 17,778 plants/ha; 1 year old	ns	**s**	ns	ns	-	**s**	ns	ns	**s**	ns	**s**	**s**	**s**
Tora; 17,778 plants/ha; 1 year old	**s**	**s**	ns	**s**	**s**	-	ns	**s**	ns	**s**	**s**	**s**	**s**
Jorr; 13,675 plants/ha; 1 year old	ns	**s**	ns	**s**	ns	ns	-	**s**	ns	**s**	**s**	**s**	**s**
Loden; 13,675 plants/ha; 1 year old	ns	**s**	ns	ns	ns	**s**	**s**	-	**s**	ns	**s**	**s**	**s**
Tora; 13,675 plants/ha; 1 year old	**s**	**s**	**s**	**s**	**s**	ns	ns	**s**	-	**s**	**s**	**s**	**s**
Jorr; 17,778 plants/ha; 1 year old	ns	ns	ns	ns	ns	**s**	**s**	ns	**s**	-	**s**	**s**	**s**
Jorr; 17,778 plants/ha; 2 year old	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	-	ns	ns
Tora; 17,778 plants/ha; 2 year old	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	ns	-	ns
Jorr & Tora; 17,778 plants/ha; 2 year old	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	ns	ns	-

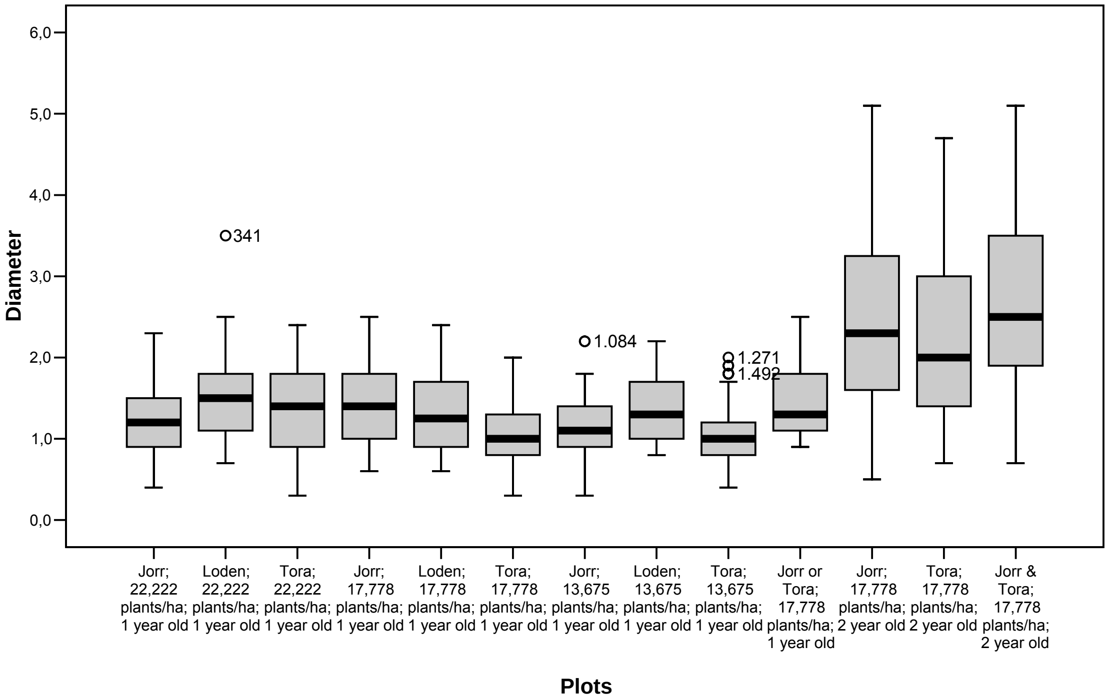


Figure 11 Box-plot with diameter per shoot per plot

Table 18 Significant differences between diameter distributions in different plots

ns = no significant difference s = significant difference	Jorr; 22,222 plants/ha; 1 year old	Loden; 22,222 plants/ha; 1 year old	Tora; 22,222 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Loden; 17,778 plants/ha; 1 year old	Tora; 17,778 plants/ha; 1 year old	Jorr; 13,675 plants/ha; 1 year old	Loden; 13,675 plants/ha; 1 year old	Tora; 13,675 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 2 year old	Tora; 17,778 plants/ha; 2 year old	Jorr & Tora; 17,778 plants/ha; 2 year old
Jorr; 22,222 plants/ha 1 year old	-	s	s	ns	ns	s	s	ns	s	s	s	s	s
Loden; 22,222 plants/ha; 1 year old	s	-	s	ns	s	s	s	s	s	s	s	s	s
Tora; 22,222 plants/ha; 1 year old	s	s	-	s	s	s	s	s	s	s	s	s	s
Jorr; 17,778 plants/ha; 1 year old	ns	ns	s	-	ns	s	s	s	s	s	s	s	s
Loden; 17,778 plants/ha; 1 year old	ns	s	s	ns	-	s	s	s	s	s	s	s	s
Tora; 17,778 plants/ha; 1 year old	s	s	s	s	s	-	s	s	ns	s	s	s	s
Jorr; 13,675 plants/ha; 1 year old	s	s	s	s	s	s	-	s	s	s	s	s	s
Loden; 13,675 plants/ha; 1 year old	ns	s	s	s	s	s	s	-	s	s	s	s	s
Tora; 13,675 plants/ha; 1 year old	s	s	s	s	s	ns	s	s	-	s	s	s	s
Jorr; 17,778 plants/ha; 1 year old	s	s	s	s	s	s	s	s	s	-	s	s	s
Jorr; 17,778 plants/ha; 2 year old	s	s	s	s	s	s	s	s	s	s	-	s	ns
Tora; 17,778 plants/ha; 2 year old	s	s	s	s	s	s	s	s	s	s	s	-	s
Jorr & Tora; 17,778 plants/ha; 2 year old	s	s	s	s	s	s	s	s	s	s	ns	s	-

Table 19 Significant differences between dry weight per plant in different plots

ns = no significant difference s = significant difference	Jorr; 22,222 plants/ha; 1 year old	Loden; 22,222 plants/ha; 1 year old	Tora; 22,222 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old	Loden; 17,778 plants/ha; 1 year old	Tora; 17,778 plants/ha; 1 year old	Jorr; 13,675 plants/ha; 1 year old	Loden; 13,675 plants/ha; 1 year old	Tora; 13,675 plants/ha; 1 year old	Jorr; 17,778 plants/ha; 1 year old*
Jorr; 22,222 plants/ha;1 year old	-	ns	ns	ns	ns	ns	ns	ns	ns	ns
Loden; 22,222 plants/ha; 1 year old	ns	-	**s**	ns	ns	**s**	ns	ns	**s**	ns
Tora; 22,222 plants/ha; 1 year old	ns	**s**	-	**s**	**s**	ns	**s**	**s**	ns	**s**
Jorr; 17,778 plants/ha; 1 year old	ns	ns	**s**	-	ns	**s**	ns	ns	**s**	ns
Loden; 17,778 plants/ha; 1 year old	ns	ns	**s**	ns	-	**s**	ns	ns	**s**	ns
Tora; 17,778 plants/ha; 1 year old	ns	**s**	ns	**s**	**s**	-	ns	**s**	ns	**s**
Jorr; 13,675 plants/ha; 1 year old	ns	ns	**s**	ns	ns	ns	-	ns	**s**	ns
Loden; 13,675 plants/ha; 1 year old	ns	ns	**s**	ns	ns	**s**	ns	-	**s**	ns
Tora; 13,675 plants/ha; 1 year old	ns	**s**	ns	**s**	**s**	ns	**s**	**s**	-	**s**
Jorr; 17,778 plants/ha; 1 year old*	ns	ns	**s**	ns	ns	**s**	ns	ns	**s**	-

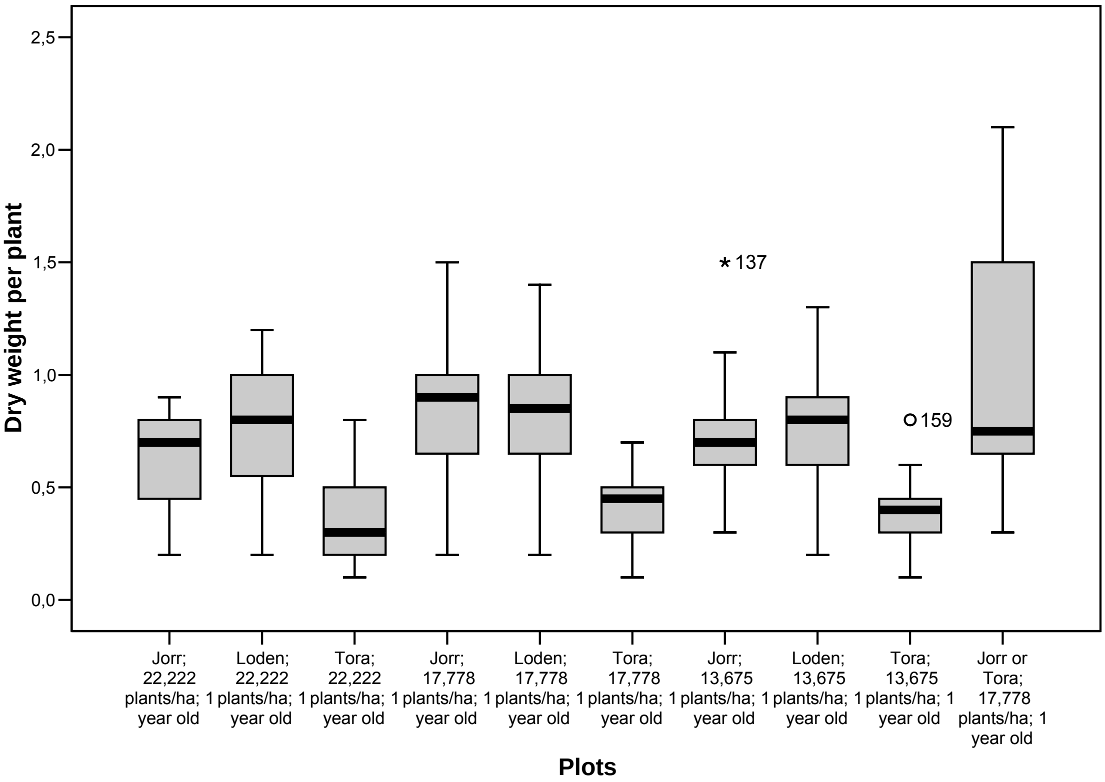


Figure 12 Box-plot with dry weight per plant per plot

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