The Effect of Irrigation and Fertilization on Willow Productivity

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Abstract

Purpose-grown shrub willow (*Salix* spp.) represents a viable bioenergy feedstock, especially if these plantations can be successfully grown on unproductive land that is marginal for annual crop production. The objective of this study is to determine the effect of irrigation and fertilization on willow biomass feedstock quantity, as well as its quality, in order to meet specific bioenergy conversion industry requirements. A split-split-plot experimental design is being used on a Sutherland clay soil in Saskatoon, SK and consists of two clones (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). For both willow clones, after two years 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 except for the 2x recommended fertilizer rate at 100% field capacity with the clone SV1. 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 reflects the relatively fertile soil at the site and the low fertilizer use efficiency of broadcasted fertilizer within these agroforestry systems.

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). Nevertheless, in order to compete with fossil fuels and renewable residues from both the agricultural (i.e., straw) and forestry (i.e., woody residues) sectors, the economic return from growing willow biomass feedstock must be competitive. In order to increase its competitiveness and, therefore promote its adoption among farmers, it is necessary to increase its value in terms of energy production efficiency and/or suitability for bioproduct development. The majority of research to date has focused on the quality of willow biomass for bioenergy conversion and increasing plantation productivity through cultural practices (Mitchell et al., 1988; Kenney et al., 1990; Kopp et al., 2001; Weih and Nordh, 2002; Kauter et al., 2003; Tharakan et al., 2003); however, no one has investigated the effects of different agronomic practices on the wood quality of willow biomass for its different potential end uses (Fig. 1).

Wood quality is a subjective term and consequently can change depending on the context of its end use (Jozsa and Middleton, 1994), such as a feedstock for different bioenergy conversion technologies (i.e., anaerobic fermentation, pyrolysis, gasification, or simple combustion) or in manufacturing varied bioproducts (i.e., plastics, adhesives, lubricants, pharmaceuticals, etc.). The principal chemical and physical biomass feedstock properties affecting end use efficiency include: the relative amount and composition of extractives, cellulose, hemicelluloses, and lignin; inorganic

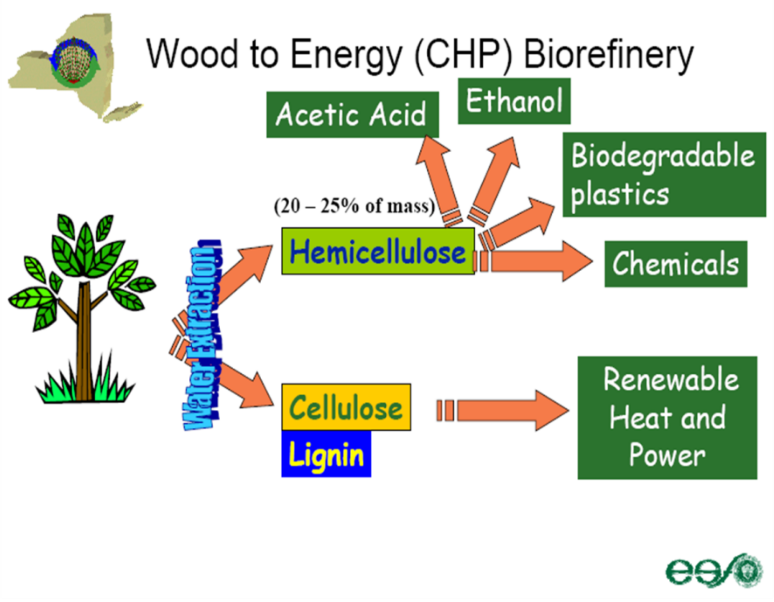

Figure 1. Potential feedstock opportunities for purpose-grown willow plantation biomass.

element content; specific gravity, calorific energy value; ratio of bark to wood, ash content; and moisture content. Substantial interspecific and interclonal variation in these biomass quality properties exist naturally and has been primarily attributed to genotype x environment (i.e., available soil moisture and nutrients) interactions (Sennerby-Forsse, 1985; Mitchell et al., 1988; Mosseler et al., 1988; Kenney et al., 1990; Tharakan et al., 2003). The potential exists, therefore, to not only increase plantation productivity through irrigation and fertilization, but also to accentuate favourable biomass quality characteristics through optimizing soil moisture and nutrient availability under an intensive management regime. The objective of this study is to determine the effect of irrigation and fertilization on willow biomass feedstock quantity, as well as its quality, in order to meet specific bioenergy conversion industry requirements, 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 is being carried out in the existing Canadian Forest Service hybrid willow clonal trial plantation, located on 14th Street and Circle Drive in Saskatoon, SK (Fig. 2; 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 ^{o}C (with 112 frost-free days) and a mean annual precipitation of 375 mm (SCSR, 1978). Growing season (May-October) precipitation during the first two years of the study was 165 and 200 mm, respectively. The soils are heavy clay Orthic Vertisols of the Sutherland Association, developed on glacial lacustrine parent material, having a Class 2 Agriculture Capability Classification rating, with moderately severe limitations due to lack of precipitation (SCSR, 1978).

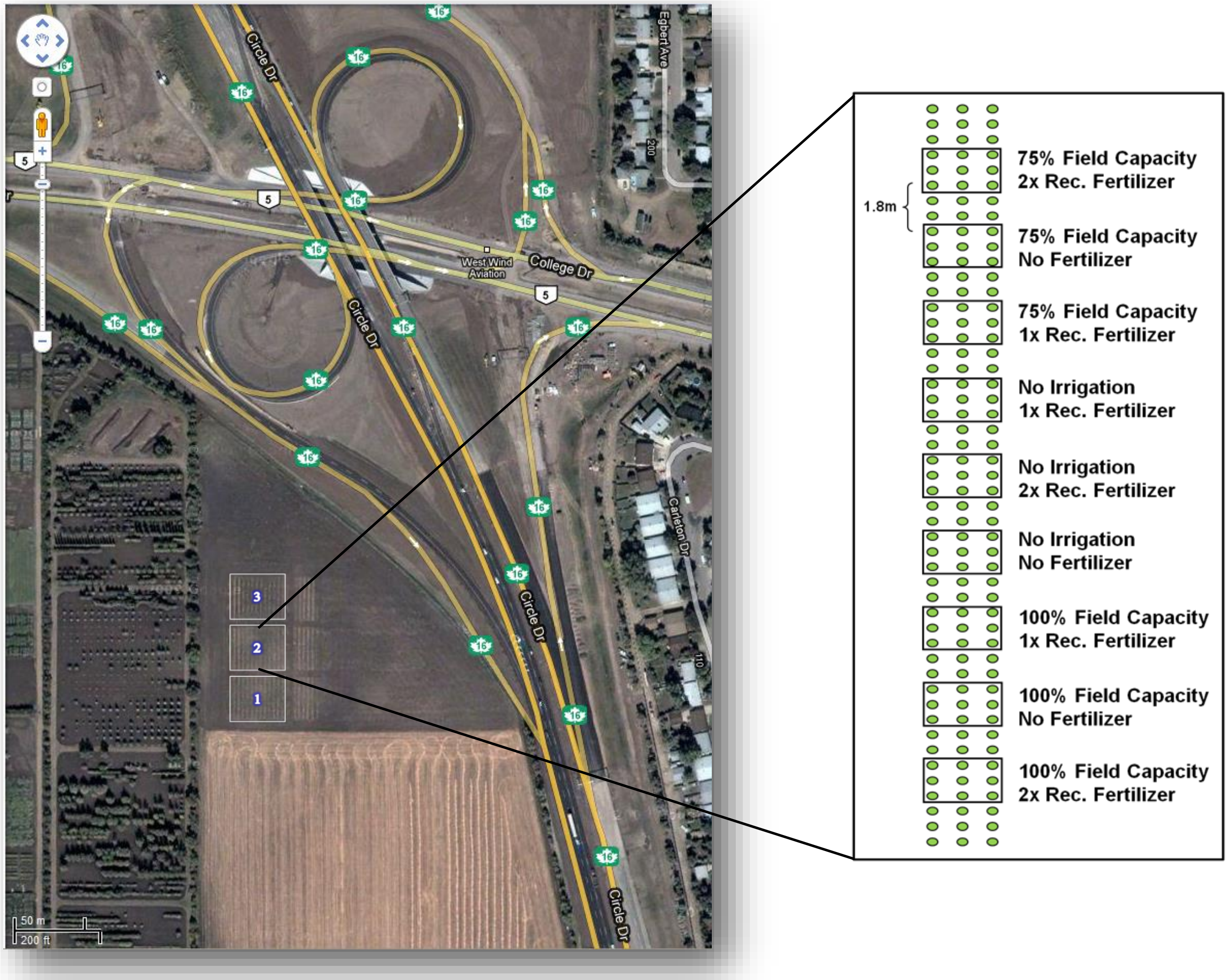

Figure 2. Saskatoon site to establish effects of irrigation and fertilizer on willow biomass quality and quantity in an established replicated (n=3) willow clonal trial.

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. 3). 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), which has been studying the cultivation and use of willow biomass as a bioenergy feedstock for more than 10 years. In the spring of 2008, prior to bud break, all of the willow plants within each bed were cut down to approximately 2-4 cm above ground level, which promotes multi-stemmed growth of the willow from the established root system and also makes it is easier to harvest the biomass after the three-year rotation (Fig. 4). Charlie has a single-stemmed tree-like growth form, while SV1 is shrub-like with typically a few stems; however, after coppicing these willows, each of these clones now have stem counts ranging anywhere from 10-20 per stems per plant (data not shown). 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. 2 and 3; whole plot factor: clone,

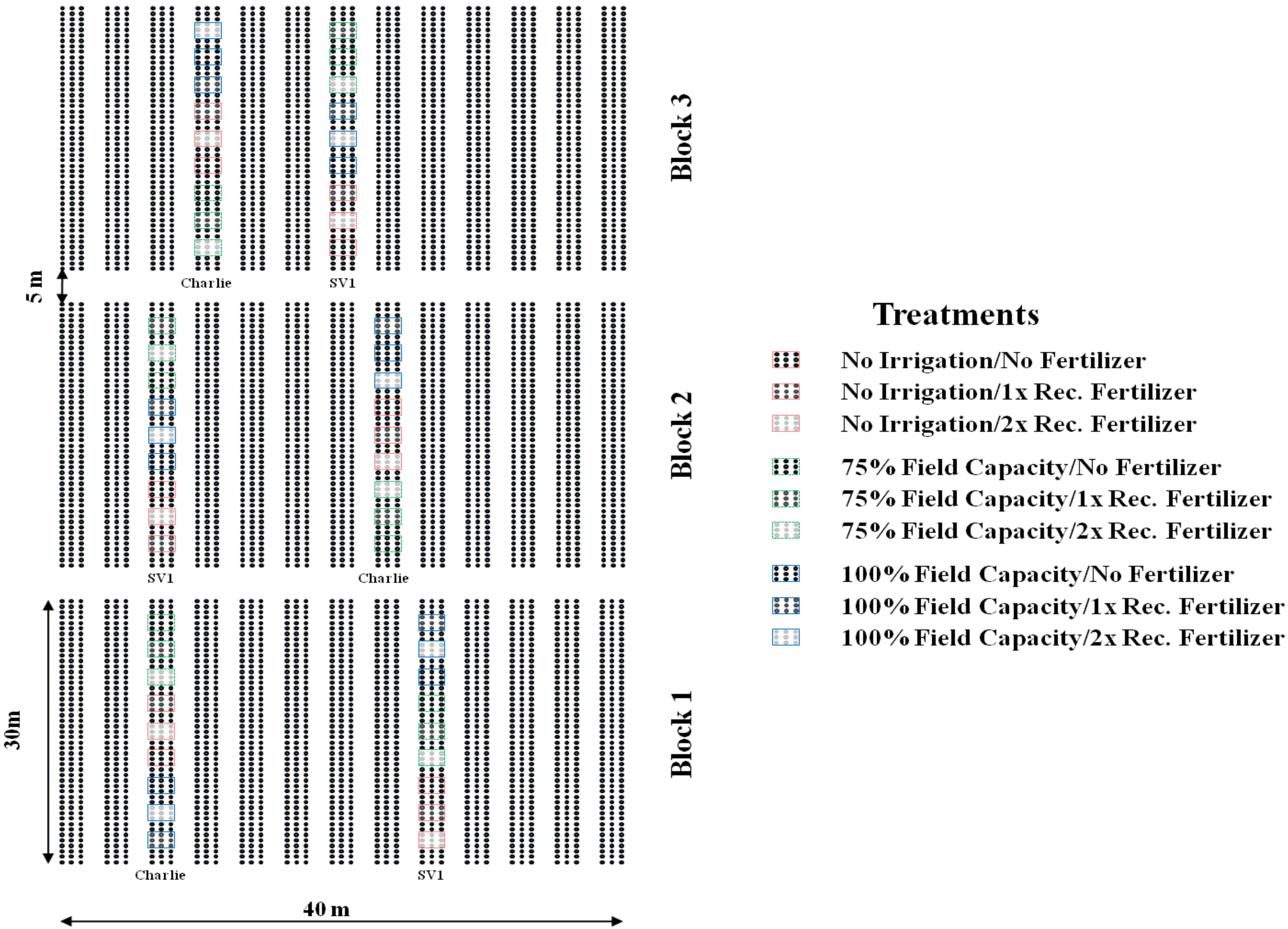

Figure 3. Split-split-plot experimental layout of willow irrigation and fertilizer trial in Saskatoon.

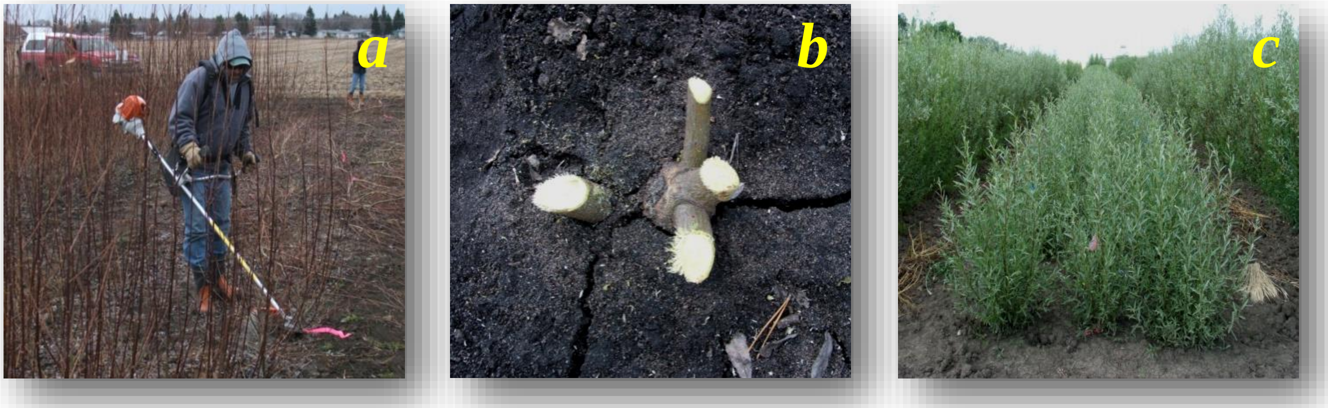

Figure 4. Cutting back one-year-old willow clones in spring (a and b) to promote multi-stemmed growth of the willow from the established root system (c).

subplot factor: irrigation rate; and, sub-subplot factor: fertilizer rate). The three irrigation treatments consist 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 is used to monitor soil moisture and control irrigation timing. The three fertilization treatments include 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 consists of a balanced fertilizer blend of 100:30:80:20 (N:P:K:S), which is 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 is intended to test the upper limit of willow growth response to added fertilizer, when grown under optimal moisture conditions, along with quantifying its influence on chemical and physical wood properties (to be determined at time of harvest). Each year the irrigation and fertilizer treatments are 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 ceases at the beginning of September, to prepare the willow for a possible early frost.

At the end of each growing season, assessments of plant survival, stem diameter, stem height, stem number (i.e., number of stems per stool), and stool biomass production is completed. These measurements are done prior to bud burst the following spring. After measuring the stem diameter and height, the entire stem (i.e., including branches) is harvested as close to the ground as possible (Abrahamson et al., 2002) and dried to a constant weight at 65 °C for biomass production estimates on a per stool basis, which then will be 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 is assessed following bud break every spring of the rotation, by measuring the average height difference between the living and dead stem tissues on each stool.

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

During each of the first two years, there was a highly significant (*P* values < 0.0001) willow growth response to irrigation for both clones, with no significant (*P* values > 0.05) effect of fertilization, except for the willow clone SV1 growing in plots receiving the 2x recommended fertilizer rate and maintained at 100% field capacity for two growing seasons (Figs. 9-11). The positive willow growth response to added water is indicative of the fact 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 growth response to added fertilizer after two years for either clone probably is attributable to the relatively fertile Class 2 Sutherland Association soils at the site. There was a measured growth response to the combined 2x recommended fertilizer rate/100% field capacity for SV1 after two years that might be explained by the low fertilizer use efficiency of broadcasted fertilizer within these agroforestry systems that is often reported in the literature (Booth, 2008). Additionally, recent work using ^{15}N-labelled broadcasted fertilizer N within short-rotation willow plantations indicates fertilizer use efficiencies of less than 1% (Sheala Konecsni, unpublished data), which is poor relative to the average fertilizer use efficiencies of approximately 30 % for annual agronomic crops (Raun and Johnson, 1999). Given the mechanical and manual weed control practices throughout the growing season, the fate of the applied fertilizer is not clear. Moreover, previous studies report negligible nitrate leaching from heavily fertilized (i.e., up to 240 kg N/ha applied annually) willow plantations grown on clay soils after the first growing season with established root systems (Dimitriou and Aronsson, 2004). Consequently, leaching is not expected to be significant in this study, even with the fertilizer rate treatment of 200 kg N/ha applied annually given the established willow root system and the heavy clay soils at this site. Accordingly, at this point it is not apparent why the willow does not utilize more of the applied nutrients.

Cold hardiness of willow following irrigation and fertilization

After the first growing season, there was no effect of irrigation and/or fertilization on the amount of winter dieback measured for either willow clone (Figs. 12 and 13). 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). Accordingly, plants capable of withstanding sub-freezing temperatures without sustaining critical damage translates into less winter damage and, therefore, greater productivity. Generally speaking, the two mechanisms allowing woody plants to withstand sub-freezing temperatures are avoidance and tolerance (Levitt, 1980; Sakai and Larcher, 1987; Malone and Ashworth, 1991). These two mechanisms are expressed in a number of different cold hardiness characteristics, including: maximum level of cold hardiness; timing and rate of both cold acclimation (i.e., in the fall) and de-acclimation (i.e., in the spring); cold hardiness stability; and, the ability to re-acclimate after unseasonably warm periods (Linden, 2002). The concern was that despite increasing plantation productivity, to fertilize and irrigate may instead make the willow more susceptible to winter injury, especially early frost episodes like that experienced in early October of 2009; however, the amount of measured dieback for either clone was negligible at less than 10 cm, considering that they typically grow more than a metre per year (data not shown).

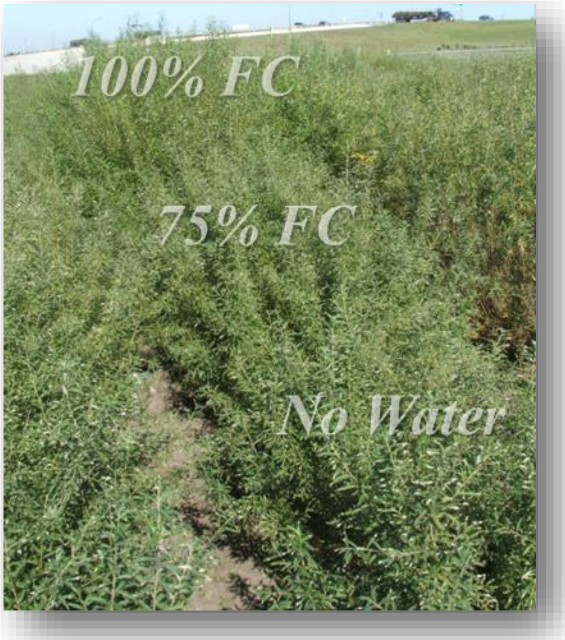

Figure 9. The growth response of the willow clone 'SV1' after two years of irrigation, at either 75% or 100% field capacity (FC), maintained throughout the growing season.

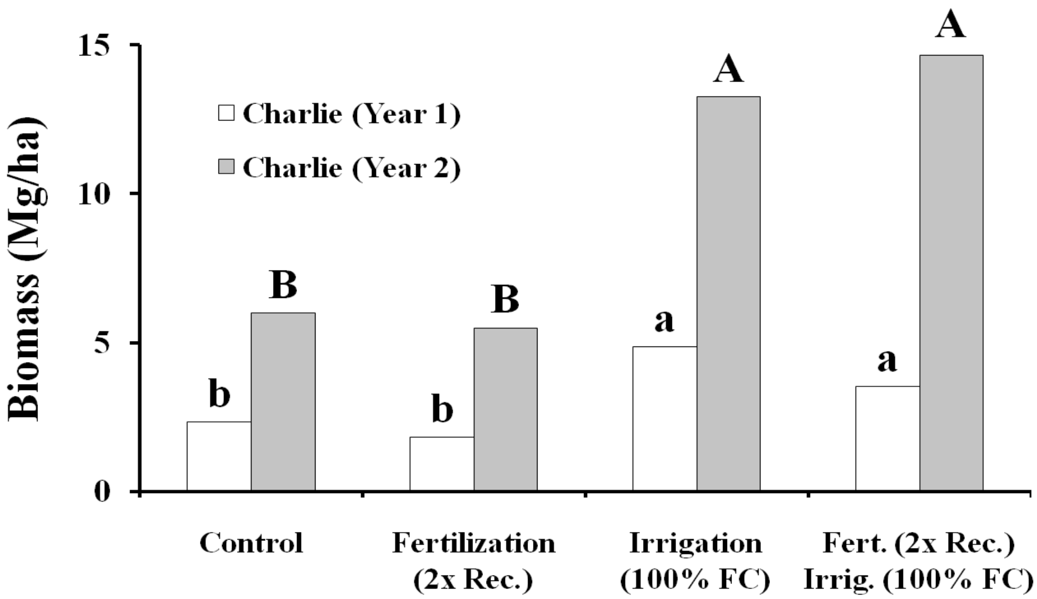

Figure 10. The effect of irrigation and fertilization on above-ground biomass production of the hybrid willow clone 'Charlie' after two growing seasons. The treatments included either no additional water or fertilizer added (Control), fertilizer addition at 2x the recommended rate (2x Rec. N:P:K:S; 100:30:80:20 kg/ha), 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 year, bars with the same letter are not significantly different ($P > 0.05$) using LSD.

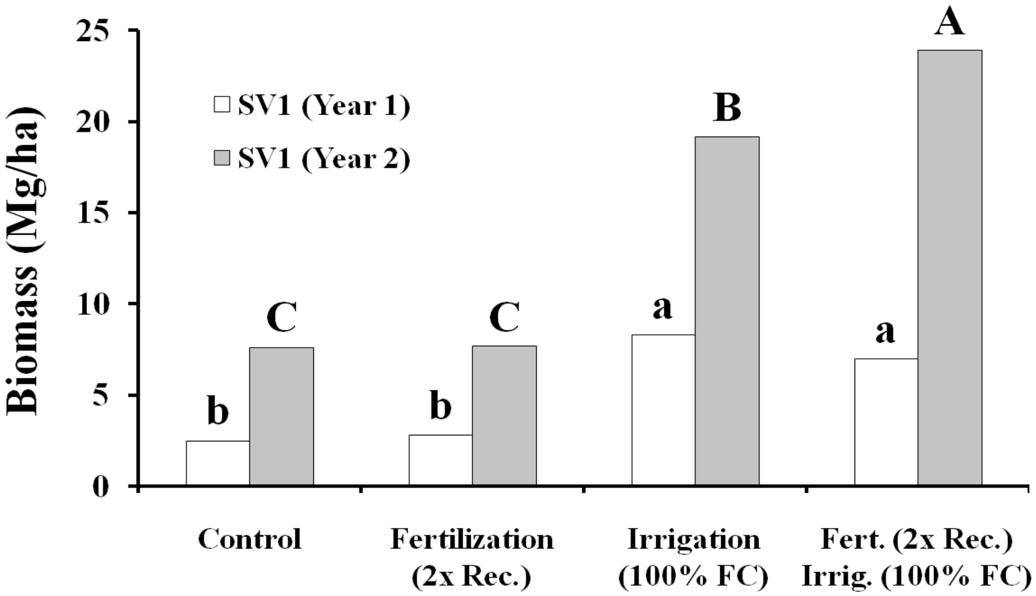

Figure 11. The effect of irrigation and fertilization on above-ground biomass production of the hybrid willow clone 'SV1' after two growing seasons. The treatments included either no additional water or fertilizer added (Control), fertilizer addition at 2x the recommended rate (2x Rec. N:P:K:S; 100:30:80:20 kg/ha), 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 year, bars with the same letter are not significantly different (*P* >0.05) using LSD.

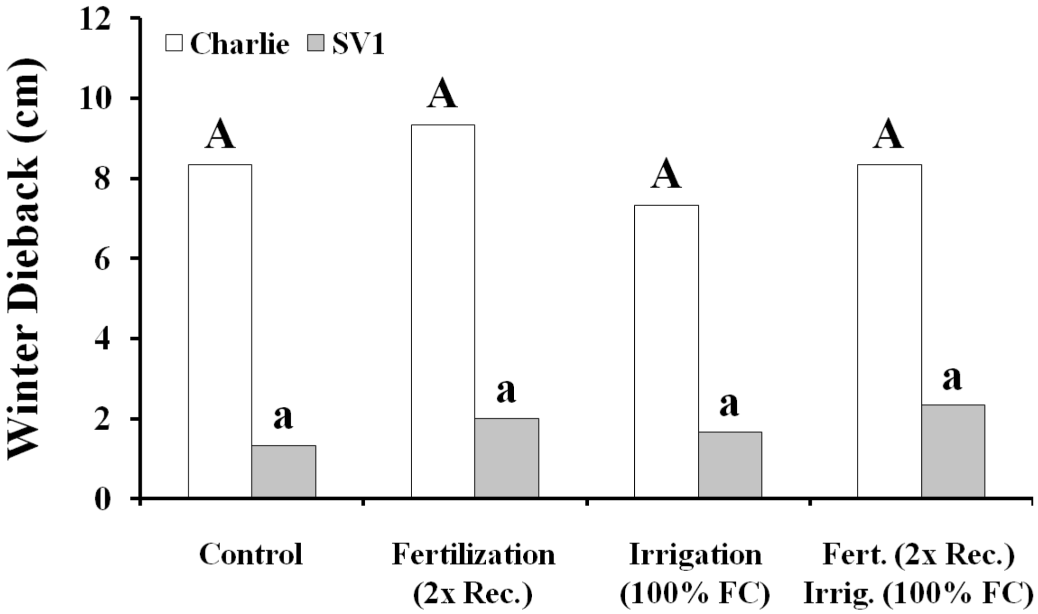

Figure 12. Mean (n = 3) effect of irrigation and fertilization on the cold hardiness of willow clones 'Charlie' and 'SV1' after the first winter. The treatments included either no additional water or fertilizer added (Control), fertilizer addition at 2x the recommended rate (2x Rec. N:P:K:S; 100:30:80:20 kg/ha), 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 clone, bars with the same letter are not significantly different (*P* >0.05) using LSD.

Figure 13. Winter die-back observed with willow clones ‘SV1’ (a) ‘Charlie’ (b) after the first winter and with ‘SV1’ following an early frost episode in October, 2009 (c).

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 clone 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 fundamental lack of measured fertilizer effect after two years possibly reflects the relatively fertile soil at the site and/or the low fertilizer use efficiency of broadcasted fertilizer within these agroforestry systems. It is important to keep in mind, however, that an important component of sustainable stewardship practices is to replenish the harvested nutrients removed from the site at the end of the three-year rotation. Specifically, although there essentially has been no measured effect of added fertilizer after two years, the recommended rate is intended to not only match hybrid willow growth requirements, but also replenish nutrients exported when harvesting the willow biomass.

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