Examining Short-rotation Willow Productivity and Nutrient Dynamics Following Three Years of Irrigation and Fertilization

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Abstract

Purpose-grown shrub willow (*Salix* spp.) represents a viable bioenergy feedstock; however, there needs to be sufficient biomass production to support the economic viability of these plantations. The objective of this three-year study was to determine the effect of irrigation and fertilization on willow biomass feedstock quantity. A split-split-plot experimental design was used on a Sutherland clay soil in Saskatoon, SK and consisted of two willow varieties (SV1 and Charlie), three irrigation treatments (no irrigation, 75%, and 100% field capacity), and three fertilization treatments (no fertilizer, 1x, and 2x recommended fertilizer rate). During the final growing season, ^{15}N-labelled fertilizer was used to determine the fate of the applied fertilizer. For both willow varieties, after the three-year rotation there was a highly significant (P values < 0.0001) growth response to irrigation, with no significant (P values > 0.05) effects of fertilization or irrigation x fertilization. Sixty-seven percent of the applied fertilizer N was accounted for, with approximately 30% present within the willow tissues (e.g., stems, leaves, and roots). The positive willow growth response to irrigation is indicative of the importance of soil moisture within the semi-arid climate of Saskatchewan. The lack of fertilizer effect probably reflects the fertile soil at the site and the apparently low nutrient requirement of willow.

Introduction

Growing willow as a renewable dedicated bioenergy and bioproduct feedstock is advantageous for a number of reasons, such as its naturally fast growth rate, along with possessing important environmental benefits like providing a much cleaner energy source relative to fossil fuels, effective vegetation filter for environmentally harmful compounds, and increasing biodiversity within the agricultural landscape (Sage and Robertson, 1994; Perttu, 1998, 1999; Reddersen, 2001; Labrecque and Teodorescu, 2003; Main et al., 2007). Before there is widespread incorporation of willow plantations into Saskatchewan agroforestry practices, however, a clear economic advantage for producers to grow willow must become apparent. It is necessary, therefore, to demonstrate that adequate yields can be attained to support the economic viability of these short-rotation intensive culture plantations. The objective of this study was to determine the effect of irrigation and fertilization on willow biomass feedstock quantity, which should help support the commercial development of short-rotation intensive culture willow plantations in Saskatchewan and abroad.

Materials and Methods

Study Site

The study was carried out in the existing Canadian Wood Fibre Centre willow clonal trial plantation, located on 14th Street and Circle Drive in Saskatoon, SK (Fig. 1; UTM Co-ordinates: 13U

389931 5776381). Prior to establishing the plantation, the land was continuously cropped to a mixture of barley and oats. Mean annual temperature for the site is 2 °C (with 112 frost-free days) and a mean annual precipitation of 375 mm (SCSR, 1978). Growing season (May-Sept) precipitation during the three years of the study was 165 and 201, and 467 mm respectively. The soil is a heavy clay Orthic Vertisol of the Sutherland Association, developed on glacial lacustrine parent material, with a pH and electrical conductivity (dS/m) of 7.1 and 0.33, respectively. The Agriculture Capability Classification rating of the soils are Class 2, with moderately severe limitations due to a lack of precipitation (SCSR, 1978). Pre- and post-planting site preparation included both mechanical (deep tillage, light cultivation, tandem disc, mowing, and hand weeding) and chemical (linuron; 1.7 kg a.i./ha and glyphosate; 2.0 kg a.i./ha) treatments to control non-crop vegetation.

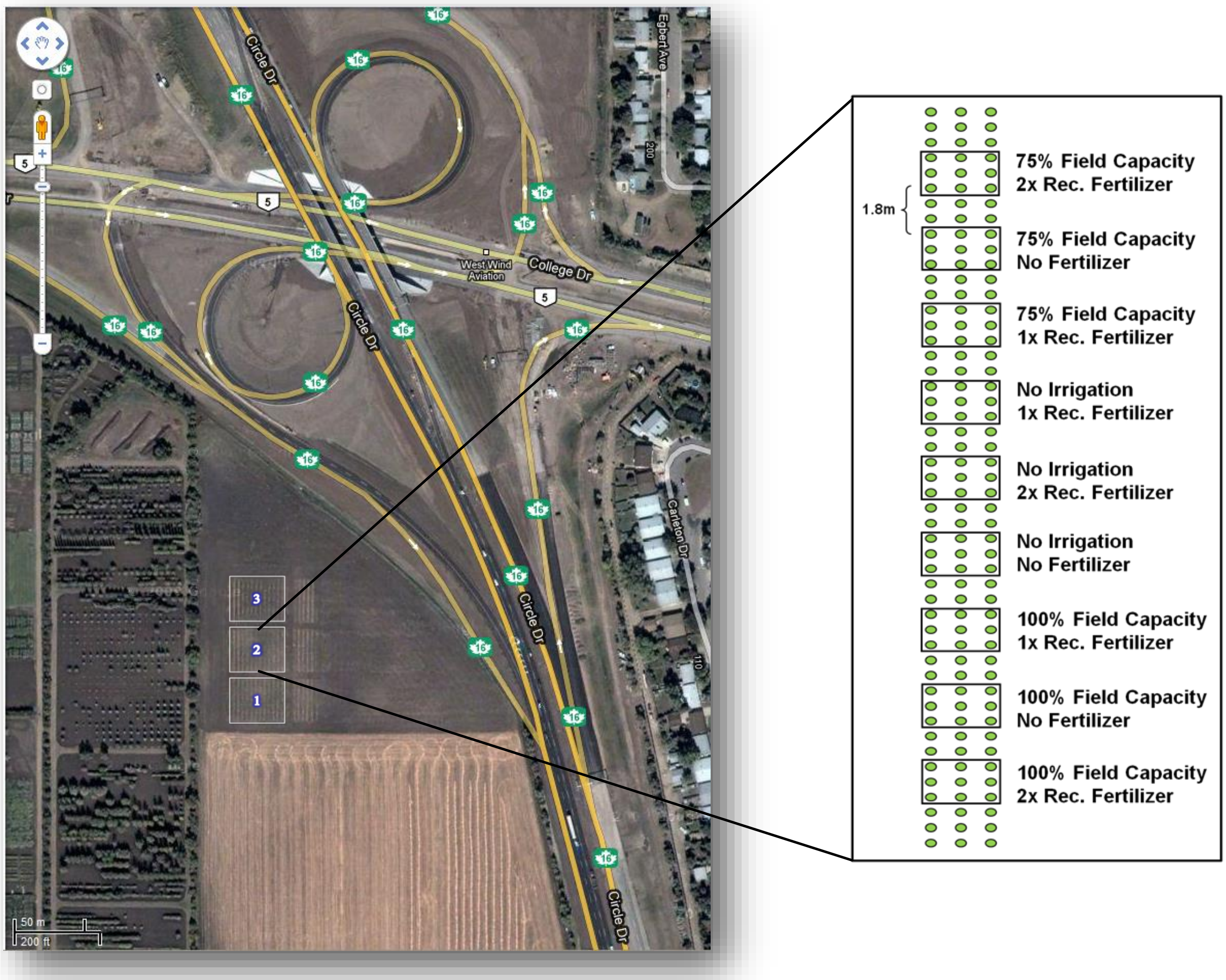

Figure 1. Saskatoon site used to establish effects of irrigation and fertilizer on willow biomass production in an established replicated (n=3) willow clonal trial.

Site preparation and experimental design

The plantation is a clonal trial with seven different clones of willow arranged in a randomized complete block design, replicated three times, using a 60 x 60 cm spacing within each triple-row bed and 200 cm spacing between beds, resulting in a density of approximately 15,625 stems/ha (Fig. 2). A single bed within each block of willow clones 'Charlie' (*S. alba* x *S. glatfelteri*) and 'SV1' (*S. dasyclados*) were utilized for this study. The protocols followed when preparing the plantation were developed by the State University of New York (Abrahamson et al., 2002). A 3 x 3 factorial design of three different rates of both irrigation and fertilizer treatments were imposed on each bed, resulting in a split-split-plot experimental design (Figs. 1 and 2; whole plot factor: clone, subplot factor: irrigation rate; and, sub-subplot factor: fertilizer rate). The three irrigation treatments consisted of either no additional water added above rainfall, or drip irrigation used to maintain soil moisture at 75 or 100 % field capacity, measured using soil moisture probes installed within each plot (Spaans and Baker, 1992). A Campbell Scientific CR10X was used to monitor soil moisture and control irrigation timing. The three fertilization treatments included no fertilizer or fertilizer applied once annually in June over the three-year rotation either at the recommended rate (1x) or twice the recommended rate (2x). The recommended rate consisted of a balanced fertilizer blend of 100:30:80:20 (N:P:K:S), which was intended to not only match hybrid willow growth requirements, but also replenish nutrients exported when harvesting willow with anticipated annual biomass production of 15-22 Mg/ha (Perttu, 1993; Danfors, 1998; Adegbidi et al., 2001). The 2x recommended rate was intended to test the upper limit of willow growth response to added fertilizer, when grown under optimal moisture conditions.

Each year the irrigation and fertilizer treatments were initiated in early June to avoid exacerbating potential frost damage in late May and also ensure the willow are vigorously growing, in order to increase the fertilizer use efficiency (Abrahamson et al., 2002). Likewise, irrigation ceased at the beginning of September, to prepare the willow for a possible early frost. At the end of the final growing season, all stems (including branches) were harvested within each treatment plot using a brush saw and dried to a constant weight for biomass measurement, which were then extrapolated to both plot and stand levels (i.e., per hectare). In order to help quantify relative differences in cold hardiness of the willow clones among treatments, percent dieback was assessed following bud break every spring of the rotation, by measuring the average length of dead stem tissues on the stems within each plot.

Determining the fate of applied fertilizer N

At the beginning of the third and final growing season, 10 kg N/ha of double ^{15}N-labeled ammonium nitrate fertilizer (10 % enrichment; Cambridge Isotope Laboratory, Inc., Andover, MA, USA) was applied to the fertilized plots as a component of the prescribed fertilizer N treatment. At the end of the growing season, the different sinks sampled for their ^{15}N content within each fertilized plot, included: non-crop understory vegetation; senescing willow leaves; willow stems; fine (i.e., < 2 mm) and coarse-size roots; willow stool; and the LFH layer (prior to leaf fall). All samples were dried to a constant weight, thoroughly milled, homogenized, and then a subsample finely ground using a rotating ball-bearing mill and analyzed for ^{15}N enrichment (TracerMass mass spectrometer interfaced to a RoboPrep sample converter; Europa Scientific, Crewe, U.K.). Additionally, 5 cm soil cores were collected from each fertilized plot at four depths (0-15, 15-30, 30-45, and 45-60 cm) using a hydraulic punch (Stumborg et al., 2007), dried to a constant weight, and finely ground. Only the 0-15 cm depth was analyzed for ^{15}N enrichment in the same manner as the plant samples.

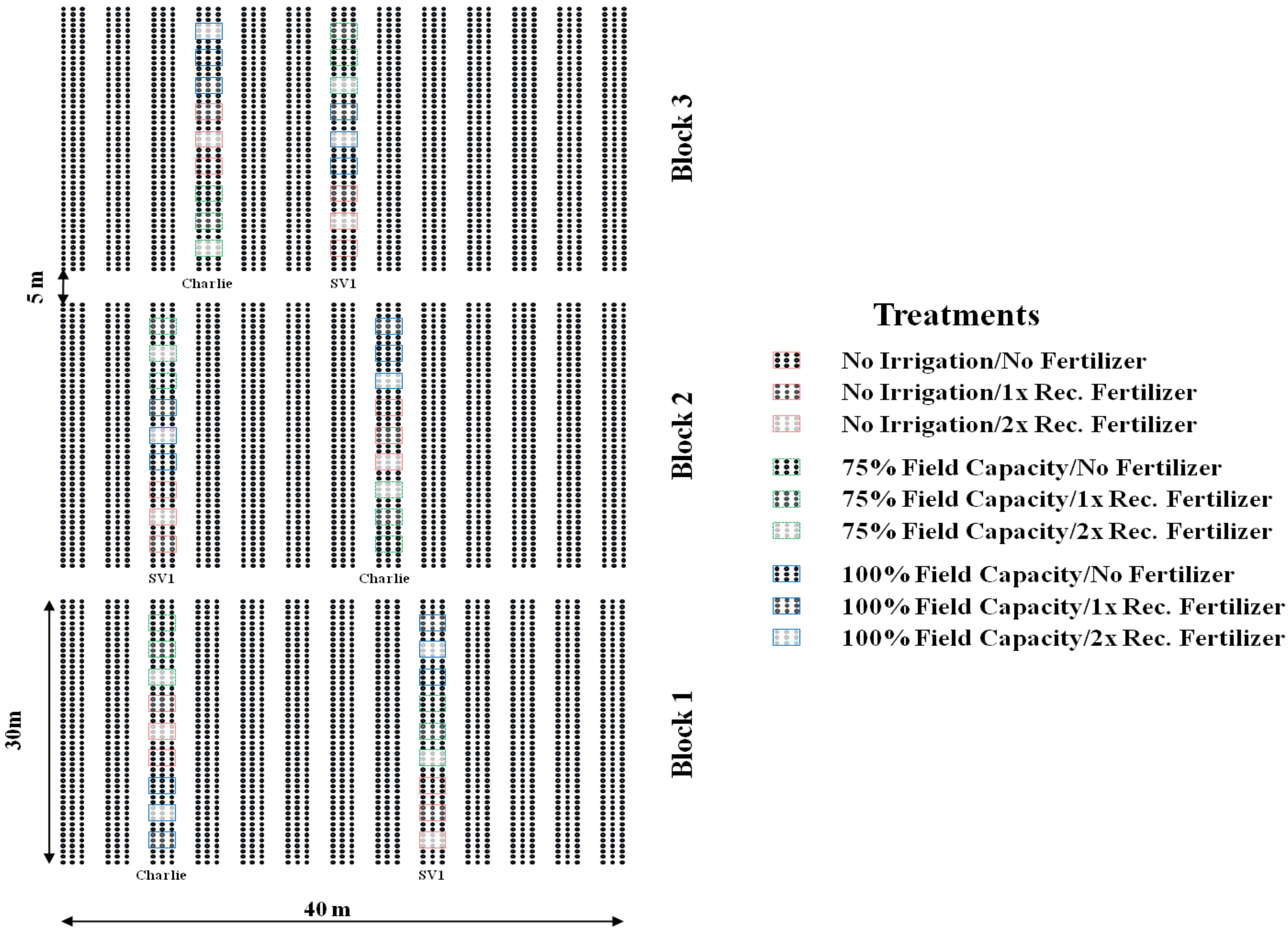

Figure 2. Split-split-plot experimental layout of willow irrigation and fertilizer trial in Saskatoon.

Figure 3. Determining the fate of applied ^{15}N-labelled fertilizer by sampling different sinks within each fertilized plot, including: non-crop understory vegetation; the LFH layer (prior to leaf fall); senescing willow leaves; willow stems; fine (i.e., < 2 mm) and coarse-size roots; willow stump; and soil cores down to 60 cm.

Statistical analyses

Measurement variables were analysed using PROC GLM in SAS (version 9.1; SAS Institute Inc., Cary, NC.). Means comparisons were performed using least significant differences (LSD) at a significance level of 0.05. Homogeneity of variances and normality of distributions of all data sets were checked prior to the analysis. No data transformations were necessary.

Results and Discussion

Willow growth response to irrigation and fertilization

For both willow varieties, the effect of irrigation on productivity was very pronounced each year and was readily apparent when walking through the plots. Specifically, there was a clear distinction between the control plots and the plots maintained at either 75 or 100% field capacity throughout the growing season (Fig. 4). After three growing seasons, there was a highly significant (P values < 0.0001) willow growth response to irrigation for both varieties, with no significant (P values > 0.05) effect of fertilization or irrigation x fertilization interaction on willow growth (Fig. 5), with harvested yields of Charlie and SV1 ranging from 10-21 and 14-33 Mg/ha among the treatments, respectively. Generally speaking, the economically viable productivity levels within these short-rotation intensive culture plantations, across a broad range of site conditions, often is considered to be 30 Mg/ha at time of harvest (Volk et al., 2006) and SV1 was able to achieve this critical yield level under optimum moisture conditions at this site without needing supplemental

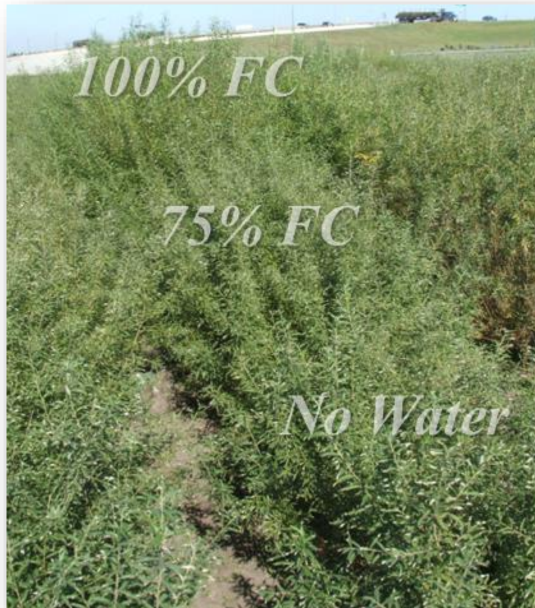

Figure 4. The growth response of the willow variety 'SV1' after two years of irrigation, at either 75% or 100% field capacity (FC), maintained throughout the growing season.

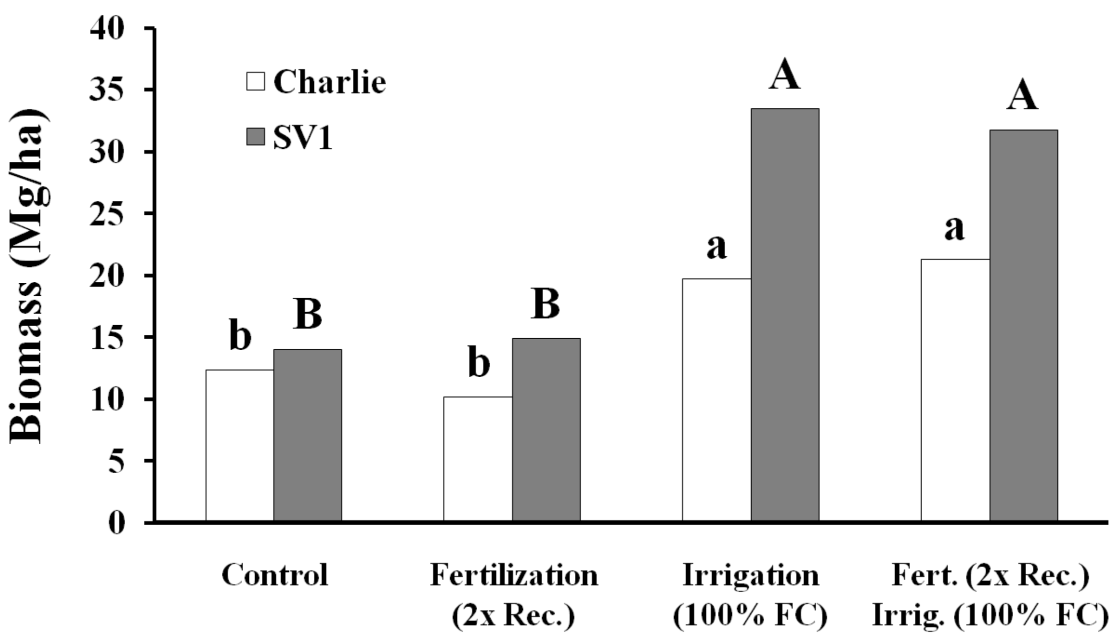

Figure 5. The effect of irrigation and fertilization on above-ground biomass production of the willow varieties 'Charlie' and 'SV1' after three growing seasons. The treatments included either no additional water or fertilizer added (Control), fertilizer addition at 2x the recommended rate (2x Rec.; 100:30:80:20 kg/ha N:P:K:S), drip irrigation used to maintain the available soil moisture at field capacity throughout the growing season (100% FC), or a combination of 2x Rec. and 100% FC. For each variety, bars with the same letter are not significantly different (*P* >0.05) using LSD.

fertility. The positive willow growth response to added water is not surprising, given that within the semi-arid climate of Saskatchewan, moisture availability often is considered the primary controller limiting growth for both annual and perennial plant species (Akinremia et al., 1996; Hogg and Schwarz, 1997). The lack of measured willow growth response to added fertilizer has been reported elsewhere (Weih and Nordh, 2002) and is presumably due to the relatively fertile Class 2 Sutherland Association soils at the site and the low nutrient requirement of willow.

Fate of Applied Fertilizer Nitrogen

At the end of the growing season after the fertilizer N application, two-thirds of the broadcasted ^{15}N-labelled fertilizer was recovered in the willow, competing non-crop vegetation, and the upper 15 cm of soil (Fig. 6). Initially, it was assumed that the unaccounted fertilizer N was leached deeper in the soil profile, however, Dimitriou and Aronsson (2004) reported negligible nitrate leaching from heavily fertilized (i.e., up to 240 kg N/ha applied annually) willow plantations grown on heavy clay soils, so it may be that a significant portion of applied fertilizer N was lost due to denitrification, especially considering the record high precipitation received following the fertilizer application along with the imperfectly drained soil at the site. Approximately 30 % of the recovered fertilizer N was taken up by the willow (Fig. 6), which represents a much greater accumulation of applied N relative to applying nitrogenous fertilizer during the first year of willow growth (Konecsni, 2010), and presumably is due to the more extensive willow root system present after two more years of growth that is more capable of accessing the applied fertilizer. The fertilizer use efficiency of willow observed in this study is comparable to the average fertilizer use efficiencies for annual agronomic crops (≈ 30 %; Raun and Johnson, 1999). The LFH layer within each fertilized plot was sampled prior to leaf fall and, therefore, the recovered fertilizer N present within the LFH was presumably immobilized by microbes decomposing the litter during the growing season (Preston et al., 1990) and will be available for willow uptake in subsequent years. The relatively small amount of fertilizer N taken up by competing non-crop vegetation in this study (Fig. 6), can be attributed to the excellent weed control using glyphosate. Woody crops are poor competitors for applied fertilizers compared to herbaceous weeds (Staples et al., 1999; Hangs et al., 2003; 2004), so adequate weed control is imperative for supporting optimal fertilizer recovery by the target species. A substantial amount of fertilizer N was present in abscissing leaves (Fig. 6). Litterfall is a primary mechanism for nutrient cycling within most ecosystems (Hughes and Fahey, 1994) and in young woody plants, nutrient storage within the foliage can account for as much as 50% of its nutrient content (Pregitzer et al., 1990). Likewise, willow fine roots (i.e., < 2 mm diameter) have rapid turnover and decomposition rates (Rytter, 1999, 2001; Rytter and Hansson, 1996) that contribute significantly to nutrient cycling within a plantation (Rytter and Rytter, 1998; Püttsepp et al., 2007), which is important considering the greater amount of fertilizer N recovered in the fine roots compared to the coarse root fraction (Fig. 6).

Cold hardiness of willow following irrigation and fertilization

Figure 7 shows the cumulative measured dieback over the first two winters, which is the average length of necrotic or dead stem tissue on each multi-stemmed willow plant. Given the temperate climate of Saskatchewan, low-temperature stress is another important factor impacting plant survival and growth of both annual and perennial plant species (Mahfoozi et al., 2001; Lu and Bors, 2004). The concern in this study was that despite increasing plantation productivity, these agronomic practices may result in increased winter injury. After two growing seasons, however, there was no effect of irrigation and/or fertilization on the amount of winter dieback measured for either willow clone. The maximum dieback observed among the treatments was 13 and 16 cm for

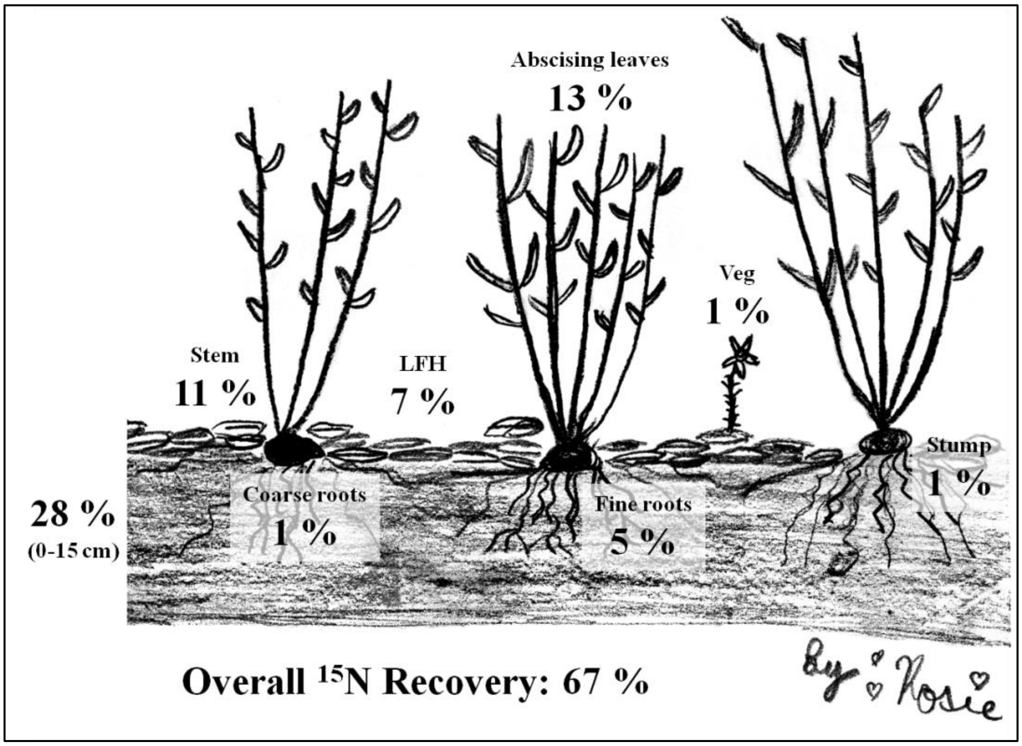

Figure 6. Recovery of broadcasted ^{15}N-labelled fertilizer at the end of the growing season.

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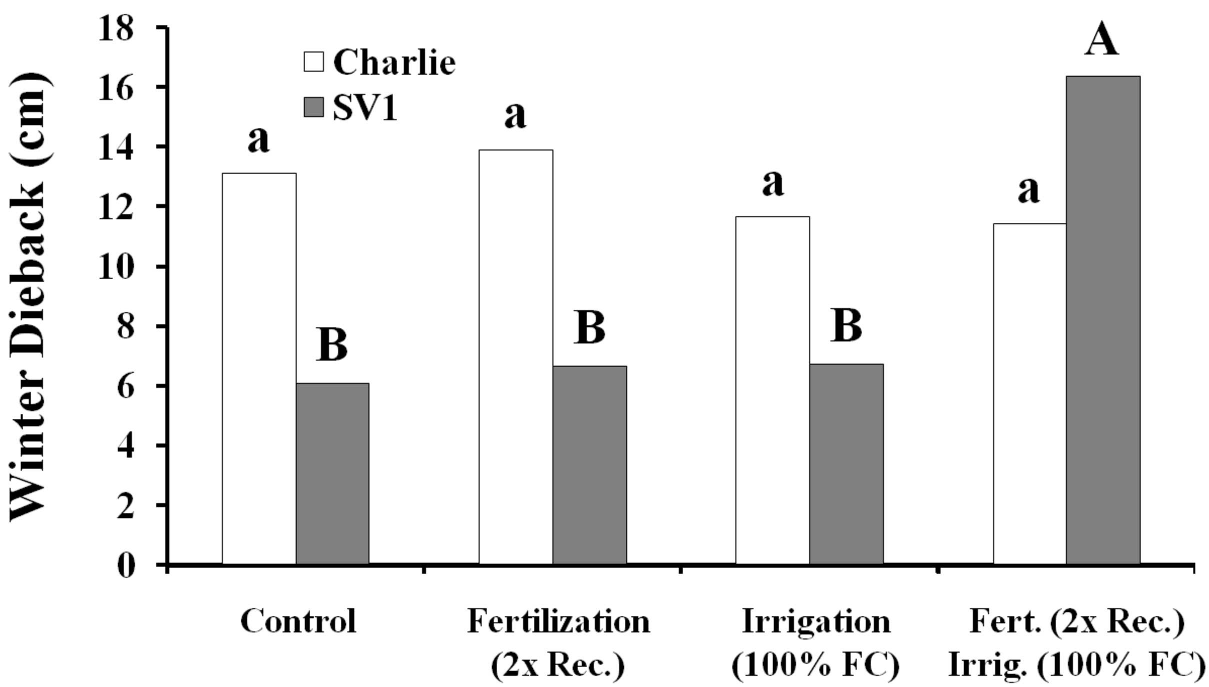

Figure 7. Mean (n = 3) effect of irrigation and fertilization on the cold hardiness of willow varieties 'Charlie' and 'SV1' after two growing seasons. The treatments included either no additional water or fertilizer added (Control), fertilizer addition at 2x the recommended rate (2x Rec.; 100:30:80:20 kg/ha N:P:K:S), drip irrigation used to

maintain the available soil moisture at field capacity throughout the growing season (100% FC), or a combination of 2x Rec. and 100% FC. For each variety, bars with the same letter are not significantly different ($P > 0.05$) using LSD.

Charlie and SV1, respectively (Fig. 7). With the variety SV1, there was an interaction effect that resulted in greater dieback with a combination of optimal irrigation and fertilization compared with the other treatments; nevertheless, SV1 grew more than two metres per year, so 16 cm is likely negligible from an operational perspective.

Conclusion

The results of this study highlight the importance of soil moisture availability for supporting optimal willow production in the semi-arid climate of Saskatchewan. Additionally, if a high-yielding willow variety is grown on fertile soil, irrigation alone should be enough to achieve the critical productivity level (i.e., generally assumed to be 10 Mg/ha/yr) to sustain the economic viability of these short-rotation intensive culture biomass energy production systems. The lack of willow growth response to added fertilizer after three years observed in this study is probably due to a combination of the low nutrient requirement of willow, along with the adequate nutrient supply rates inherently provided by the Class 2 agricultural soil at the site.

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