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Research paper

Influence of soil chemical and physical characteristics on willow yield in Connecticut

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ABSTRACT

Willows (*Salix*) are the focus of investigation as renewable feedstock for bioenergy in the Northeastern region of the US. The potential increase of acreage for willow biofuel production requires new information about how yield is influenced by variances in soil factors. The objectives of this experiment were to compare yields across several different soil series and to identify factors that may influence plant productivity. Four cultivars of shrub willow were planted in 2011 at five sites in Connecticut. Biomass yields were measured at the end of the fourth growing season. The best conditions for willow growth were recorded on Watchaug soil series, where the highest yield values for 'SX67' and 'SX61' (17.3 and 14.4 Mg ha^{-1} yr^{-1}, respectively) are setting benchmarks for the potential of willow yield in Connecticut. These two willows were the most productive cultivars across all sites. 'Allegany' and 'SV1' performed better on sites with specific soil characteristics, clearly demonstrating greater cultivar × site interactions. Important soil characteristics that correlated with willow growth were soil organic matter, pH, as well as phosphorus, iron, magnesium and aluminum availability. All cultivars responded similarly to aluminum toxicity: the yields increased when exchangeable soil aluminum levels were below 200 mg kg^{-1}. The yields also increased for most cultivars when the phosphorus levels were high. The yields consistently reached a maximum when the phosphorus to aluminum ratio was greater than 0.05. This study showed that soil factors correlated with willow yields and revealed that soil amendments could be exploited for yield gains.

1. Introduction

Cellulosic crop production systems include fast growing woody species, which are cultivated for the purposes of biomass yield [1]. Shrub willow is a viable cellulosic crop, which is increasingly being grown in the Northeastern region of the US as a short rotation woody crop (SRWC) [2]. Studies on willow grown as SRWC have been conducted in New York state for more than 20 years, and it has been demonstrated that the specific climatic and soil conditions of the Northeastern region are conducive to the development of this crop for biofuel production [3,4].

Although decades of research and experience have resulted in the accumulation of wide-ranging technical knowledge [5], some specific questions related to willow production still need to be answered. Limited empirical knowledge is currently available about the effects of various physical and chemical soil characteristics on willow growth. The potential increase in acreage for willow production in the Northeastern region raises a need for precise information on how biomass yield is influenced by variances in soil factors.

There is sufficient evidence that fast growing SRWC species can be grown on former arable sites with favorable soils [6–8]. It has also been suggested that due to the adaptability of willows to nutrient poor and polluted soils, production of willow for biofuel may be feasible on brownfields and marginal lands [9,10]. Also, if willow is to be grown on marginal land to avoid competition with food production, a clear evaluation of yield potential on sub-optimal land and understanding of edaphic factors affecting profitability of the biomass enterprises have become important considerations when determining economic returns on investment. The overall need to better understand the influence of environmental conditions on willow growth and the interaction of environmental factors and plant genetics for optimization of yield were emphasized [11]. Various willow cultivars were tested across broad geographic regions to gain insights of how plants interact with the environment, and these studies emphasized the importance of clear understanding of yield potential on a regional basis [1,11–14]. In addition to plant genetics, other factors that influence crop yield, including soil properties, weather conditions, pests and diseases, site preparation and weed control, were identified [11,15,16].

Abbreviations: SRWC, short rotation woody crop; SOM, soil organic matter

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Regarding the soil factors, a few studies were conducted: some studies primarily used site specific soil data, i.e. collected and analyzed soil samples from the plots. A study by Kiernan et al. [17] found no strong relationship between soil physical and chemical properties and willow yield. Aylott et al. [15] studied yields of three willow cultivars grown at 49 locations in the UK in relation to edaphic and climatic variables. They found that rainfall patterns affected yields, and one cultivar was sensitive to soil pH. In a Swedish study, Dimitrou et al. [18] reported that differences in willow yield were affected by soil particle size distribution: generally, plantations established on coarse sand and heavy clay yielded lower biomass while organic soils and medium clay soils produced the highest yields, followed by light clay, silt and fine sand soils. However, these data were not empirical and were collected as grower surveys without precise identification of soil texture. Other factors, including climatic, could also influence the yields in addition to soil textures as the data were collected across the whole country. Sevel et al. [16] found that willow yield in Denmark depends on the combined site effects of soil, climate, and management, but the effects of each of these factors were not separated and identified. Fabio et al. [1] did not find significant correlations of willow yield with soil pH or organic matter across the US and Canada. It has been suggested that the greatest amount of variability among the test sites was dominated by climatic factors as the study sites were located over a broad geographic range.

In addition, some studies did not use site specific soil analyses but rather interpreted general data from national soil surveys such as the USDA NRC Soil Survey in the US, or World Soil Resources Reports. For example, Krzyżaniak et al. [19] reported lower biomass yield when willows were grown on poor sites with loamy sand compared to organic loamy soils using soil data collected through World Soil Resources Reports. The data from these soil surveys represents 'natural' (prevalent) soil conditions and do not account for site specific variation, or soil management (e.g. fertilizer, tillage) or impacts from activities (e.g. erosion, compaction).

Soil properties influence the qualitative and quantitative attributes of yield for many crops [20]. A number of physical and chemical characteristics, including soil structure, particle size distribution, soil pH, SOM content, and nutrient deficiency, are reported to have considerable effects on vegetation establishment and growth [21–23].

Acidic soils constitute the majority of arable land in the Northeastern US region [24], and it is important to investigate willow tolerance to soil acidity and to determine the optimal pH range for biomass production. Aluminum (Al) toxicity is an important yield-limiting factor in acidic soils, although low pH per se may also be limiting the development of plants [22]. Soil pH affects plant growth by directly negatively impacting nutrient availability. When it is too high or too low, nutrients can become insoluble and thus unavailable for plant uptake. At pH less than 5.0, toxic levels of Al^{3+}, H^{+}, and Mn^{2+}, in addition to deficiencies of macro- and micronutrients, decrease plant growth [25]. At soil pH higher than 5.5, most Al is present in insoluble forms. As the soil becomes more acidic, Al is solubilized, and toxic Al species (Al^{3+}) are released into the soil solution [26]. Some acid-loving species resist higher levels of soluble Al^{3+} in the root environment, while other species are very susceptible. On the other hand, an increase in pH results in deficiencies of phosphorus, iron, boron, zinc and Mn.

A few sources indicate that the range of optimal pH for willow growth varies by species. For example, some references list various soil pH ranges for different *Salix* species: 5.0–6.0 for *S. babylonica*, and 6.5–8.0 for *S. discolor* [27]. Skvortsov [28] observed that *S. alpina*, and *S. elaeagnus* prefer a more basic substrate in their native habitats, while *S. glauca* and *S. helvetica* favor acidic soils. Gobran et al. [29] found that the above and below-ground biomass of *S. viminalis* was negatively influenced by the presence of Al^{3+} and, therefore, reduced uptake of nitrogen, Ca^{2+}, Mg^{2+} and P. Fenn and Gobran [30] examined the remedial effects of calcium on H-and Al- depression of basket willow and suggested that the Ca-Al balance may be useful in predicting species performance under acidic conditions. The results from our previous study suggested that a highly acidic soil at one location in Connecticut (pH 4.4–4.6) did not impede the growth of willows [31], although no comparison of growth rates at sites with higher soil pH was conducted.

Fig. 1. *Salix* 'SX61' grown at the cultivar trial established at Storrs, Connecticut, on Woodbridge soil series in 2009 as part of the Sun Grant Feedstock Initiative. Two plots of 'SX61' across the road (circled) were planted on the same day and were managed identically. The differences in biomass illustrate the influence of soil factors.

The potential increase of willow acreage for biofuel production in the Northeast US region highlights a need for new information, including optimal nutrition and soil pH requirements, for further optimization of yields. The interactions of many physicochemical properties in soils dramatically influence the availability of plant nutrients and affects crop yields (Fig. 1).

The objective of this study was to identify soil factors that influence willow productivity. In previous studies, the use of various cultivars, different management protocols and variations in weather conditions between sites created difficulties with the interpretations of specific plant responses to edaphic factors.

The novelty of our approach stems from the separation of the combined effects of soil, climate, and management on willow yield. This was achieved by comparing aboveground biomass yields of four willow cultivars grown simultaneously on five proximal sites with the implementation of identical management practices at each site. The proximity of the sites reduces the variability of climatic factors and makes the identification of relationships between yield and soil factors more accurate.

The specific goals of this study were (i) to examine willow above-ground biomass yields at five sites with different soil series in Connecticut, (ii) to examine relationships among biomass yields and soil characteristics and (iii) to identify soil and site factors that are most important to determine productivity of four willow cultivars.

2. Materials and methods

Site descriptions. The five sites were selected to represent several soil series in the state of Connecticut (USA) and to create a range of soil factors that may influence the growth of shrub willow for biomass production (Table 1). The distances between Storrs, Griswold, Hamden and Windsor are approximately 54.4, 93.2 and 44.7 km, respectively. Before establishment of the willow, all sites laid fallow for five years. According to USDA's Web *Soil Survey* [32], all soil series are classified as inceptisols with an average soil texture of coarse-loamy, except for the Windsor soil series, which is an entisol soil with a loamy sand texture.

Experimental design and treatments. The plantings were established and maintained in a consistent manner following the previously defined standardized protocol described in "Standard Operating Procedures for Measurement of Yield Trials" (Version 1.0. April 2008, SUNY-ESF [24,26]). The experimental design was a balanced latin square arranged in four blocks with four replicates per treatment (the treatment being the willow cultivar) – for a total of 16 experimental units per site. Each experimental unit measured 8.0 × 7.0 m and