Short-Rotation Woody Crops Program

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Biomass Power for Rural Development Technical Report:

ROOT DYNAMICS IN WILLOW BIOMASS CROPS

Interim Report

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Executive Summary

Short-rotation woody crops (SRWC) have been studied extensively over the last few decades in the United States, Canada, and Europe. To date, the vast majority of work has focused on the aboveground biomass production since this is the marketable portion of the system. The aboveground portion of the plant is relatively easy to observe and monitor. In contrast, it is difficult to obtain accurate and consistent measurements of the belowground portion of SRWC systems.

While relatively little is known about the belowground portion of SRWC, it is widely recognized that it plays an essential role in the development and success of these systems. Roots conduct crucial functions including anchoring the plants in the ground; storing carbohydrates and nutrients, which is especially important in coppice systems; and acquiring and transporting nutrients and water that are essential for the growth and development of the entire plant. Early root production in hybrid poplars has been strongly correlated with aboveground biomass production. Quantifying belowground biomass and rates of root growth and turnover is important in understanding carbon dynamics as well as improving the effectiveness of different management techniques for willow biomass crops.

Fine roots (usually defined as roots < 2 mm in size) comprise a surprisingly large percentage of the total root biomass in SRWC. Studies of hybrid poplar have shown that fine root biomass accounts for up to 60% of the total root biomass in one-year-old trees, about 40% of the total root biomass in two-year-old trees, and 21-40% of the total root biomass in four-year-old trees. These data were based on single point in time biomass assessments. An important characteristic of fine roots that is excluded from single point in time sampling methods is the turnover rate. Inclusion of fine root turnover rates increased estimates of belowground root biomass of short-rotation willow by 200 - 400% compared to single point in time biomass estimates. Understanding and quantifying these differences is important for calculations of carbon cycling and sequestration in these systems.

Vertical and horizontal root development in SRWC systems is influenced by the clones planted, soil characteristics, plant spacing, and management activities. Generally, studies have shown that the majority of fine roots in SRWC willow and poplar systems are concentrated in the upper 20 – 30 cm of the soil. The vertical distance that roots cover can be up to several meters in length. The spatial distribution of fine roots is an important characteristic to understand in order to improve the management and sustainability of SRWC.

Understanding root growth and dynamics is especially important for willow biomass crops because these SRWC systems are based on coppice regeneration. The understanding of root characteristics and dynamics in short-rotation willow and poplar is clearly in its infancy. The information available already has some implications for the management of these systems. However, additional information is required to improve the production system and more accurately quantify environmental benefits associated with the system. This project was designed to address knowledge gaps on belowground root dynamics of willow biomass crops. The objectives are:

1) to assess fine root production and turnover in short-rotation willow biomass crops,

2) to determine the effect of composted chicken manure as an organic nutrient amendment on short-rotation willow fine root distribution, production and turnover.

Minirhizotrons were selected to study the belowground dynamics of willow biomass crops because fine root production and turnover were assessed. Twenty-four minirhizotrons were inserted into in the root zone of willow research plots in Tully, NY. Over 20,000 images have been collected over the course of one and one half growing seasons in 1998 and 1999. The images are currently being digitized and data analyzed.

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Introduction

Short-rotation woody crops (SRWC) have been studied extensively over the last few decades in the United States, Canada, and Europe. The two genera that have received the most attention are *Populus* and *Salix*. To date the vast majority of work has focused on the aboveground portion of the crop. One reason for this is that the aboveground biomass is the product from the system that is harvested and utilized. Another factor is that this portion of the plant is easy to observe and monitor.

Increasingly there is recognition that the belowground portion of these systems has an essential role in development and success of these plantations. Roots play crucial roles including anchoring the trees in the ground, storing carbohydrates and nutrients, which is especially important in coppice systems, and acquiring and transporting nutrients and water which are essential for the growth and development of the entire plant. The belowground portion of SRWC can constitute more than 50% of the annual net primary productivity (Rytter 1999). Early root production in hybrid poplars is strongly correlated with aboveground biomass production. Differences in root production and development among clones and across sites may be partially responsible for the observed aboveground differences in production (Friend et al. 1991, Heilman et al. 1994a, Tschaplinski and Blake 1989). The current level of understanding about SRWC is incomplete without a better knowledge of the belowground portion of the crop. As a result the management of these systems is not optimized.

The goal of this interim report is to:

1. summarize the current understanding of roots in willow and poplar biomass crops,
2. report on current progress in the research on fine root dynamics in willow biomass crops located in Tully, NY.

In particular, the distribution, biomass allocation, and impact of different soil properties on roots will be discussed. Summaries of some of the techniques used to study roots will be covered in order to illustrate that comparisons among studies can be very difficult. A brief discussion of the management implications that arise from an increased understanding of root systems is included.

Current Understanding of Root Systems in Short-Rotation Woody Crops

Challenges in Studying Tree Root Systems

The root systems of both perennial crops and trees in general are poorly understood because of the difficulty of studying them. Over the years a wide variety of sampling techniques have been developed to observe and measure roots. Mackie-Dawson and Atkinson (1991) grouped these techniques into the following three general categories:

1. soil sampling methods including total or partial root system excavation, profile walls, and soil coring,
2. observation methods including rhizotrons, minirhizotrons and microrhizotrons,
3. indirect methods including soil moisture depletion, nutrient budget approaches, and radio isotopes.

Each of these approaches yields information about certain characteristics of root systems. For example soil sampling methods can be used to provide single point in time biomass estimates but will not provide information on fine root turnover or longevity. Each approach to sampling has its own set of limitations and restrictions. In addition, results from the various techniques are summarized differently. Some studies use fine root length density (FRLD) - defined as the root length (cm) per volume (cm^3) of soil - to report results. Other studies use root weight or root length. Weight or length measurements are often divided up by different soil layers or at set intervals in the profile depending on the objectives of the study. The components of the belowground system that go into each of these measurements vary. For example, some studies on young trees established from unrooted cuttings will exclude the cutting from belowground biomass calculations, whereas others will include it. In coppice systems, the situation becomes more complex because the stool can become a significant portion of the total biomass of the plant, but it can be allotted either to the above or belowground portion of the plant.

Due to these factors, results from different methods are usually not directly comparable (Rytter 1999). There are complications from site to site variation, and the application of various treatments, especially nutrients and water, that affect root development. These various limitations need to be recognized when comparing results from different studies. However, despite the number of complications, some trends can be identified. Summarizing this information is an important step in improving the management and production of the willow biomass crop system.

Vertical and Horizontal Distribution of Roots

Studies have shown that the majority of fine roots (usually defined as roots < 2 mm in diameter) in SRWC willow and poplar systems are concentrated in the upper layers of the soil surface. Rytter and Hansson (1996) found that the mean rooting depth in an irrigated and fertilized *Salix viminalis* plantation, with four-year-old roots with three-year-old tops, was between 25 and 30 cm for most of the first year of measurement. During the second year, the mean rooting depth fluctuated, beginning at about 20 cm in early April and shifting to 40 cm by mid July. The increase in mean rooting depth may have been due to an extreme drought during - precipitation was 90% lower than the previous July. Even with the irrigation system, the authors speculate that the decrease in surface moisture was responsible for decreasing the number of roots at the soil surface. About 40-45% of the root biomass from the top 50 cm of the soil was concentrated in the top 10 cm of soil. Other studies on SRWC willow have confirmed that the majority of roots are in the top 10 to 20 cm of the soil. Ericsson (1984) found that a three-year-old *S. dasyclados* planting with one-year-old tops, grown on a peat soil that was cultivated and limed to 20 cm depth, had 90% of its root biomass in the top 12 cm of the soil. Elowson and Rytter (1984) found that 60% of the root biomass for a three-year-old *S. viminalis* plantation with one-year-old shoots was located in the top 10 cm of a peat soil. Results for SRWC poplar systems are similar to those for willow. Heilman et al. (1994a) found that over 50% of the fine root biomass of four-year-old hybrid poplar measured in the soil to a depth of 3.1 m was found in the first 36 cm of soil. A similar pattern was found when

FRLD was assessed. FRLD was 3 - 3.5 times greater in the top 18 cm compared to the next 18 cm of soil.

While the pattern of roots concentrated at the soil surface holds true for both willow and poplar SRWC systems, the vertical distance that roots cover in these systems can be surprisingly large. Friend et al. (1991) found that roots from one-year- old poplars extended beyond one meter in depth. Two-year-old tree roots extended beyond 1.5 m. Heilman et al. (1994a) found roots from four-year-old hybrid poplars at depths greater than three meters.

Assessing the horizontal distribution of roots in SRWC systems is particularly difficult because the high planting densities result in significant overlap of roots from different trees. The limited work that has been done has focused on the distance covered by the longest roots. The horizontal distance covered by roots is extensive and, as expected, increases with tree age. The surprising point is just how extensive the root systems are during the early years of growth. Hansen (1981) found that the maximum root length for one-year-old hybrid poplar trees was 2.2 m, with all trees having at least one root of 1.5 m in length. By age three the maximum root length had increased to 5.2 m. Friend et al. (1991) found that lateral roots of hybrid poplar extended up to two meters after one year of growth and up to four meters after two years. In this tightly spaced plantation (1.0 x 1.0 m) the spread of the roots was up to six times the crown radius. Horizontal spread of roots was the most distinct belowground morphological characteristics between the four clones examined, although it did not correlate with aboveground production.

Other studies have found a correlation between the extent of root distribution and aboveground growth. Faulkner and Fayle (1979) reported that three- year-old hybrid poplars had root lengths of 4.0 - 6.6 m. Five-year-old trees in their study had root lengths ranging from 8.3 - 10.2 m. They noted that stem wood production was greater for clones that occupied more soil volume because of their more extensive and highly branched root systems. Heilman et al (1994b) found that root lengths of one-year-old hybrid poplar were somewhat shorter and depended on the origin of the root. Roots that originated from the base of cutting reached lengths of 0.6 – 1.1 m after one year. In contrast roots that originated from the side of the cuttings only had lengths ranging from 0.4 – 0.5 m. The exact reason for these differences is not clear, but may include factors such as the type of tissue the roots originated from or the initial orientation of the roots. Basal roots in this study, and in work conducted by Friend et al (1991), tended to originate from callous tissue and have a more vertical orientation. Due to the high planting density of SRWC stands these vertically oriented roots may be favored, especially as the trees age and there is more competition among surface roots.

Work on the horizontal distribution of willow roots is even more limited because planting densities are extremely high (10,000 - 20,000 trees ha^{-1}). This means that very early in the life of the plantation there is extensive root overlap and in some cases grafting occurs. One study that did measure root lengths found that the longest roots on three-year-old *S. dasyclados* were 4.3 m long (Ericsson 1984).

Several studies have found that the fastest growing poplar clones had the largest amount of early root development (Pallardy and Kozlowski 1979, Tschaplinski and Blake 1989, Rhodenbaugh and Pallardy 1993 and Heilman et al. 1994a). Early and rapid root development would provide plants with a greater surface area to take up necessary water and nutrients. An extensive root system, especially of vertically oriented roots, would mean that these plants would be more likely to maintain a favorable water balance during times of moisture stress. This stress could be due to a drought period or a combination of a lack of precipitation and severe weed competition. A root system that is distributed through a large volume of soil would allow photosynthesis in these plants to occur for a longer time during periods of moisture stress compared to plants with a more limited root system. It has been noted in a variety of studies that field productivity of poplar clones is correlated with net photosynthetic rates or leaf area (Isebrands et al. 1983, Pregitzer et al. 1990, Rhodenbaugh and Pallardy 1993). New root biomasss in natural aspen stands was strongly correlated with leaf area index and basal area (DesRochers and Lieffers 2001). The rapid growth and extensive distribution of roots from willow and hybrid poplar clones, which provide access to a large soil volume and thus a significant amount of soil resources, may be a key factor in the high rate of production, especially on marginal sites.

Root System Biomass

While there has been a lot of research conducted on aboveground biomass production in SRWC systems, relatively little has been done on root biomass production. The main reason is the difficulty in obtaining accurate and consistent measurements of the belowground portion of the biomass. Quantifying belowground biomass as well as how it changes over the coarse of a single year and during a rotation is important to better understand carbon dynamics of SRWC.

Soil sampling methods, such as excavations and coring have commonly been used to make biomass assessments, but fine roots are frequently missed or left in the soil. Separating fine roots from the soil matrix is difficult, especially in soils of heavier texture or high levels of organic matter. Friend et al (1991) worked in a lighter texture sandy loam soil and found that only 60% of the root biomass was recovered during the extraction. Two additional steps were employed to increase the recovery rate. Coarse sieving the soil added another 16% of the total root biomass and sorting through this sieved soil recovered the remaining 24%. Because of difficulties like these, other approaches to assess root biomass in SRWC systems have been tried. Chapman (1992) used root enclosures made of a hydrophilic membrane with 3 μm diameter pores. Pore size was large enough to permit the flow of water and nutrients across the membrane but small enough to restrict root penetration. Even with this technique, he found that there was 20 - 33% loss of fine root biomass as roots escaped from the enclosures along the seams. He developed a complicated and labor intensive secondary collection technique that recovered about 15- 20% of the root mass. In many cases the amount of time and effort that is required to reduce the variability to a level that will allow for the detection of differences in root characteristics is prohibitive.

The fine roots in the system comprise a surprisingly large percentage of the total root biomass. Studies of hybrid poplar have shown that fine root biomass accounts for up to 60% of the total root biomass in one-year-old trees (Dickman and Pregitzer 1992), about 40% of the total root biomass in two-year-old trees (Friend et al. 1991), and 21-40% of the total root weight in four-year-old hybrid poplar (Heilman et al. 1994a). These assessments were based on single point in time biomass assessments. An important characteristic of fine roots that is often excluded when soil sampling methods are used is the turnover rate. In a study of willow, Rytter (1999) found that fine root turnover rates ranged from 4.9 - 5.8 yr^{-1}. With these figures included, fine roots accounted for between 28 - 50% of the net primary production of the plant. Inclusion of fine root turnover rates increased estimates of belowground biomass of willow by 200 - 400% compared to single point in time biomass estimates. However, fine roots remain one of the most difficult portions of the belowground system to study and are therefore often not fully incorporated into belowground biomass estimates.

The high density of SRWC plantings is another complicating factor in trying to assess root biomass. It is often difficult to separate the roots of one tree from another. Various approaches have been used to address this issue. One approach to get around field partitioning problems is to establish pot studies (e.g. Pregitzer et al. 1990). These have a set of different problems that make interpretation of the data difficult. Pot studies are often set up under ideal moisture and nutrient conditions, which affects the partitioning of above and belowground biomass. In some studies root growth is restricted. Pot studies only allow assessment of relatively young trees and, as will be discussed below, the biomass distribution in young trees may not accurately represent the biomass distribution in older trees.

With all these caveats in mind, it is still worth examining the data on biomass partitioning in SRWC systems because roots make up a significant portion of a plant's biomass. Root:shoot ratios for poplar after the first growing season are in the range of 0.5 - 1.7. The ratio ranges from 0.20 - 0.94 for two-year-old plants and from 0.14 to 0.17 for three-year-old plants (Dickman and Pregitzer 1992). In general, it appears that the proportion of biomass in the roots decreases after the first year of growth and the root:shoot ratio generally drops below 0.25.

The few studies of root:shoot ratios for willow suggest a similar pattern of decreasing root:shoot ratios as the plants get older. However, the coppice management system for willow creates some changes in the patterns. A study of willow clone SP3 (*Salix purpurea*) in central New York planted at very high densities (30 cm x 30 cm spacing) found that during the establishment year (i.e. first-year above and belowground growth) the root:shoot ratio ranged from about 1.1 in June, to 2.1 in late September, to 1.5 in November. In the first year of growth after coppice (i.e. first- year aboveground growth on a two-year-old root system), the root:shoot ratio varied from 10 to 1.43 over first the growing season (Sah 1990). Chapman (1992) found that root:shoot ratios for first-year coppice growth on two-year-old rootstock of the same willow clone varied from 5.5 at the beginning of the growing season, to a low of 0.27 in August, to 0.39 in October. Chapman used a wider spacing (0.6 x0.9m), worked at a different site, and used different methods, which may explain some of the differences in the root:shoot ratios. However, the pattern for root:shoot ratios is similar over the course of the growing season. It starts very high since the trees were coppiced during the winter, rises to a peak late in the growing season, and than drops off during the fall. Rytter and Hansson (1996) found that root growth in a *S. viminalis* plantation started in the spring before shoot growth was observed. They also found that root growth continued for several weeks in the fall after shoot growth had already stopped. This early and late season root growth contributes to the shifts in root:shoot ratios over the growing season. Studies with poplar have found similar patterns in root:shoot ratios over the course of the growing season. Pregitzer et al (1990) found that roots >1mm in diameter comprised 30% of the whole plant biomass in August and almost 50% in November. Almost all of the root biomass increase was in the larger roots suggesting that it was due to the accumulation of nonstructural carbohydrates in the roots. Heilman et al. (1994b) found that the root:shoot ratios were high in mid July, decreased in early August and increased in early September.

Some Factors Affecting Root Distribution and Biomass Allocation

A wide range of factors influences the distribution of roots and biomass allocation in SRWC systems. The studies noted above support the general findings that the majority of tree roots are found near the soil surface. Fine roots tend to concentrate in areas where the soil is well aerated but still has a high capacity for moisture and nutrient retention (Dickman and Pregitzer 1992). Rytter and Hansson (1996) and Heilman et al. (1994a) suggested that the water supplied through surface drip irrigation systems contributed to the high concentration of willow and poplar roots respectively near the soil surface. Low soil moisture conditions have been shown to significantly reduce rooting and delay sprouting of several clones of poplar (Hansen and Phipps 1983). The current recommendation to soak willow and poplar cuttings in water for 24 - 48 hours before planting is based on these observations and the fact that soaking stimulates both rooting and sprouting. Rhodenbaugh and Pallardy (1993) found that a dry soil treatment (-0.3 Mpa) significantly lowered root length for all three clones studied versus a moist soil treatment (field capacity). However, total root biomass was only significantly lower under the dry conditions for one of the clones, NE308. The dry treatment significantly reduced stem dry weight for all three clones. Root:shoot ratio and root length:leaf area ratios of all three clones tested also remained about the same in the both the dry and moist soil treatments. Since the root:shoot balance did not shift, the authors suggest that none of the clones used were very well adapted to dry site conditions.

Soil moisture can have a negative impact on root growth and development when the soil becomes saturated for an extended period. Pregitzer et al. (1990) found that a high water treatment (eight times the application rate of the low water treatment) reduced the biomass production of both of the poplar clones (Tristis and Eugenei) tested. The leaf area of the Tristis clone was reduced under the high water treatment, but no effect was evident in the Eugenei clone. In contrast, root biomass was often lower in the Eugenei clone under the high water treatment, but no difference was detectable for the Tristis clone. Elowson and Rytter (1984) and Ericsson (1984) noted that the vertical distribution of roots was severely restricted by the saturated soil conditions at a depth of 20 – 30 cm.

High levels of soil resources, especially nitrogen, have been shown to cause higher growth rates in shoots compared to roots. This is illustrated in the work by Pregitzer et al. (1990) where the root:shoot ratio of two different hybrid poplar clones decreased significantly as the level of nitrogen was increased. The shift was largely due to an increase in the leaf area under the higher nitrogen treatment rather than a decrease in root biomass. In other studies, roots were found to concentrate in areas of higher nutrient resources when plants were exposed to a gradient. Rytter and Hansson (1996) suggested that the fertilizer additions and the nutrient rich surface litter layer were factors influencing the concentration of willow roots at the soil surface. Heilman et al. (1994a) found strong trends in FRLD through the soil profile. When they examined the entire soil profile, percent organic matter and nitrogen level in the soil - which were highest at the surface - had strong positive correlations (R^2 = 0.71 and 0.73 respectively) with FRLD.

Soil pH, which affects nutrient availability, has been shown to influence root distribution in SRWC plantations. Ericsson (1984) found that *S. dasyclados* root distribution and pH of the peat were strongly correlated. A pH above 4.5 with a good moisture supply resulted in good root growth. Elowson and Rytter (1984) noted that the liming of the peat - which raised soil pH from below 5 to about 6 - increased *S. viminalis* root development in the area of the soil where the lime was mixed. They suggested that a pH of 5.5 or higher is required for good root development. Ericsson and Lindsjö (1981) also found that peat with a pH lower than 5.0 restricted willow root growth and caused the death of some root tips. The current recommended soil pH range for hybrid poplar is similar, 5.5 to 7.5 (Boysen and Strobl 1991).

Other characteristics that influence site quality for SRWC have an effect on belowground biomass production. Ericsson (1984) found that a good quality site had almost four times the standing root biomass compared to the poor site that was examined. He suggested that low nutrient and water holding capacity were the factors that restricted growth on the poor site. However, soil parameters were not quantitatively compared between the two sites.

Soil physical characteristics such as soil texture, bulk density, structure, horizon thickness, and mechanical resistance all influence root distribution in the soil (Bennie 1991). In the case of SRWC systems, the use of heavy equipment has raised concerns about soil compaction. Although there is less frequent traffic on these sites compared to agricultural fields where annual crops are grown, there is also less soil tillage. An increase in bulk density and destruction of structure due to compaction may restrict root development and distribution in these systems. Almost no work has been done in SRWC systems looking at differences in root development based on some of these characteristics. Heilman et al. (1994a) found that in the subsoil, sand content had a negative correlation with FRLD of poplar. Roots found in the lenses of sandy soil had larger diameters and fewer branches than roots found in adjacent finer textured soils.

Additional work on the relationship of root growth and development to soil physical and chemical characteristics would promote matching clones to soil types and would facilitate the design of management systems across a range of soil conditions.

Limiting either the vertical or the horizontal distribution of roots in SRWC systems will have an impact on the soil volume available for root development. Elowson and Rytter (1984) and Ericsson (1984) noted that a rooting depth of 20 cm - which was limited by saturated soil conditions - severely limited the soil volume that the roots could exploit. This resulted in lower than expected aboveground biomass production. They suggested that this rooting depth would probably not allow for sustainable production of willow biomass crops at economically productive yields. The current recommended practice of deep plowing or ripping to break up plow pans or other hardpans is aimed at increasing the soil volume that can be exploited by the roots (Ledin and Willebrand 1995).

Planting configuration for SRWC systems also affects root distribution. Ericsson's (1984) study of *S. viminalis* roots showed that root biomass in the top 20 cm of a peat soil decreased with increasing distance between the double rows used in commercial plantations. Roots from the three-year-old trees were found across the entire 1.5 m space between the double rows, but root biomass was 60 - 70% lower in the 1.5 m space than the areas directly under the canopy of the trees. Limited development of root systems both horizontally and vertically may increase the risk of nutrient losses, particularly nitrogen, in connection with high rainfall events after fertilizers have been applied. The degree of root development during the establishment year is important since fertilizers are typically applied in the spring right after the plants have been coppiced. Ericsson (1984) has suggested that a fine root concentration of 0.5 g l^{-1} of soil is required in order to make the best use of applied nutrients and to minimize losses through leaching. If fine root concentration can be used as an indication of the plant's ability to make use of nutrients, than the timing and placement of fertilizers can be managed to optimize nutrient use and minimize nutrient losses. For Ericsson's (1984) study, two of the areas examined had root concentrations below the recommended 0.5 g l^{-1}. He notes that there were nutrient losses at the site but he was unable to directly pinpoint the source. Having a better understanding of root distribution, turnover, growth rates and uptake activity of roots in SRWC systems, would help eliminate some of these losses. Fertilizer could be applied in the areas where roots are concentrated and at times when the roots are most active.

The density of SRWC plantations has been shown to have an effect on aboveground growth and development (DeBell et al. 1996, Kopp et al. 1997, Willebrand and Verwijst 1993). It is also likely that changes in spacing influence the distribution of the belowground portions of the plant. While no specific research has been published to date on the effect of plant density on root distribution and growth in SRWC systems, inferences can be made from other studies. Atkinson et al. (1976) showed that apples grown at a higher density (0.3 x 0.3 m versus 2.4 x 2.4 m spacing) had root systems that were much more compact in the horizontal plane and extended further in the vertical plane. Studies done in central New York with *S. pupurea* clone SP3 give some indication of the effect of density on root biomass. Chapman (1992) planted clones at a 0.6 x 0.9 m spacing while Sah (1990) planted at a 0.30 x 0.30 m spacing. After one year of shoot growth on two-year-old root stock Chapman (1992) reported root biomass per plant of 255.6 $\pm$ 38.6 g versus Sah's (1990) 33.6 $\pm$ 5.3 g. Despite the differences in soil conditions and measurement techniques, it appears that the denser systems reduced the root biomass production on a per plant basis. However, on an area basis the root biomass was surprisingly similar. Chapman (1992) measured 4.71 $\pm$ .71 Mg ha^{-1} versus Sah (1990) 3.72 $\pm$ .47 Mg ha^{-1}. The aboveground biomass production in the two studies followed a similar pattern.

Studies of the root systems of *Populus* and *Salix* indicate that there is a strong genetic component influencing root growth and production. For example, Pregitzer et al. (1990) found that root biomass of *Populus euramericana* cv. *Eugenei* was consistently lower than *P. tristis* x *P. balsamifera* cv. *Tristis*. This pattern was consistent under a range of moisture and nitrogen fertilizer treatments. Other studies with these two clones have also found similar biomass partitioning pattern (Isebrands and Nelson 1983). The consistent differences in allocation to roots between Tristis and Eugenei suggest that Tristis may be more successful on harsh sites where water and/or nutrients are limiting.

Heilman et al (1994a) found that four-year-old hybrid crosses of *P. trichocarpa* and *P. deltoides* consistently had higher aboveground biomass production than either of their parents. There were differences in root distribution between the hybrid clones. Two of the clones that had intermediate aboveground productivity also had consistently lower - by almost 50% - FRLD in the surface soil compared to the other clones. Total root biomass between the five clones was similar. While there is no direct testing or evidence of the management implications of this pattern, it does present some interesting opportunities. Clones with lower concentration of roots in the soil surface may less susceptible to short periods of drought. They may be damaged less by mechanical weed control operations and surface application of herbicides. Differences in surface root distribution may be important for agroforestry systems where crops and trees are mixed. Lower surface root density would be an attractive feature because it would probably reduce the competition between crop plants and trees.

Root Silviculture and Management

In short-rotation willow and poplar systems, management has focused largely on the aboveground portion of the system. This is not surprising since this portion of the plant is easy to observe and produces the desired product. In addition, the root system is especially difficult to study and understand. As further work is done on root systems it is becoming clear that the belowground portion of the system is critical for, and often influences, the aboveground production. This is especially true with willow biomass crops because these systems are based on coppice regeneration. As the understanding of the root distribution and dynamics increases it is likely that different aspects of SRWC management will be modified to include specific practices focused on the root system.

The type of management modifications for SRWC that can be based on increased understanding of roots will probably vary depending on the goal that is being pursued. One important issue is the need to match the specific clones to particular sites in order to optimize production. An understanding of root distribution and sensitivity to different soil conditions would facilitate making the best matches. If the goal of the system is to maximize aboveground biomass production the rooting characteristics selected for would be different from systems whose goal is to maximize the uptake of nutrients in filter strips or riparian buffer strips, or the uptake of heavy metals on contaminated sites.

Since rooting patterns are under some degree of genetic control, these characteristics will be a factor in the tree improvement process. Breeding work on other woody crops such as fruit trees has focused considerable effort on the belowground portion of the plant and has yielded some very beneficial results. For example, the most productive trees in apple and citrus orchards have genetically different root stock and the scion stock. The root stock material was chosen based on belowground characteristics such as root growth and disease resistance while the scion stock was selected for production of fruit. Rooting ability is already a factor that is assessed in the selection of clones for sweetgum and cottonwood (Riemenschneider et al. 2001).

Weed competition is perhaps the single largest factor limiting the successful establishment of SRWC plantations. In many situations competition between the weeds and the woody crop is for moisture and nutrients, not for light. So it is the belowground competition that is most important. Some clones of willow and poplar may compete more effectively with weeds because of differences in root growth or distribution. It may become possible to select individual clones that will compete more effectively under different levels of weed competition. The morphology and development of root systems in SRWC clones may also affect the types of weed control that are used. To date the majority of weed control has been chemical. However, different types of cultivation are being developed, especially in the first year of establishment (Ledin and Willebrand 1995). The amount of root disturbance that occurs during mechanical weed control is frequently a concern, but has not been assessed. Potential root damage could be managed more effectively if there was a better understanding of the time and extent of early root development of various clones.

In SRWC systems aboveground biomass yield is a stand level phenomenon. Work has been done on the optimal spacing and planting densities of different species of biomass crops to maximize biomass productions (e.g. DeBell et al. 1996, Kopp et al. 1997, Willebrand and Verwijst, 1993). Soil moisture and nutrients, especially nitrogen, are often identified as factors that limit biomass production (Pregitzer et al. 1990). Since the competition for these resources occurs belowground, systems should be designed so that root, as well as aboveground, competition is minimized so the plants can make the most efficient use of the water and nutrients in the soil.

In order to make the most efficient use of fertilizers applied to SRWC woody crops there needs to be a well established root system. This is one of the reasons why the current recommended fertilizer regime for willow biomass crops does not include fertilizer application in the establishment year. The first application occurs after coppice regrowth has resumed the first year after cutback. The indication that certain root concentrations are required to minimize leaching of nutrients, particularly nitrogen, and knowledge about root distribution suggests that this information can be used to determine the timing and placement of fertilizers.

Study Objectives

The understanding of root characteristics and dynamics in short-rotation willow and poplar is clearly in its infancy. The information available already has some implications for the management of these systems. However, additional information is required in order to improve the production system and reduce the environmental impacts associated with the system. This study was designed to address some of the knowledge gaps on belowground root dynamics of willow biomass crops. The objectives for this study are:

1) assess fine root production and turnover in short-rotation willow biomass crops established using a double row system with density of 15,000 stems ha^{-1}.
2) determine the affect of composted chicken manure as an organic nutrient amendment on short-rotation willow fine root production and turnover.

Methods

The short-rotation willow research plots for this study are located at the Genetics Field Station in Tully, NY. The stand was planted with willow clone SV1 (*Salix dasyclados*) in 1995 following the standard late summer-fall site preparation regime in

1994 (Volk et al. 1999). The commercial double row spacing was used resulting in a stand density of 15,300 plants ha^{-1}. The stand was cutback in the late fall of 1995. Shortly after growth started in the spring of 1996 applications of two organic nutrient amendments (lime stabilized sludge, and composted chicken manure), plastic mulch and slow release nitrogen fertilizer were applied. Three replicates of each treatment, and a control (no nutrients added), were established in a completely randomized design (See Fillhart et al. 2000 for details). The control and composted chicken manure treatments were selected for the study of belowground root dynamics.

Belowground Root Dynamics

Minirhizotrons were selected to study the belowground root dynamics of willow biomass crops because fine root production and turnover were assessed. Minirhizotrons are a non-destructive method for studying roots. The ease of data collection relative to destructive methods means that larger sample sizes can be obtained for the same amount of effort. Due to their permanent position, the high degree of spatial variation encountered when using repeated destructive sampling methods is reduced.

Four minirhizotron tubes were permanently inserted into the soil in early of 1998 on each of three replicated plots of the control and chicken manure treatments (Figures 1 and 2). The tubes were inserted at a 45^0 angle to the soil surface to a depth of one meter. The portion of the tube remaining above the surface was painted with layers of black and white paint and the opening was capped to prevent light from entering the tubes. Monthly observations were made from August to October in 1998 and 1999 using a small video camera inserted into each minirhizotron tube (Figure 3). Data from each tube were recorded along four different axis points around the tube at 12.5 mm intervals along the length of the tube. The pictures were recorded onto videotape, which are currently being digitized and analyzed. The data will be used to determine root distribution, root density and number, root diameters, and fine root turnover and growth rates.

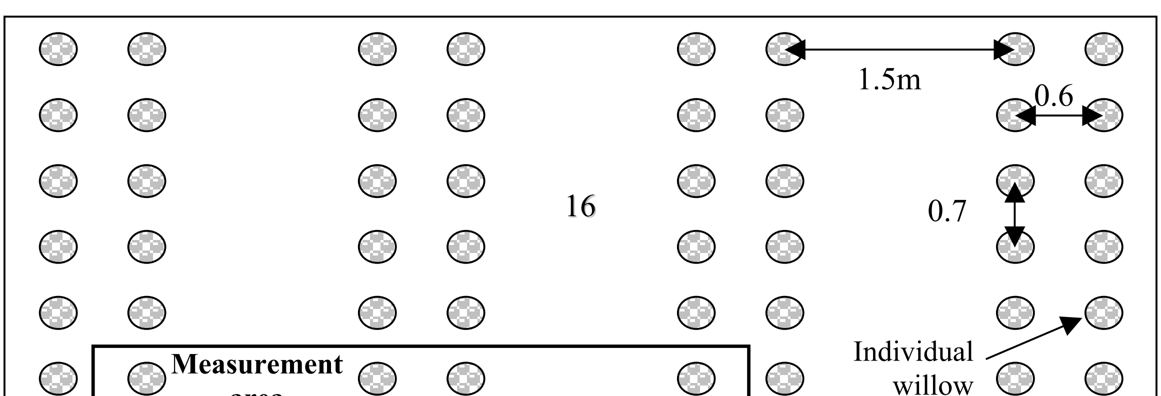

Figure 1. Layout of an individual plot in the willow biomass crops root dynamics study located in Tully, NY.

Figure 2. Minirhizotron tubes inserted in willow biomass research plots in Tully, NY. (A) Two tubes located in the 1.5 m space between the willow double rows. (B) Four tubes are inserted across the double row in each of six different plots. (C) The minirhizotron camera inserted and hooked up to recording instruments to collect images belowground.

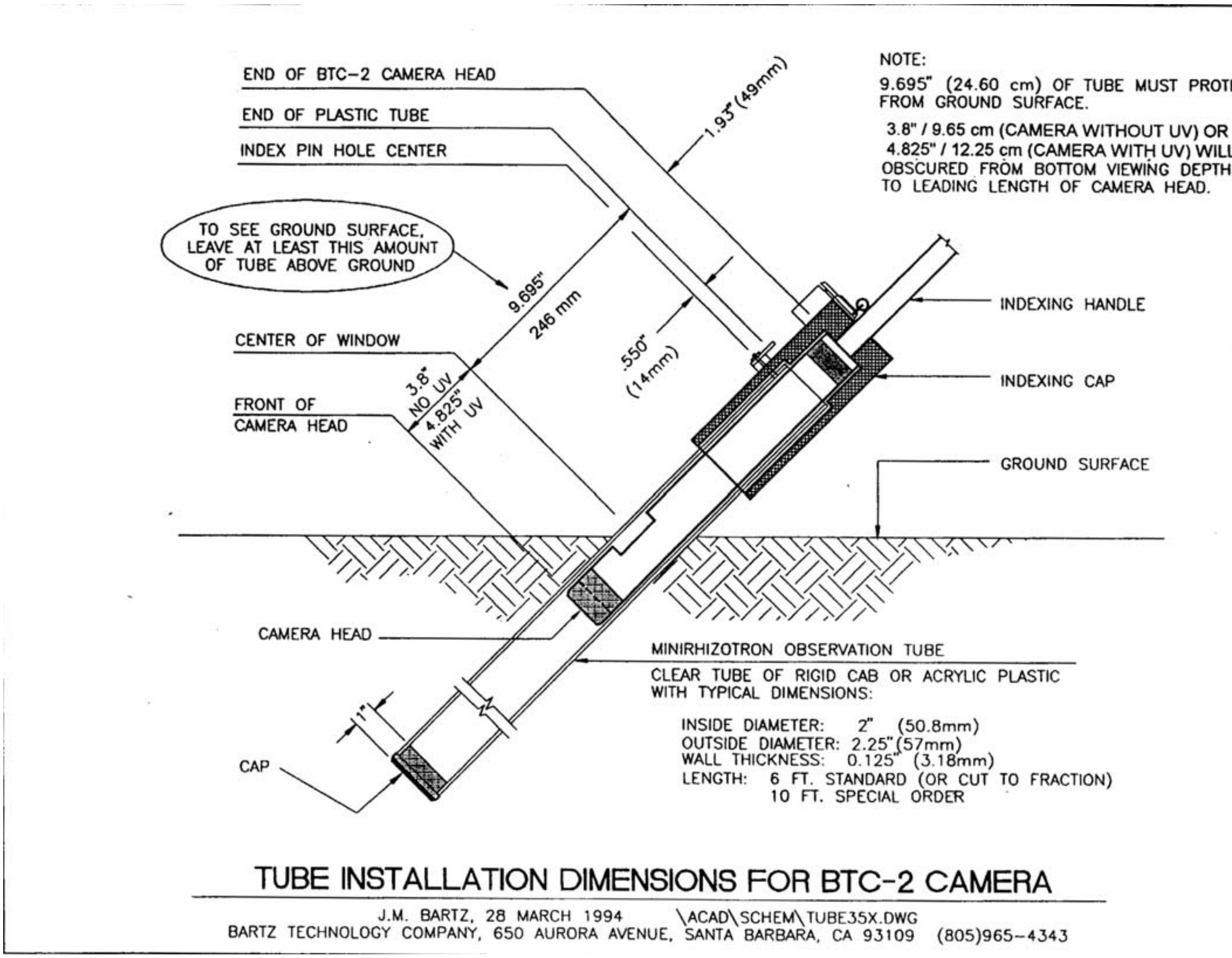

Figure 3: Schematic of minirhizotron tube and video camera equipment used to study root dynamics in willow biomass crops in Tully, NY.

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Aboveground Biomass

These willow research plots reached the end of their first three-year rotation in the fall of 1999. Biomass was assessed during the late fall and winter by directly weighing the material (Fillhart et al. 2000). The plots were fertilized in the spring of 1999 with composted chicken manure or 100 kg N ha^{-1} in the form of slow release nitrogen. The control plots did not receive any additional nutrient amendments. At the end of the 1999 growing season height, basal diameter and number of stems per stool were measured. Using these data, estimates of aboveground biomass will be made using allometric equations developed for clone SV1 (Ballard et al. 2000).

Soil moisture was measured at 0 - 15 cm, 15 – 30 cm and 30 – 45 cm intervals in each plot each time minirhizotron images were collected. An assessment of leaf area index (LAI) was made using a LI-COR 2050 (Li-Cor, Lincoln, NE) each time images were collected from the plots.

Results

Over 20,000 belowground images have been collected over the course of the 1998 and 1999 growing seasons. The images are currently being digitized and analyzed.

Summary

Roots conduct critical functions in SRWC, such as the acquisition of water and nutrients, that effect aboveground biomass production. They can account for a significant portion of the carbon budget in these system. Because the vast majority of the carbon accumulated in the roots remains underground over the life span of the crop, roots are an important component in the carbon sequestering ability of this crop.

Despite their importance, root systems of SRWC are seldom studied and are poorly understood. This study will improve the understanding of belowground root biomass and fine root longevity, distribution, and turnover in willow biomass crops. From a management perspective, understanding fine root dynamics will help determine the timing of management practices such as fertilization or mechanical weed control. Quantifying rates of root growth and turnover for willow biomass crops is important in our understanding of carbon dynamics as well as improving the effectiveness of different management techniques.

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