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Research paper

A critical analysis of species selection and high *vs.* low-input silviculture on establishment success and early productivity of model short-rotation wood-energy cropping systems

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ABSTRACT

Most research on bioenergy short rotation woody crops (SRWC) has been dedicated to the genera *Populus* and *Salix*. These species generally require relatively high-input culture, including intensive weed competition control, which increases costs and environmental externalities. Widespread native early successional species, characterized by high productivity and good coppicing ability, may be better adapted to local environmental stresses and therefore could offer alternative low-input bioenergy production systems. To test this concept, we established a three-year experiment comparing a widely-used hybrid poplar (*Populus nigra* × *P. maximowiczii*, clone 'NM6') to two native species, American sycamore (*Platanus occidentalis* L.) and tuliptree (*Liriodendron tulipifera* L.) grown under contrasting weed and pest control at a coastal plain site in eastern North Carolina, USA. Mean cumulative aboveground wood production was significantly greater in sycamore, with yields of 46.6 Mg ha^{-1} under high-inputs and 32.7 Mg ha^{-1} under low-input culture, which rivaled the high-input NM6 yield of 32.9 Mg ha^{-1}. NM6 under low-input management provided noncompetitive yield of 6.2 Mg ha^{-1}. Sycamore also showed superiority in survival, biomass increment, weed resistance, treatment convergence, and within-stand uniformity. All are important characteristics for a bioenergy feedstock crop species, leading to reliable establishment and efficient biomass production. Poor performance in all traits was found for tuliptree, with a maximum yield of 1.2 Mg ha^{-1}, suggesting this native species is a poor choice for SRWC. We conclude that careful species selection beyond the conventionally used genera may enhance reliability and decrease negative environmental impacts of the bioenergy biomass production sector.

1. Introduction

An ecologically and economically sustainable wood-energy industry depends on development of regionally-appropriate silvicultural methods that maximize operational efficiency, contains costs, and has high tolerance to prevailing biotic and abiotic environmental stresses. Short-rotation woody crops (SRWC) culture using a variety of hardwood species has long been considered the mainstay of wood-energy cropping [1]. Because wood-energy is a low marginal-value commodity, energy farming with trees will only be widely adopted by the forest products industry and farmers if plantation establishment and SRWC culture are optimized for operational efficiency, offering reliable economic returns on investment. The efficiency and reliability of wood-energy plantations will be intricately linked to their environmental performance [2]. In this sense, a key aspect of environmental performance is the ability to reliably and repeatedly establish wood-energy plantations with the same efficiency and probability of success as farmers achieve with other major crops such as corn, soybean and wheat. Another important aspect of bioenergy SRWC environmental performance will be maintaining high productivity in the face of varying environmental conditions with a minimum of expensive and unsustainable silvicultural inputs (labor, fertilization, irrigation,

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herbicides, and insecticides).

Much of what is known about the productivity of potential SRWC systems [3–7] has been garnered from research trials, which differ from operational systems in terms of scale and subsequently the amount of care taken in establishment/cultivation and regard for economics (i.e. more intensive culture). Therefore, research is needed to optimize the establishment phase and early productivity of SRWC bioenergy systems under more realistic and sustainable low-input management regimes.

Establishment is the most vulnerable phase of a tree's life due to limited capacity to tolerate interacting biotic and abiotic stresses [2,8–10]. There has been much less success in developing reliable hardwood (Angiosperm) establishment systems compared to widespread commercial conifer (Gymnosperm) plantation species, such as loblolly pine in the U.S. Southeast [11,12]. Establishment of commercial tree plantations using containerized or bare-root seedling stock involves planting the seeds in nursery beds or greenhouse containers, culturing the seedlings for one or several growing seasons, lifting/packaging, cold storage, transportation, and finally planting at the field location [13,14]. Once planted, the seedlings must establish root systems and develop mycorrhizal relationships, compete with herbaceous vegetation for above- and belowground resources, and tolerate environmental stresses such as freezing, heat, drought, insect pests, etc. [14]. This is an important aspect of what makes some species suitable for widespread commercial development and deployment [13–16]. On the other hand, it has long been known that effective herbaceous competition control is an essential part of intensive pine management that enables crop trees to quickly capture a site and enhances early survival and productivity, which has contributed to decreasing mean rotation length in the U.S. Southeast from 50 to 25 years [11]. The cost of the multiple competition control treatments of modern pine silviculture (pre-plant, 2–3 years, sometimes at 8–10 years) can be economically justified in light of the high-value saw timber produced and decrease in rotation length [11,14]. However, aside from *Eucalyptus* spp., there are very few broadleaved species that have been shown to tolerate well the combined handling and biotic-abiotic stressors associated with commercial tree plantation establishment [13]. This explains why the majority of hardwood products, at least in the U.S., are from naturally regenerated forests and not intensively-managed plantations [17].

In terms of wood-energy SRWC, the family Salicaceae with genera of *Populus* (poplars) and *Salix* (willows), has received by far the most research attention and commercial development, especially in Europe and North America [2–5,18–20]. Both genera are propagated by means of hardwood cuttings rooted directly in the soil in early spring. Despite the great adaptability, *Populus* and *Salix* are mostly mid to high latitudes taxa that require relatively large amounts of available soil water, and thus may not be suitable for all sites and geographic locations [4,21]. Further, research has shown that although these genera reach moderate productivity of 8–10 Mg ha^{-1} y^{-1} under operational conditions [4,5], they are extremely sensitive to herbaceous competition [10], soil resources availability, and a wide-array of pests and pathogens [6,10,18,22–24]. It has been shown that perennial weeds can lead up to 90% reduction of annual yields in the first rotation and up to 80% mortality if left untreated [6]. Competition with weeds is likely to be higher on former agricultural land due to a large amount of weed seeds inherently present in the soil [25], and due to potentially higher ability of weeds to take advantage of available soil resources compared to cuttings during the early establishment stage [6,24]. Successful weed management during the first years is, in fact, a key to successful plantation establishment, fast growth and high biomass production [6,22,24,26]. For regions like the Southeast U.S., where the climate can be hot and dry, pests and pathogens are abundant, and the soil is nutrient-poor with high exchangeable acidity (H^+, hydroxides of Fe and Al), research on development of regionally-appropriate SRWC species and robust cropping systems, similar to widely commercially deployed pine plantations, still has far to go [2,7,10–12,27–29].

The objectives of the current study were to compare the establishment success and growth performance of three representative bioenergy SRWC systems that typify different hardwood species, including one interspecific poplar hybrid, for potential commercial deployment in the eastern U.S. under a low-input management regime. Establishment success and growth performance were quantified in terms of tree survival, biomass productivity, stand uniformity and weed competitiveness. We selected two species with known coppicing ability and native to the eastern U.S. with widespread distributions [13], suggesting tolerance to a wide range of environmental conditions: American sycamore (*Platanus occidentalis* L.) and tuliptree (*Liriodendron tulipifera* L.). Both of these species can be considered as potential bioenergy feedstocks [7,10,12]. We compared these native species to an interspecific hybrid of the *P. nigra* × *P. maximowiczii* taxon propagated as clonal variety ‘NM6’. NM6 was originally bred in Germany and has been extensively used and studied across North America and Europe, and therefore has well-known productivity and tolerance to environmental stress [2,5,30,31]. Although the optimum environmental conditions of NM6 cover mainly northern latitudes [5,31], satisfactory early productivity and survival have been documented in the Southeast U.S. [2,29]. Because weed control is a necessary part of plantation silviculture [6,24] but represents a significant expense [12], we wanted to examine relative species performance with and without competition control. Finally, as it has been shown that protection of new pine plantations from common insect pests can greatly enhance establishment success and early productivity [32,33], we wanted to test whether use of a commercially available systemic insecticide had any benefit for establishing hardwood SRWC bioenergy plantations.

We hypothesized that i) native species are better adapted to the local environment and would have higher establishment success with fewer silvicultural inputs compared to a non-native interspecific hybrid; ii) however, hybrid poplar is specifically bred for high growth performance and therefore would have higher productivity if the herbaceous competition and insect infestations were eliminated. To test these hypotheses, we set up a field study of replicated factorial combinations of species × herbaceous competition control × systemic insecticide treatments at a coastal plain site in eastern North Carolina (NC), USA, and monitored establishment success and growth performance for three years.

2. Materials and methods

2.1. Site description and experimental design

The study was conducted from 2012 to 2014 at the NCSU Bioenergy Field Laboratory experimental site (34.7605 N, 78.0985 W) near Wallace, North Carolina, USA. The area is classified as humid subtropical climate, and due to its proximity to the Atlantic Ocean in the upper coastal plain, the site experiences relatively warm and humid conditions. Weather data obtained from a meteorological station (Climate Retrieval and Observations Network of the Southeast) located ~0.5 km northeast from our site provided long-term (1981–2010) mean annual temperature (17.4 °C) and mean annual precipitation (1338 mm). Soil is characterized as a moderately well-drained loamy fine sand belonging to the Noboco series [34] with a hydric regime influenced by the presence of a relatively shallow water table (~1.5 m). The agricultural land had previously been used in sweet potato and soybean production.