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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.

Response to Reviewers: Thank you for careful review of our manuscript JBB-D-17-00029 and its acceptance under minor revisions. We consider all of them in the new revised version which we are re-submitting. Here we provide a point-by point summary of the revisions we have done:

- We changed the first two highlights as suggested.
- We changed the word "year" used as a unit to an abbreviation "y" throughout the entire manuscript including the Figure 4.
- L 178 and L 696 – "10,000 trees ha-1" This is actually the only thing which we left unchanged but we are completely opened to hear your opinion/suggestion. After you pointed out the issue with units, we consulted the literature: namely Avery and Burkhart (2015), Forest Measurements: Fifth Edition, 465 pp; and also a few studies from JBB - e.g. Bergante et al. 2016, 87 (p 39-45), and Nielsen et al. 2014, 64 (p 99-109) where we found the expression "trees ha-1" is used. We also found other studies in JBB using e.g. expression of 10,000 plants ha-1, 10,000 stools ha-1, 10,000 trees per hectare, or quite often used "a planting density of 10,000 ha-1". We would prefer to avoid the last expression because we think it lacks the unit of quantity which is not substituted by the word density. Please, if you have any preference let us know and we will change the stand density expression accordingly.
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- L 181-184- the description about the herbicide application was modified in a way to avoid using terms like "L of water".
- L 223- "hectare basis" was changed to "an area basis".
- L 469- We removed the first part of the first paragraph of the discussion and we moved the second part of the paragraph in a slightly adapted form into conclusions – L 731-737.
- Part of conclusions about the further research was distributed into discussion to L 606-609 and L 665-667.

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19 January, 2017

Manuscript re-submission

Dear Dr. Ralph Overend,

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Please, let us know in case of any further concerns about the manuscript or if you have any other questions.

On the behalf of the authors, sincerely,

Milan Fischer

***Detailed Response to Reviewers**

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***Highlights (for review)**

- High-input management is needed for establishment of traditional bioenergy systems
- Low *vs.* high-input bioenergy hardwood systems were evaluated in North Carolina, USA
- Overall growth performance ranked as follows: Sycamore > NM6 >> Tuliptree
- Low-input sycamore productivity matched widely reported high-input poplar cultures
- Species selection for robust establishment may confer further bioenergy benefits

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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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Keywords: American sycamore, bioenergy, pest control, poplar clone NM6, tuliptree, weed control

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, 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 2012-2014 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.

The experimental design consisted of three blocks composed of twelve split-split-plots. Each block consisted of two whole plots differing in weed control treatment – herbicide (H) and control (C), where weed control was applied as a whole-plot treatment. Each of the whole-plots was split into two split-plots where insecticide was (I) or was not (C) applied. Finally, within each of the split-plots, three split-split-plots with different species were randomly nested. The combination of treatments resulted in plots with herbicide + insecticide (HI), herbicide + no insecticide (HC), no herbicide + insecticide (CI) and no herbicide + no insecticide = control (CC) for each of the three species (36 plots in total). The species used in our study were American sycamore (*Platanus occidentalis* L.), yellow-poplar or tuliptree (*Liriodendron tulipifera* L.), and hybrid poplar clone NM6 (*Populus nigra* × *maximowiczii*) – note that some studies taxonomically classify this hybrid as *P. nigra* × *P. suaveolens* subsp. *maximowiczii* [21, 31].

Sycamore and tuliptree were planted as one-year-old 0.3-0.7 m tall bare-root seedlings obtained from the North Carolina Forest Service Claridge Nursery (Goldsboro, NC) on 17 February, 2012. NM6 was planted as 0.2 m long hardwood stem cuttings obtained from nursery trees sourced locally from another bioenergy experiment on 24 February, 2012. Although the difference in the planting material could provide theoretical advantage in rooting of seedlings compared to cuttings, it represents the common way of propagation for the selected species [9, 35].

The fields were disked and graded prior to tree planting. Trees were planted in the split-split-plot design at 1 ×1 m spacing, representing a density of 10,000 trees ha^{-1}. Each split-split-plot was surrounded by a 1 m border area, making a 2 m distance between pest control treatment levels. The split-plot units within a weed control treatment were separated by 3 m, while each whole plot was separated by 5 m within the blocks. For the initial weed control treatment, 0.3% (v/v) solution of Goal® 2XL (Dow AgroSciences, Indianapolis, IN, USA) concentrate and tap water was applied at a rate of 2,250 L ha^{-1}. This was equivalent to an active ingredient oxyfluorfen: 2-chloro-1-(3-ethoxy-4-nitrophenoxy)4-(trifluoromethyl)benzene applied at a rate of 1.7 L ha^{-1}. Within each whole plot, half the trees received an application of SilvaShield™ Forestry Tablet (Bayer Environmental Science, Research Triangle Park, NC, USA). SilvaShield™ is comprised of the neonicotinoid insecticide, imidacloprid, and a small amount of available nutrients (NPK) in slow-release form. During planting, one tablet was placed in each planting hole prior to inserting the seedling or cutting. Due to some periods of no precipitation at establishment, we applied drip-irrigation on 26 April, 2012, and 3 May, 2012, with 13 mm of water for each irrigation event in order to protect the experiment from the effects of drought stress while the root systems were developing. No irrigation was applied for the remainder of the study.

2.2. Biometric measurements

Within two weeks of planting the seedlings and cuttings, the initial height and diameter of each plant was measured to allometrically estimate the initial biomass. Height of each tree was then measured monthly until mid-October when vertical height increments ceased. During these regular measurements, occurrence of eventual pests, stand vigor and development were visually assessed and recorded. At the end of the first growing season, the heights and diameters (both at 10 cm, i.e. ground-level, and at 130 cm, i.e. breast height, if applicable) were measured for each tree. If a single tree had multiple stems, the height and diameter of each stem was measured. Stem height was measured with an extendable pole and stem diameter at the base (cutting height) and at breast height was measured with calipers. If the tree consisted of multiple shoots the tree diameter was calculated from the apparent circle created by the entire tree basal area rather than as arithmetic mean of all the shoot diameters. This sampling protocol, which provides similar results as quadratic mean diameter [36], was more practical because using the arithmetic mean could significantly underestimate the diameters whose upper limit is important from a harvesting perspective. In addition, close to the base, the shoots often grew together and acted as one piece when cutting. Finally, diameter calculated from the basal area is directly proportional to the volume and biomass in contrast to the arithmetic mean of the diameters [36]. The height of the dominant shoot was considered as the tree height of multi-stemmed individuals. The heights for 2013 and 2014 were estimated from the dominant shoot diameter using species-specific allometric equations (A.1-A.3) obtained *in-situ* during regular inventories.

2.3. Standing stock, annual productivity and tree mortality

The diameters on all stems of all trees were measured during the winter inventory of 2012, 2013 and 2014. Species specific *in-situ* parameterized allometric equations (A.4-A.9) between the

ground level diameter or diameter at the breast height (for trees higher than 2 m) and the dry matter aboveground woody biomass (AWB) were used to estimate standing stock by inventorying each stem of all trees at the end of each year. Annual productivity was determined by difference of standing stock between subsequent years. In order to minimize edge effects, we excluded border trees from all analyses. The sum of AWB from each plot represented by the 16 center trees was scaled to an area basis. The tree inventories were also used for tree mortality assessment. Due to an extremely low performance of tuliptree, we were not interested in further quantifying annual productivity and did not carry out the inventory in 2013 for this species.

2.4. Stand biomass uniformity

Along with AWB standing stock in 2014, we quantified the within-stand uniformity of AWB. As a metric of the stand uniformity, or its inverse inequality, we used the Gini coefficient [37, 38]. In order to derive the Gini coefficient, trees within a plot were sorted by AWB in ascending order, then the relative tree number and the relative AWB were calculated. Subsequently, these relative tree numbers and the relative AWB were expressed cumulatively. The Lorenz [39] curve can be derived by plotting the cumulated relative number of trees on the abscissa and the corresponding cumulated AWB on the ordinate [38]. If each tree had the same share of AWB as of tree number, then the Lorenz curve would be identical with the plot diagonal. The Gini index is computed as the ratio of the area separated by the Lorenz curve and the diagonal and the whole area below the diagonal [38]. The Gini index ranges between 0 and 1, where the more homogeneous a population is, the smaller the Gini index [37, 38]. The Lorenz asymmetry coefficient summarizes the degree of asymmetry in a Lorenz curve. This is important since populations with different Lorenz curves can have identical Gini coefficient, depending on whether most of the inequality is due to large or small individuals [40]. The Lorenz asymmetry coefficient is defined as the point at

which the slope of the Lorenz curve is parallel to the line of equality. When Lorenz asymmetry coefficient is higher than unity, the inequality is mostly due to a small number of very large individuals. When it is smaller than unity, the inequality is mostly due to a large number of very small individuals [41].

2.5. Weed biomass quantification

Aboveground weed biomass was collected in mid-May, 2012, November, 2012, and November, 2013. All aboveground weed biomass was sampled from a 0.25 m^2 quadrat defined by a plastic frame placed in the center of each plot, and dried at 70 °C.

2.6. Statistical analyses

Statistical analyses were performed with R software (R Core Team 2015). All statistical analyses considered the split-split-plot as the main experimental unit. The data were processed by multifactorial analysis of variance (ANOVA) using a linear mixed effects (lme) model with denominator degrees of freedom (DF) calculated according to Pinheiro and Bates [42]. Since mortality was the only variable following a binomial distribution [43], we used general linear mixed effect models [44] with subsequent ANOVA (type II Wald chi-square tests) to analyze this special case. Both of the abovementioned models accounted for hierarchical nesting within the split-split-plot experimental design. In addition, we used autocorrelation function structure for the linear mixed effects model when the measurements were repeated in time and variance function structure to account for heteroscedasticity [42]. Height, ground-level diameter, weed biomass, AWB productivity, standing stock (biomass), mortality, Gini coefficient and Lorenz asymmetry index were considered as response variables. Species, weed control, application of insecticide, time, and their interactions were then the fixed effects and block with several levels of nesting

(weed control/pest control/species and /year or period in case of repeated measures) was treated as a random effect to account for variation in soil, land-use history, or other environmental conditions across the field. Tukey's honestly significant difference post-hoc test with Westfall's adjustment for multiplicity [45, 46] was subsequently applied on both mixed effects linear models to identify statistically significant differences in particular interactions between the fixed effects. Assumptions on distributions of residuals of the linear models were checked by visual inspection of quantile-quantile probability plots and by analysis of skewness and kurtosis. In most cases, original values needed to be transformed according to the Box-Cox procedure [47]. Data are presented as (back-transformed) means ±standard errors [48]. Effects were considered significant when $P \leq 0.05$.

3. **Results**

3.1. Weather conditions

Mean daily air temperature in 2012 averaged 17.1 °C, just 0.3 °C below the 30-year normal. The subsequent years, 2013 and 2014, were characterized by colder weather with mean annual temperatures of 16.2 and 16.1 °C, respectively. Mean daily temperature was consistently above 10 °C from the fourth week in April till the end of October during all of the three investigated years. Precipitation in 2012 (1621 mm y^{-1}) and 2013 (1561 mm y^{-1}) exceeded the 30-year normal by 21 and 17 %, respectively. In 2014, annual precipitation (1340 mm) was consistent with the long-term average. Reference evapotranspiration [49] ranged between 1107 (2014) to 1170 (2012) mm y^{-1}, which together with annual precipitation totals indicates that water availability was adequate at the site.

3.2. Phenology, tree height and diameter growth

After the planting in 2012, budburst of NM6 occurred during the first two weeks of March coincident with the last frosts. The budburst of sycamore and tuliptree occurred at the end of the third week in March. These dates represented effective cumulative heat (>5°C) sums of ~300 and ~500 °C, which were ~7 and ~12 % of the entire annual heat sum, respectively. In addition to differences in onset of budburst, the species showed different growth phenology patterns (Fig. 1).

Fig.1.

Height growth increments of NM6 were observed as early as April. The early increments represented about 5 % of the entire annual increment for HI and HC, but ~25 % of annual height increment for CI and CC treatments. This was nearly equivalent to the June and July

contribution, representing 25-35 % of annual height increment for all treatments. This suggests low competition with weeds during April and high competition during the following months, suppressing the growth of NM6. The contribution of August growth ranged from 6-23 %. In September, when the NM6 trees had dropped most leaves it was less than 3 %. For sycamore, most of the growth occurred during May-September with the peak in July and no significant modulation of the relative growth by the treatments. In April, the growth was very small (< 5 %) and just slightly higher in October, at 4-8 %. In contrast to NM6, the September growth of sycamore was not negligible, since 12-22 % of annual height was gained during that time. Tuliptree grew mainly in June to July with almost no increments since August, and relatively little growth in April and May (< 15 %).

Apart from the small modulation of growth pattern described for NM6, we did not find any significant effect of treatments on relative growth phenology. However, we found pronounced differences in the absolute values of the height growth. In all cases, there was significant difference in height growth with and without the herbicide treatment. In addition, we found significant difference between the HI and HC in the case of NM6. The species with the greatest height growth in 2012 was NM6, which reached 4.1 m and 3.3 m for HC and HI, respectively. The heights of CI and CC were significantly lower than those on the plots with herbicide application, reaching only 0.8 and 1.0 m, respectively. For sycamore, the one meter difference between the treatments with (2.7 m) and without herbicide (1.7 m) was smaller, but still significant. Very poor performance was shown by tuliptree, reaching only 1.1 m and 0.7 m with and without herbicide application, respectively. Differences between treatments remained almost unaltered in the case of NM6 throughout the following two years of the study (Fig. 2a). At the end of the experiment, NM6 reached 6.5 m for HC, just 0.3 m less than for HI, and 4.4 and 4.0 m

for CI and CC, respectively, resulting in a pronounced difference between weeded and unweeded treatments. Sycamore was characterized by between-treatment convergence of height growth, reaching almost identical heights across treatments, at 6.7 m as the maximum for HI and 6.2 m as the minimum for CC. Final height of tuliptree ranged between 1.9 and 1.7 m for HI and CC, respectively.

Ground based diameter showed very similar within-treatment variability and growth dynamics as tree height (Fig. 2b). The largest diameters were reached by sycamore, ranging between 68 and 60 mm for HI and CC, respectively. Comparable values were reached by NM6, with 62 mm and 59 mm for HC and HI, respectively. Significantly lower values, slightly below 40 mm, were measured for no herbicide treatments in NM6. Very small diameters were found for tuliptree, ranging between 25 and 21 mm for HI and HC, respectively.

Fig. 2.

The interaction of species and herbicide treatments varied over time and significantly affected both tree height and diameter growth (Table 1). While NM6 showed rapid growth in 2012 and consistent treatment responses through time, sycamore showed very consistent growth increment over time, but treatment responses declined. In general, all fixed effects varied with time resulting in significant interactions with the years.

Table 1

In the case of NM6, the trees had several shoots per tree which were included in the diameter value but the height of the tree was determined only by the dominant shoot. In 2012, the average number of shoots of NM6 was 3.9 and 2.5 in the treatments with and without herbicide application, respectively. In 2014, these values were reduced to 3.0 and 1.6 due to within-tree shoot competition. No difference was found due to insecticide treatment. In contrast to NM6, for both sycamore and tuliptree the number of shoots per tree was reduced from ~1.1 to almost unity during 2012 to 2014, with no important differences between species and treatments.

Although the planting material was fully randomized, we tested whether there were any treatment differences in heights, diameters and biomass within the species groups immediately after planting. Although we did not find any of such differences for NM6 and sycamore, we found significant ($P = 0.0022$) differences in initial diameters, heights and biomass within the tuliptree seedlings. However, these initial differences disappeared a few months after planting and were not detectable at the end of the first year (Figs. 1 and 2). As expected, there were inherent significant differences in the planting material biometric parameters among the species, since NM6 was planted as cuttings and sycamore and tuliptree as bare-root seedlings. This could be a possible reason of the above-mentioned differences in number of shoots per tree between NM6 and the other two species.

3.3. Weed biomass productivity

Weed control affected the early growth of all species and affected growth of NM6 throughout the entire experiment. Application of herbicide was very effective and resulted in significant inhibition of weed development shortly after application (Fig. 3). At the end of the 2012 growing season, the effect of herbicide was still highly detectable, although sycamore had significantly lower understory weed biomass compared to the other species. As expected, the effect of

herbicide decreased over time resulting in a significant herbicide × period interaction (Table 2). This was mainly evident with tuliptree, which showed the lowest ability to inhibit weed growth by shading; the differences in weed biomass with and without herbicide decreased the least with time (treatment convergence). Further, weed biomass productivity of the tuliptree plots with herbicide remained relatively constant. In contrast, the weed biomass productivity in NM6 and sycamore non-herbicide treatment significantly decreased with time, to almost zero in the case of sycamore, resulting in a significant species × period interaction. Between these two species we observed that sycamore was able to decrease weed growth earlier than NM6, and sycamore had lower weed productivity for both herbicide treatments levels as compared to NM6.

Fig. 3.

Biomass of weeds was not quantified in 2014 since herbaceous competition was very low for NM6 and sycamore by the end of 2013. In the case of tuliptree, high mortality and low tree productivity resulted in almost no shading and therefore little inhibition of weeds. Visual observation suggested that the weed productivity in 2014 was very similar as in 2013 for all species.

Table 2

3.4. Annual aboveground woody biomass productivity, standing stock, and mortality

Corresponding with diameter and height growth, we found significant differences in the NM6 AWB annual productivity with and without herbicide (Fig.4, Table 3). The effect of weed control was the greatest in the year after planting and tended to be smaller during subsequent years,

although it remained highly significant over time. For instance, just before harvest in 2014 the herbicide treated NM6 averaged 14.0 Mg ha^{-1} y^{-1}, whereas the control averaged just 5.3 Mg ha^{-1} y^{-1}. The effect of herbicide on sycamore productivity was significant only in the first two years. All fixed main effects and first-order interactions had a significant impact on productivity (Table 3). At establishment, the effect of herbicide was more important than the effect of species since the productivity (Fig. 4) and the growth parameters (Figs. 1 and 2) differed more between the weed control treatments as compared to species. This was reversed in the second year when species became the dominant factor affecting productivity (Fig. 4). We observed consistently lower productivity of sycamore without insecticide in 2013 and 2014. In contrast, we observed significantly higher productivity of NM6 without insecticide when treated with herbicide during the first two years. This pattern was smaller in 2013 and reversed in 2014, as insecticide treatment resulted in higher NM6 productivity across herbicide treatments (though this was not significant).

Fig. 4.

The average AWB annual productivity of NM6 with weed control was 10.4 Mg ha^{-1} y^{-1}, whereas that of sycamore averaged 14.3 Mg ha^{-1} y^{-1}. The highest increment reached by NM6 occurred in 2014 and was 15.5 Mg ha^{-1} y^{-1} for HI treatment. The highest AWB productivity of 22.1 Mg ha^{-1} y^{-1} for sycamore occurred one year earlier, in the HI treatment. The productivity of NM6 consistently and significantly increased with time. In contrast, the productivity of sycamore with weed control sharply increased and peaked in the second year, with a significant drop in 2014. Sycamore without weed control showed comparable productivity in 2013 and 2014.

Table 3

The cumulative AWB standing stock was significantly affected by both herbicide and insecticide treatments, by species, and by insecticide × species and herbicide × species interactions (Table 4). We found a positive significant effect of the insecticide on the standing stock only in the case of sycamore. There were significant differences within the herbicide treatments for NM6, where the herbicide treated trees averaged 31.7 Mg ha^{-1} and trees without herbicide averaged 7.3 Mg ha^{-1} (Fig. 5a). Less pronounced though significant differences were found for sycamore, with a mean AWB standing stock of 43.3 Mg ha^{-1} with and 35.3 Mg ha^{-1} without herbicide. Tuliptree showed very poor performance with a mean yield of 0.7 Mg ha^{-1} and maximum of 1.2 Mg ha^{-1} for HI treatment. Final production of tuliptree was not significantly affected by any treatment.

Fig. 5.

The very low growth performance of tuliptree corresponded to the very high mortality, averaging 23.5 % and additionally characterized by large (17 %) between-plot variability (Fig. 5b). Both NM6 and sycamore showed favorably low mortality, with a mean of 0.9 % and a maximum of 2.6 % reached by HC sycamore. The overall F-statistics comparison indicated that species and species × insecticide were the only significant fixed effect explaining the variation in mortality (Table 4). The interactive effect of insecticide and species was attributed to the consistent zero mortality of sycamore treated with insecticide.

Table 4

3.5. Stand uniformity of final harvestable biomass

NM6 was characterized by the highest between-plot and between-treatment variability in growth (Figs. 1, 2 and 4), with moderate but unbalanced within-stand uniformity (Fig. 6ab). Sycamore showed the most consistent and relatively high uniformity (Gini coefficient ~ 0.2) of the final standing stock AWB (Fig. 6a). In contrast, tuliptree showed the significantly lowest uniformity.

Fig. 6.

In the overall F-statistics comparison (Table 5), these differences resulted in species as the main significant fixed effect affecting stand uniformity. In addition, insecticide was found also to be significant since the absence of insecticide typically resulted in slightly higher uniformity. We found a significant herbicide × species interaction, characterized by a small positive effect of weed control on NM6 and sycamore uniformity (Fig. 6a, Table 5). The low uniformity of tuliptree was related to very low performance, high weed competition, and high mortality.

Table 5

In overall comparison, we found a significant negative relationship ($R^2 = 0.59$, $P < 0.001$) between the Gini coefficient and standing stock, and a significant although weak negative trend between Lorenz asymmetry coefficient and AWB standing stock ($R^2 = 0.21$, $P = 0.0052$). By combining Gini and Lorenz asymmetry coefficients in the multiple regression we were able to explain more variability than by using these two variables individually ($R^2_{adj} = 0.62$, $P < 0.001$), meaning that the highest yields are related to high uniformity with little pronounced dominance of individual trees (compare Fig. 5a with Figs. 6ab).

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4. **Discussion**

4.1. Weed control

Weed biomass in spring, 2012, early after tree establishment was almost equivalent to the end-of-season value, suggesting that the majority of weeds developed during the spring months. This caused strong competition with the planted trees resulting in no tree species producing more aboveground biomass than concurrent weeds during the year of establishment in treatments where herbicide was not applied. Many studies have shown that controlling herbaceous competition is an essential practice in poplar and willow SRWC cultures, especially during the establishment phase [3, 22, 24, 51]. The current study clearly demonstrated that growth of NM6 was severely impeded without weed control during establishment, causing significant declines in first-rotation productivity that would negatively affect economic returns. Albertson *et al.* [22] found very small differences in ability to compete with weeds among willow clones, suggesting that despite large plasticity of this genus it might not be feasible to breed willows with higher tolerance of weed competition. With weed control, NM6 provided satisfactory biomass production, with a mean of 10.4 Mg ha^{-1} y^{-1}, falling well within the average range 8-10 Mg ha^{-1} y^{-1} reported in the literature [4, 5] and within the range generally considered economically viable [52, 53]. A large majority of studies on *Populus* and *Salix* SRWC, reviewed by Fischer et al. [5], reported that weed control was needed during establishment. Together with results of the current study, this suggests that without early competition control the widely reported average yields would be not attainable. The 70 % reduction in NM6 yield without herbicide in our study underlines the necessity for weed control in poplar plantations, especially during the establishment phase before trees reach canopy closure and outcompete the weeds. Poor performance of NM6 without weed control also suggests that this non-native interspecific hybrid has limited capacity to capture sites with similar environmental conditions as the eastern NC

coastal plain if not supported by intensive management. Therefore, invasiveness of this hybrid may be limited in such settings – a trait that should always be considered when introducing new species or varieties into an area [54].

In contrast to NM6, much less is known about the productivity and weed control effectiveness of sycamore and tuliptree in high density SRWC systems. Both sycamore and NM6 were characterized by a well-developed canopy and ability to eventually inhibit the growth of weeds due to strong reduction of available light beneath the canopy. This occurred by the end of the first year in sycamore compared to end of the second year in NM6 (e.g. Fig. 3), conferring an early advantage in productivity that compounded through time resulting in the high biomass yields of sycamore that out-performed NM6 in all treatments. This supports our hypothesis that native species might be better suited to SRWC in conditions similar to the eastern NC coastal plain, but did not support the hypothesis that hybrid poplar can achieve higher yields when supportive management is provided, at least for this particular genotype (although NM6 productivity reported here is representative of a wide range of *Populus*/*Salix* genotypes reported in the literature [5]). The production of ~12.0 Mg ha^{-1} y^{-1} without any weed control strongly suggests that sycamore is worthy of consideration for the developing bioenergy industry in the southeastern U.S. In addition, average yields of ~14.0 Mg ha^{-1} y^{-1} in the herbicide treatment exceeded the previously reported range of 5.5 to 9.5 Mg ha^{-1} y^{-1} [2, 12, 28], ranking sycamore among the most productive bioenergy hardwood species [4]. The higher yields found in our study might be explained by considerably greater planting density, but also due to lack of pronounced effects of drought as reported elsewhere [28]. Considering that we only saw a 15 % decline in biomass production and no effect on survival after three years of growth in sycamore when managed entirely without herbicide, it raises the question of whether this species might permit

significantly decreased use of weed control altogether. This would provide some economic advantage relative to genera needing more intensive management, but it mainly shows that sycamore SRWC represents a robust bioenergy system in terms of its establishment. It is likely that during the second and subsequent rotations, coppiced stands with well-developed root systems will reach canopy closure shortly after re-sprouting, resulting in even less benefit from weed control from that shown here. Although anecdotal, we also observed high litter fall characterized by slower decomposition under sycamore, which covered the soil the entire year, as compared to NM6. Apart from suppressing the weed understory, this leaf mulch can offer other benefits such as moisture conservation, soil protection, moderation of soil temperature, and perhaps increased soil organic carbon [9]. Repeated suppression of weed flora may additionally inhibit their reproduction and thus reduce the soil seed bank, providing further ecological benefits if the field is returned to agricultural crops.

The third species in our study, tuliptree, was never able to capture the site and productivity was far below that of competing weeds. The very low yields were somewhat surprising given that tuliptree is a widespread and productive early successional species, commonly dominating naturally regenerated sites over its wide range in the eastern U.S. [13, 55]. Final average standing stock of tuliptree after three years of growth averaged below 1.0 Mg ha^{-1}, close to annual yields reported in the literature [4]. This strongly suggests that tuliptree is not a viable species selection for SRWC bioenergy production. Apart from the first year, herbicide did not significantly improve tuliptree performance. Our hypotheses that native species can better cope with environmental pressures under low-input management was therefore supported only for sycamore. We have had similar results in several other studies (unpublished data) and suspect tuliptree is unable to tolerate the stress associated with commercial seedling production and

transplanting as well as other species (e.g. sycamore, loblolly pine). A wide geographic range, good coppicing ability, relatively high physiological process rates and growth potential in natural communities does not necessarily mean a bioenergy candidate species can be successfully deployed in SRWC systems, and therefore, thorough field testing of any candidate species is needed.

It might be argued that sycamore and tuliptree had a significant advantage over the NM6 due to the differences in planting material (seedlings *versus* cuttings) making the productivity comparison biased. However, the comparison of weed-controlled sycamore and NM6 heights, diameters and AWB productivity suggests that it was not a serious issue because the NM6 had the highest annual increment during the first year of the study. The significant difference between these two species occurred during the second year, indicating factors other than the difference in the planting material were the cause. It is noteworthy that the price of the hardwoods seedlings and poplar cuttings are equivalent, alleviating questions related to the economic benefits of using one or another type of planting stock.

4.2. Insecticide

In general, fast growing trees are the most susceptible to pests during establishment due to indeterminate growth of the shoots that produce leaves with high water and nutrient contents, and relatively low fiber concentration [10]. In the current study, the most common pests observed were from the group of defoliating insects represented by poplar tentmaker (*Clostera inclusa*) on the leaves of NM6 and Japanese beetle (*Popillia japonica*) on sycamore. These insects and their damage were typically more apparent in the late summer when their populations are at the peak [24], in some cases initiating significant early leaf area reduction. Therefore, these insect pests did not influence the yield during the year of their appearance, but it is possible a cumulative

effect might influence yield in subsequent years. This may be why the effect of insecticide in our study appeared to be cumulative and characterized by a significant insecticide × year interaction. Based on our observations, application of a systemic insecticide had a small, yet detectable effect on AWB production of NM6 and sycamore, and no effect on tuliptree. In contrast to herbicide, it is less clear that application of systemic insecticides confers economic advantage with these species for bioenergy as has been documented for intensively managed pine [33]. Decreasing establishment costs and avoiding potential negative ecological effects associated with insecticide use [56] is another example of the potential benefits of careful species selection for bioenergy SRWC.

4.3. Plot size constraints

It is useful to consider whether the levels of yield found in our study, especially those attained by sycamore, can be achieved in operational plantations or larger-scale trials [6, 57]. Firstly, small scale plots are inherently managed more intensively than operational plantations, and pest depredations are not adequately accounted for [3]. Secondly, the productivity is typically affected by so-called “edge effects” where the border trees have higher resource availability [57]. In our study, we tried to avoid this edge effect by excluding the border trees from analysis and limiting the study to only three years (a realistic SRWC rotation). To estimate the eventual edge effect, we calculated the annual AWB productivity using all trees and compared it with the productivity derived from interior trees only. NM6 did not show any indications of edge effect, since the difference between these two sets of data were within 5 % and did not dramatically change over time. Similarly, there were very small differences (< 3 %) between the productivity calculated from the two data sets in the case of sycamore during the first two years. However, we found strong evidence of edge effects in sycamore in the third year (2014), where the productivity

estimated from all trees was on average 70 % higher than the productivity based on the interior trees alone. It is possible that the increased dominance of the edge trees suppressed the interior trees, explaining the reduced sycamore productivity in 2014. The greatest differences in the productivity of the two data groups were observed in HC treatment, where we observed also the strongest productivity decline in 2014, the highest sycamore mortality, and the lowest Lorenz asymmetry coefficient indicating stand non-uniformity due to a large number of suppressed trees. Likewise, when we estimated the productivity from all trees (including the edge individuals) no decline of productivity was observed. This also means that the productivity of sycamore estimated from our small scale plots in 2014 (Figs. 4 and 5) might have been underestimated due to suppression of interior trees by edge trees. This is in contradiction with the assertion that the edge effect is characterized by overestimated biomass in several rows from the edge towards the center [57]. An alternative explanation might be that the productivity of sycamore reached its peak at the year two and that its decline during the third year did not affect the border trees because they were not limited by space as opposed to the interior individuals. Despite this uncertainty in yield estimation, the treatment effects on relative growth responses remain representative. In addition, we also suggest that the species inter-comparison was not greatly impacted by the dimensions of the plots, since the main patterns were already observable during the first two years, when no important edge effects were recorded. Further research on biomass productivity of sycamore at larger spatial and temporal scales is necessary. Variation in spacing and length of rotations should be tested in order to optimize productivity and return on investment (e.g. operational costs), and to further assess impacts on ecosystem function.

4.4. Implications for SRWC bioenergy production systems

In our study, sycamore performed better than the hybrid poplar NM6 and tuliptree in terms of survival, biomass increment, treatment convergence, and between-plot and within stand uniformity. Together these traits suggest sycamore is a serious but perhaps under-appreciated bioenergy SRWC candidate. Tuliptree, on the other hand, was not found to be a suitable SRWC species due to its unreliable establishment and very low productivity. Robust stand establishment is crucial for the survival and productivity of the SRWC system, and therefore, directly relevant to the economic viability of the first and subsequent rotations. Taking into account an SRWC culture life expectancy covering 7—8 rotations without significant yield losses [58], the first three years could represent at least 13 % of the entire SRWC plantation lifespan. Additionally, stool mortality is often caused by initial weed competition and causes unrecoverable productivity losses due to the compounding nature of early plant growth [2, 6, 29]. In contrast to tuliptree, we observed favorably low mortality in NM6 and sycamore, below a commonly accepted range of 10 % [5, 51, 59].

While sycamore outperformed the hybrid poplar NM6 in our study, we should take into account that the genus *Populus* is characterized by wide genetic variation and there may be other species/genotypes that might be more productive [5, 30]. Under high-input culture (repeated application of fertilization and herbicide), clones of eastern cottonwood (*Populus deltoides*) and its hybrids, showed generally superior growth performance over NM6 in South Carolina [2, 29]. Although NM6 was a competitive genotype during first 3-year rotation [2, 29], its productivity declined during subsequent years [29]. The most productive clone of *P. deltoides* in that study reached three times higher stem volume than NM6 when irrigated, however the rank of NM6 among all 31 *Populus* genotypes tested was much higher (3rd) in non-irrigated plots, and also had

some of the highest survival. This supports the suitability of NM6 as a good choice for the current study in which we tested for establishment success and early productivity explicitly under low-input silviculture. Although NM6 clearly did not represent the potential productivity of *Populus* in our region (under high inputs), the large difference between the weeded and unweeded treatments illustrates well a typical characteristic of *Populus*, that is, requirement for intensive site preparation and high-input management during the establishment stage [12, 29]. In addition, this difference (in silvicluture) might explain much of the large gap in yields between research trials and commercial *Populus* plantations reported by practitioners across the Southeast U.S [12].

In our study, NM6 was phenologically characterized by relatively early leaf fall (enhanced by defoliators) which significantly shortened its growing season and thus was not entirely able to fully realize site potential. Further, this early leaf fall exacerbated by late summer pest activity might have cumulative long-term negative impacts since during the last stage of the growing season, assimilates are stored and then depleted the following spring for the initial surge of growth until the first leaves are fully expanded [60]. Stored carbohydrate reserves are additionally important for the development of winter hardiness [60]. Sycamore attained about 20 % of the vertical growth during the September-October period, in contrast to NM6, which had almost no vertical growth during that time. Furthermore, the relatively early phenology of NM6, also likely due to its high-latitude provenance, might increase the risk of damage due to late spring frost events under climate change [61]. We found that the spring phenology, characterized by bud break, began when the cumulative heat sum reached 7 % of the annual sum, similar to Fischer et al. [62], who reported 6 % for the same hybrid (but different clone, J-105) in central Europe. This suggests that the cumulative heat sum is a robust predictor of the onset of leaf

development and is suitable for predicting the length of the growing season for other bioenergy species. Phenology [63] and careful species/genotype selection [7, 29] are therefore important factors to take into account in the design of climatically robust, efficient bioenergy systems. As shown in other experiments in Europe, some poplar species, including *P. nigra* × *P. maximowiczii*, keep their leaves until late November [51, 62], similar to sycamore in the current study. Such a poplar species with similar autumn phenology as that of sycamore may have correspondingly higher productivity and perform similarly to sycamore. A comparison of sycamore with other poplar clones and fast growing species adapted to the eastern U.S. would have value in assessing the wood-bioenergy potential of the region.

Stand uniformity analyses in our study support the hypothesis that stands with higher uniformity (low Gini coefficient) are more productive [64, 65]. The Lorenz asymmetry coefficient < 1 was generally associated with high AWB standing stock. The lowest Lorenz coefficient was found for sycamore HC, where we observed the most pronounced productivity decline in the third year and the highest suppression of interior trees by the edge trees. As low Lorenz asymmetry is associated with non-uniformity due to large amount of small trees, it generally indicates a high number of suppressed trees by a few dominant individuals. In contrast, the highest Lorenz asymmetry coefficient was found for all tuliptree plots and NM6 without herbicide. This indicates that in these non-uniform stands suppressed by weeds, a few dominant trees were able to pull through the weed competition and produce a significant part of the overall stand productivity, although still not able to capture the site. Stand uniformity analysis is used in forestry [38, 65] and agriculture [66], but it has received limited attention in bioenergy research.

In addition to effects on productivity, stand uniformity could be important to harvesting-handling-processing efficiency of SRWC feedstocks [67]. In general, the higher the crop

uniformity the higher efficiency of harvest processing [68]. In addition, adoption of stand uniformity analysis might be useful in addressing the question of optimum density and rotation length, where the highest yields can be theoretically achieved by the most uniform stands with little pronounced dominance of individual trees. Stand uniformity can change with variation in rotation length and when within-stand competition starts to develop [64, 69]. However, in SRWC between-tree competition, and related dominance, can also emerge when single-stem stands become multi-stemmed after the first coppice [70]. Because there has been still no consensus about the optimum length of the rotation cycle, as likely it may vary due to local circumstances, it would be interesting to quantify development of within-stand variability in tree size with different rotation lengths and examine tradeoffs between productivity, net carbon balance, and economics across a wide range of climatic conditions.

In the current study, a three-year rotation length seems to have been adequate for sycamore to achieve high yields at a planting density of 10,000 trees ha^{-1} in the first rotation cycle. High uniformity and treatment convergence suggest successful establishment for sycamore in all treatments, including the low-input control. From this perspective, sycamore proved to be a very promising bioenergy candidate. As bioenergy is a low marginal value commodity, SRWC needs to be as reliable as possible for adoption by farmers, and amenable to low-input culture to keep operational costs down. Sycamore would probably perform well in this capacity with minimal management across much of and perhaps beyond the eastern NC coastal plain, although testing under extreme environmental conditions, especially drought, is still needed. Anecdotal industry experience suggests sycamore may be susceptible to diseases, which can negatively affect plantation survival in later years [12]. In fact, sycamore was grown in plantations for pulp and paper in 1970's and 1980's but disease problems hampered further utilization [13]. However, it

has not been determined whether the short rotation length of SRWC (typically 2 to 5 years) might decrease disease susceptibility, perhaps through maintenance of tree juvenility [71]. More research is needed on sycamore tolerance to pests and pathogens in SRWC settings, especially as affected by other interacting environmental stresses (e.g. drought, temperature, poor nutrition, etc.).

Finally, the finding that some native species may be more tolerant to low-input management compared to those conventionally considered in bioenergy SRWC culture is important because a higher diversity of suitable species may increase the ecological as well as economic resilience of bioenergy systems. The diversification of bioenergy feedstocks may ultimately augment biodiversity of SRWC ecosystems, alleviating what has been considered an important externality of integrating energy farming into agricultural landscapes [72, 73]. Further, employing species that require limited weed control results in more environmentally-sound management that simultaneously improves the net carbon balance of bioenergy, a main attribute desired in bioenergy systems [74, 75]. To fully address this question, it is necessary to evaluate carbon cycling throughout the entire SRWC culture life span, including the pre-planting phase in the nursery of each species. Improving the environmental footprint of bioenergy, leading to higher environmental sustainability and potential climate benefits appeared as a primary goal of the recent COP 21 commitments reached in Paris in late 2015. Results of the current study indicate that careful species selection to support low-input management might play an important role in achieving that goal.

5. **Conclusions**

Results of this study support the premise that silvicultural treatments common to intensive forest management in the Southeast U.S. may be advantageous for hardwood SRWC bioenergy systems. However, there were important differences in species response to weed control and protection from insect pests. Sycamore yield under low-input culture matched that of a widely-used hybrid poplar clone (NM6) under high-inputs. Tuliptree, a highly productive, economically valuable native species across the region, turned out to be entirely unsuitable for bioenergy SRWC. We found that American sycamore was the most productive and at the same time least susceptible to weed competition of the three investigated SRWC species. These results suggest that sycamore is a promising bioenergy candidate, especially suitable to low-input culture yielding economic and environmental benefits. The productivity of native sycamore, with and without weed control, was fully competitive to what is normally achieved in bioenergy systems based on specifically-bred *Populus* and *Salix* clones under high-input culture. Our study illustrates how use of sycamore, and other species, in a widespread bioenergy industry must be preceded by better understanding of the ecophysiological performance, environmental tolerances to biotic/abiotic stresses, and resource-use efficiencies in order to design the most efficient, productive and ecologically sustainable energy systems for the future.

6. **Acknowledgements**

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7. **References**

[1] Anderson HW, Papadopol CS, Zsuffa L. Wood energy plantations in temperate climates. Forest Ecology and Management. 1983;6:281-306.

[2] Coyle D, Coleman M, Durant J, Newman L. Survival and growth of 31 *Populus* clones in South Carolina☆. Biomass and Bioenergy. 2006;30(8-9):750-8.

[3] Dickmann D. Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. Biomass and Bioenergy. 2006;30(8-9):696-705.

[4] King JS, Ceulemans R, Albaugh JM, Dillen SY, Domec J-C, Fichot R, et al. The challenge of lignocellulosic bioenergy in a water-limited world. BioScience. 2013;63(2):102-17.

[5] Fischer M, Fichot R, Albaugh J, Ceulemans R, Domec J-C, Trnka M, et al. *Populus* and *Salix* grown in a short-rotation coppice for bioenergy: Ecophysiology, aboveground productivity, and stand-level water use efficiency. In: Bhardwaj Ajay K, Zenone T, Chen J, editors. Sustainable Biofuels, An Ecological Assessment of the Future Energy. Berlin-Beijing: HEP deGruyter; 2015. p. 157-94.

[6] Kauter D, Lewandowski I, Claupein W. Quantity and quality of harvestable biomass from *Populus* short rotation coppice for solid fuel use—a review of the physiological basis and management influences. Biomass and Bioenergy. 2003;24:411-27.

[7] Coleman MD, Coyle DR, Blake J, Britton K, Buford M, Campbell RG, et al. Production of short-rotation woody crops. Southern Research Station: Forest Service; 2004. p. 26.

[8] Niinemets Ü. Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: Past stress history, stress interactions, tolerance and acclimation. Forest Ecology and Management. 2010;260(10):1623-39.

[9] Stanturf JA, Oosten Cv, Netzer DA, Coleman MD, Portwood CJ. Ecology and silviculture of poplar plantations. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J, editors. Poplar Culture in North America. Ottawa: NRC Research Press; 2001. p. 153-206.

[10] Coyle DR, Nebeker TE, Hart ER, Mattson WJ. Biology and management of insect pests in North American intensively managed hardwood forest systems. Annu Rev Entomol. 2005;50:1-29.

[11] Fox TR, Jokela EJ, Allen HL. The development of pine plantation silviculture in the southern United States. Journal of Forestry 2007;105:337-48.

[12] Kline KL, Coleman MD. Woody energy crops in the southeastern United States: Two centuries of practitioner experience☆. Biomass and Bioenergy. 2010;34(12):1655-66.

[13] Burns RM, Honkala BH. Silvics of North America: 1. Conifers; 2. Hardwoods. Agriculture Handbook 654. Washington, DC. : U.S. Department of Agriculture, Forest Service; 1990.

[14] Schultz RP. Loblolly pine - The ecology of loblolly pine (*Pinus taeda* L.): U.S. Department of Agriculture Forest Service, Washington, D.C.; 1997.

[15] Wahlenberg WG. Loblolly pine: its use, ecology, regeneration, protection, growth, and management. [Durham, N.C.]: School of Forestry, Duke University; 1960.

[16] Zobel B, Talbert J. Applied Forest Tree Improvement. New York: John Wiley & Sons Inc. ; 1984.

[17] Stanturf JA, Zhang D. Plantations forests in the United States of America: past, present and future. XII World Forestry Congress. Québec City, Canada, 2003.

[18] Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J. Poplar culture in North America. Ottawa: NRC Research Press; 2001.

[19] Ceulemans R, Deraedt W. Production physiology and growth potential of poplars under short-rotation forestry culture. Forest Ecology and Management. 1999;121(1-2):9–23.

[20] Isebrands JG, Richardson J. Poplars and Willows - Trees for society and the environment. Croydon: FAO&CABI; 2014.

[21] Dickmann DI, Kuzovkina J. Poplars and willows of the world, with emphasis on silviculturally important species. In: Isebrands JG, Richardson J, editors. Poplars and Willows - Trees for society and the environment. Croydon: FAO&CABI; 2014. p. 8-91.

[22] Albertsson J, Verwijst T, Hansson D, Bertholdsson NO, Åhman I. Effects of competition between short-rotation willow and weeds on performance of different clones and associated weed flora during the first harvest cycle. Biomass and Bioenergy. 2014;70:364-72.
[23] Albertsson J, Hansson D, Bertholdsson NO, Åhman I, Kempenaar C. Site-related set-back by weeds on the establishment of 12 biomass willow clones. Weed Research. 2014;54(4):398-407.
[24] Buhler DD, Netzer DA, Riemenschneider DE, Hartzler RG. Weed management in short rotation poplar and herbaceous perennial crops grown for biofuel production. Biomass and Bioenergy. 1998;14(4):385-94.
[25] Trnka M, Trnka M, Fialová J, Koutecký V, Fajman M, Žalud Z, et al. Biomass production and survival rates of selected poplar clones grown under a short-rotation system on arable land. Plant, Soil and Environment. 2008;54(2):78–88.
[26] Larsen SU, Jørgensen U, Kjeldsen JB, Lærke PE. Long-term yield effects of establishment method and weed control in willow for short rotation coppice (SRC). Biomass and Bioenergy. 2014;71:266-74.
[27] Stout AT, Davis AA, Domec J-C, Yang C, Shi R, King JS. Growth under field conditions affects lignin content and productivity in transgenic *Populus trichocarpa* with altered lignin biosynthesis. Biomass and Bioenergy. 2014;68:228-39.
[28] Davis A, Trettin C. Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina☆. Biomass and Bioenergy. 2006;30(8-9):769-77.
[29] Kaczmarek DJ, Coyle DR, Coleman MD. Survival and growth of a range of *Populus* clones in central South Carolina USA through age ten: Do early assessments reflect longer-term survival and growth trends? Biomass and Bioenergy. 2013;49:260-72.
[30] Eckenwalder JE. Key to species and main crosses. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J, editors. Poplar Culture in North America. Ottawa: NRC Research Press; 2001. p. 331-82.
[31] Zalesny RS, Hall RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR. Biomass and genotype × environment interactions of *Populus* energy crops in the midwestern United States. BioEnergy Research. 2009;2(3):106-22.
[32] Asaro C, Creighton J. Use of systemic fipronil and imidacloprid to control regeneration pests of loblolly pine. Journal of Economic Entomology. 2011;104(4):1272-9.
[33] King JS, Kelley AM, Rees R. Systemic control of nantucket pine tip moth (*Rhyacionia frustrana* Scudder in Comstock, 1880) enhances seedling vigor, plantation establishment, and early stand-level productivity in *Pinus taeda* L. Forest Science. 2014;60(1):97-108.
[34] US National Cooperative Soil Survey. Available online at https://soilseries.sc.egov.usda.gov/OSD_Docs/N/NOBOCO.html

10/2007 ed.
[35] Land Jr SB, Elam WW, Khna M. Rejuvenated sycamore cuttings for energy plantations. Biomass and Bioenergy. 1995;8(4):255-64.
[36] Curtis R, O. , Marshall D, D. Why quadratic mean diameter? West Journal of Applied Forestry. 2000;15(3):137-9.
[37] Gini C. Measurement of Inequality of Incomes. The Economic Journal. 1921;31(121):124-6.
[38] Duduman G. A forest management planning tool to create highly diverse uneven-aged stands. Forestry. 2011;84(3):301-14.
[39] Lorenz MO. Methods of measuring the concentration of wealth. Publications of the American Statistical Association. 1905;9(70):209-19.
[40] Weiner J, Solbrig OT. The meaning and measurement of size hierarchies in plant populations. Oecologia. 1984;61(3):334-6
[41] Metsaranta JM, Lieffers VJ. Inequality of size and size increment in *Pinus banksiana* in relation to stand dynamics and annual growth rate. Annals of Botany. 2008;101(4):561-71.
[42] Pinheiro JC, Bates DM. Mixed-Effects Models in S and S-PLUS. New York: Springer; 2000.
[43] Crawley MJ. The R book: John Wiley & Sons, Ltd; 2007.

[44] Bates D, Maechler M, Bolker B, Walker S. Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software. 2015;67(1):1-48.
[45] Bretz F, Hothorn T, Westfall P. Multiple Comparisons Using R: CRC Press; 2010.
[46] Westfall PH. Multiple testing of general contrasts using logical constraints and correlations. American Statistical Association. 1997;92:299-306.
[47] Venables WN. Modern applied statistics with S / W.N. Venables, B.D. Ripley. New York: Springer; 2002.
[48] Jøregensen E, Pendersen AR. How to obtain those nasty standard errors from transformed data - and why they should not be used. Aarhus Universitet, Det Jordbrugsvidenskabelige Fakultet; 1997. p. 20.
[49] Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. Rome, 1998.
[50] Kelley AM, King JS. Pest pressure, hurricanes, and genotype interact to strongly impact stem form in young loblolly pine (*Pinus taeda* L.) along the coastal plain of North Carolina. Trees. 2014;28(5):1343-53.
[51] Broeckx LS, Verlinden MS, Ceulemans R. Establishment and two-year growth of a bio-energy plantation with fast-growing *Populus* trees in Flanders (Belgium): Effects of genotype and former land use. Biomass and Bioenergy. 2012;42:151-63.
[52] Price L, Bullard M, Lyons H, Anthony S, Nixon P. Identifying the yield potential of *Miscanthus* × *giganteus*: an assessment of the spatial and temporal variability of *M.* × *giganteus* biomass productivity across England and Wales. Biomass and Bioenergy. 2004;26(1):3-13.
[53] Faasch RJ, Patenaude G. The economics of short rotation coppice in Germany. Biomass and Bioenergy. 2012;45:27-40.
[54] Barney JN. Bioenergy and invasive plants: Quantifying and mitigating future risks. Invasive Plant Science and Management. 2014;7(2):199-209.
[55] Kellison RC. A geographic variation study of yellow-poplar (*Liriodendron tulipifera* L.) within North Carolina. Technical Report 33. Raleigh: North Carolina State University School of Forestry; 1967. p. 41.
[56] Diekötter T, Kadoya T, Peter F, Wolters V, Jauker F. Oilseed rape crops distort plant-pollinator interactions. Journal of Applied Ecology. 2010;47(1):209-14.
[57] Zavitkovski J. Small plots with unplanted plot border can distort data in biomass production studies. Canadian Journal of Forest Research. 1981;11:9-12.
[58] Dillen SY, Djomo SN, Al Afas N, Vanbeveren S, Ceulemans R. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. Biomass and Bioenergy. 2013;56:157-65.
[59] Al Afas N, Marron N, Van Dongen S, Laureysens I, Ceulemans R. Dynamics of biomass production in a poplar coppice culture over threee rotations (11 years). Forest Ecology and Management. 2008;225:1883–91.
[60] Dickmann DI, Isebrands JG, Blake TJ, Kosola K, Kort J. Physiological ecology of poplars. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J, editors. Poplar Culture in North America. Ottawa: NRC Research Press; 2001. p. 77-118.
[61] Gu L, Hanson PJ, Post WM, Kaiser DP, Yang B, Nemani R, et al. The 2007 eastern US epring freeze: Increased cold damage in a warming world? BioScience. 2008;58(3):253-62.
[62] Fischer M, Trnka M, Kučera J, Deckmyn G, Orság M, Sedlák P, et al. Evapotranspiration of a high-density poplar stand in comparison with a reference grass cover in the Czech–Moravian Highlands. Agricultural and Forest Meteorology. 2013;181:43-60.
[63] Pellis A, Laureysens I, Ceulemans R. Genetic variation of the bud and leaf phenology of seventeen poplar clones in a short rotation coppice culture. Plant Biol (Stuttg). 2004;6(1):38-46.
[64] Binkley D. A hypothesis about the interaction of tree dominance and stand production through stand development. Forest Ecology and Management. 2004;190(2-3):265-71.
[65] Aspinwall MJ, King JS, McKeand SE, Bullock BP. Genetic effects on stand-level uniformity and above- and belowground dry mass production in juvenile loblolly pine. Forest Ecology and Management. 2011;262(4):609-19.

[66] Pan X-Y, Wang G-X, Yang H-M, Wei X-P. Effect of water deficits on within-plot variability in growth and grain yield of spring wheat in northwest China. Field Crops Research. 2003;8080(3):195-205.
[67] Turnbull JW, Booth TH. Eucalyptus in cultivation: an overview. In: Coppen JJW, editor. Eucalyptus: The Genus *Eucalyptus*: CRC Press; 2003. p. 51-73.
[68] Silversides CR, Sundberg U. Operational Efficiency in Forestry : Vol. 2: Practice. Dordrecht: Springer Netherlands : Imprint: Springer; 1989.
[69] Binkley D, Senock R, Bird S, Cole TG. Twenty years of stand development in pure and mixed stands of *Eucalyptus saligna* and nitrogen-fixing *Facaltaria moluccana*. Forest Ecology and Management. 2003;182(1-3):93-102.
[70] Laureysens I, Deraedt W, Ceulemans R. Population dynamics in a 6-year-old coppice culture of poplar. Forest Ecology and Management. 2005;218(1-3):115-28.
[71] Filer Jr. TH, Cooper DT, Collins RJ, Wolfe R. Survey of sycamore plantations for canker, leaf scorch, and dieback. Plant Diseases Reporter. 1975;59(2):152-3.
[72] Berg A. Breeding birds in short-rotation coppices on farmland in central Sweden-the impportance of Salix height and adjacent habitats. Agriculture, Ecosystems and Environment. 2002;90:265-76.
[73] Sage RB. Short rotation coppice for energy: towards ecological guidelines. Biomass and Bioenergy. 1998;15(1):39-47.
[74] Djomo SN, Kasmioui OE, Ceulemans R. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. GCB Bioenergy. 2011;3(3):181-97.
[75] Isebrands JG, Karnosky DF. Environmental benefits of poplar culture. In: Dickmann DI, Isebrands JG, Eckenwalder JE, Richardson J, editors. Poplar Culture in North America. Ottawa: NRC Research Press; 2001. p. 207-18.

Figure captions

Fig. 1. Mean ±SE (3 replicates) canopy height growth of interior trees in 2012. For multi-stem trees, the length of dominant shoot was considered as the tree height. Note that all measurements were taken at the same time, although they are depicted with small shifts to avoid overlapping of the points.

Fig. 2. Mean ±SE (3 replicates) end-season mean tree height ±SE (in 2012 measured, in 2013-2014 estimated from allometry with diameter) and mean plot ground-level (at 10 cm above ground) diameter of living trees. Note that measurements were taken at the same time, although they are depicted with small shifts to avoid overlapping of the points.

Fig. 3. Mean ±SE (6 replicates) weed biomass productivity. Bars associated with the same letters are not significantly different (P > 0.05) from each other across all periods. Spring refers to mid-May, and autumn to end of November.

Fig. 4. Mean ±SE (3 replicates) annual aboveground woody biomass productivity. Bars associated with the same letters are not significantly different (P > 0.05) from each other across all years.

Fig. 5. Mean ±SE (3 replicates) total aboveground woody biomass standing stock cumulated during the 3 years (a) and mortality (b) at the time before harvest in 2014. Bars associated with the same letters are not significantly different (P > 0.05) from each other.

Fig. 6. Mean ±SE (3 replicates) of Gini coefficient (a) as a metric of the final within-plot standing stock biomass inequality (inverse to uniformity) and related Lorenz asymmetry coefficient (b) describing whether inequality is due to large number of very small individuals (<1) or small number of very large individuals (>1). Bars associated with the same letters are not significantly different (P > 0.05) from each other.

8. **Tables**

Table 1

Results of the analysis of variance (p-values) of pest and weed control, species and time effects on tree height and ground-level diameter during the first three years after establishment.

	Denominator DF	Tree height	Ground-level diameter
(Intercept)	48	<.0001	<.0001
Insecticide	4	0.0006	0.0026
Herbicide	2	0.0044	0.0030
Species	16	<.0001	<.0001
Year	48	<.0001	<.0001
Insecticide × Herbicide	4	0.1873	0.0083
Insecticide × Species	16	0.0732	0.8790
Herbicide × Species	16	<.0001	<.0001
Insecticide × Year	48	<.0001	0.0040
Herbicide × Year	48	0.0046	<.0001
Species × Year	48	<.0001	<.0001
Insecticide × Herbicide × Species	16	0.2717	0.2720
Insecticide × Herbicide × Year	48	0.4354	0.2188
Insecticide × Species × Year	48	0.3493	0.8664
Herbicide × Species × Year	48	0.0125	<.0001
Insecticide × Herbicide × Species × Year	48	0.9174	0.8573

Table 2

Results of the analysis of variance (p-values) of weed control, species and time effects on aboveground weed biomass production during the first two growing seasons after establishment.

	Denominator DF	Weed biomass
(Intercept)	54	<.0001
Herbicide	2	0.0041
Species	8	<.0001
Period	24	<.0001
Herbicide × Species	8	0.0187
Herbicide × Period	24	<.0001
Species × Period	24	<.0001
Herbicide × Species × Period	24	0.5007

Table 3

Results of the analysis of variance (p-values) of pest and weed control, species and time effects on annual aboveground woody biomass production during the first three years after establishment.

	Denominator DF	Annual yield
(Intercept)	32	<.0001
Insecticide	4	<.0001
Herbicide	2	0.0025
Species	8	<.0001
Year	32	<.0001
Insecticide × Herbicide	4	<.0001
Insecticide × Species	8	<.0001
Herbicide × Species	8	0.0004
Insecticide × Year	32	0.0455
Herbicide × Year	32	<.0001
Species × Year	32	<.0001
Insecticide × Herbicide × Species	8	0.3467
Insecticide × Herbicide × Year	32	0.7680
Insecticide × Species × Year	32	0.7806
Herbicide × Species × Year	32	0.4763
Insecticide × Herbicide × Species × Year	32	0.5590

Table 4

Results of the analysis of variance (p-values) of pest and weed control and species effects on cumulative aboveground woody biomass production and stool mortality at the end of the first rotation cycle three years after establishment.

	Denominator DF	Standing stock	Mortality
(Intercept)	16	<.0001	<.0001
Insecticide	4	0.0002	0.9474
Herbicide	2	0.0220	0.5950
Species	16	<.0001	<.0001
Insecticide × Herbicide	4	0.5050	0.4424
Insecticide × Species	16	0.0042	0.0368
Herbicide × Species	16	<.0001	0.3667
Insecticide × Herbicide × Species	16	0.3840	0.6879

Table 5

Results of the analysis of variance (p-values) of pest and weed control and species effects on stand uniformity described by Gini and Lorenz asymmetry coefficients at the end of the first rotation cycle three years after establishment.

	Denominator DF	Gini coefficient	Lorenz asymmetry coefficient
(Intercept)	16	<.0001	<.0001
Insecticide	4	0.0180	0.4677
Herbicide	2	0.0493	0.0805
Species	16	<.0001	0.0028
Insecticide × Herbicide	4	0.1123	0.8680
Insecticide × Species	16	0.2231	0.0983
Herbicide × Species	16	<.0001	0.1284
Insecticide × Herbicide × Species	16	0.8177	0.4915

Appendix A

The tree heights, H (m), during 2013 and 2014 were estimated using following *in-situ* parameterized species-specific allometric equations:

$$H_{NM6} = -55.47 \times 10^{-5} \times DBH^2 + 14.81 \times 10^{-2} \times DBH + 0.99 \quad (R^2 = 0.92,\ n = 36), \quad \text{Eq. (A.1)}$$

$$H_{Sycamore} = -43.59 \times 10^{-5} \times DBH^2 + 12.03 \times 10^{-2} \times DBH + 1.07 \quad (R^2 = 0.96,\ n = 36), \quad \text{Eq. (A.2)}$$

$$H_{Tuliptree} = -20.91 \times 10^{-5} \times DBH^2 + 79.98 \times 10^{-3} \times DBH + 1.03 \quad (R^2 = 0.97,\ n = 36), \quad \text{Eq. (A.3)}$$

where DBH is the diameter at the breast height (mm).

The allometric equations for estimate of AWB (kg of dry matter) parameterized in this study were as follows:

$$AWB_{NM6} = 39.16 \times 10^{-5} \times DBH^{2.3191} \quad (R^2 = 0.99,\ n = 36), \quad \text{Eq. (A.4)}$$

$$AWB_{Sycamore} = 78.34 \times 10^{-5} \times DBH^{2.2227} \quad (R^2 = 0.97,\ n = 36), \quad \text{Eq. (A.5)}$$

$$AWB_{Tuliptree} = 67.59 \times 10^{-6} \times DBH^{2.7324} \quad (R^2 = 0.98,\ n = 36), \quad \text{Eq. (A.6)}$$

$$AWB_{NM6} = 10.64 \times 10^{-7} \times GLD^{3.6785} \quad (R^2 = 0.96,\ n = 36), \quad \text{Eq. (A.7)}$$

$$AWB_{Sycamore} = 16.52 \times 10^{-6} \times GLD^{3.01} \quad (R^2 = 0.97,\ n = 36), \quad \text{Eq. (A.8)}$$

$$AWB_{Tuliptree} = 85.75 \times 10^{-8} \times GLD^{3.5937} \quad (R^2 = 0.95,\ n = 36), \quad \text{Eq. (A.9)}$$

where GLD is the ground level (10 cm above the ground) diameter (mm).

Figure 1
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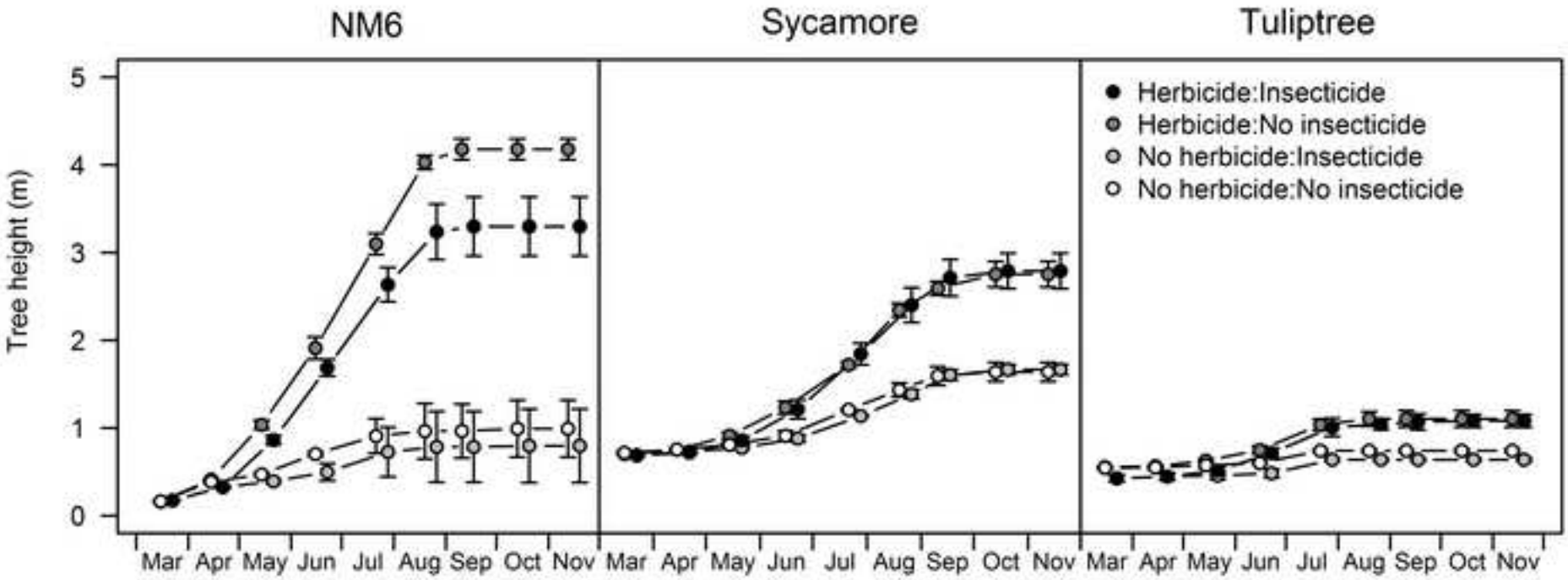

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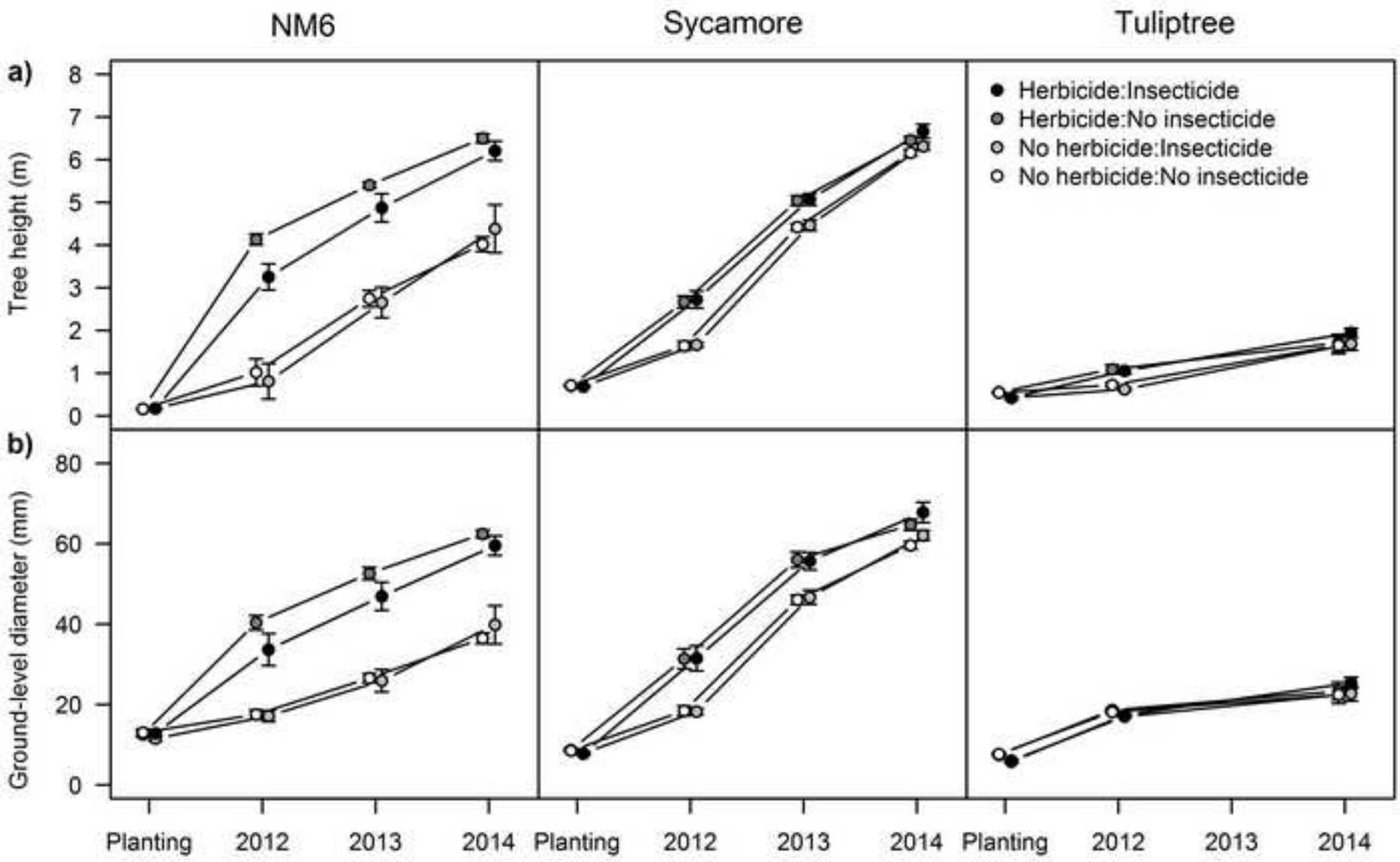

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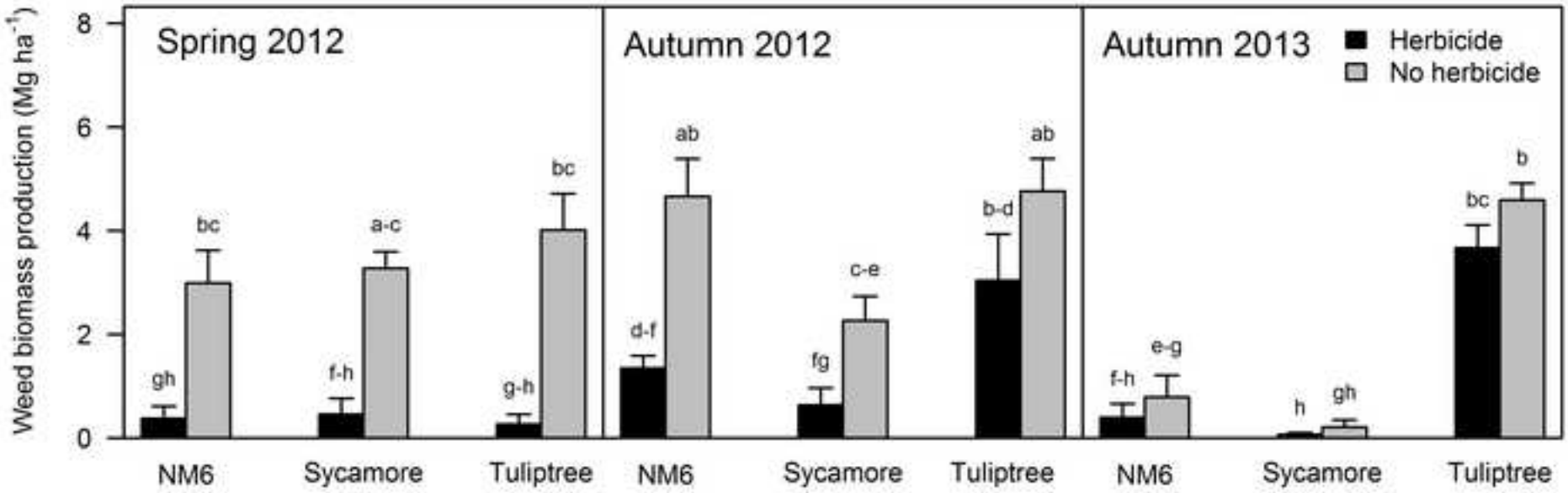

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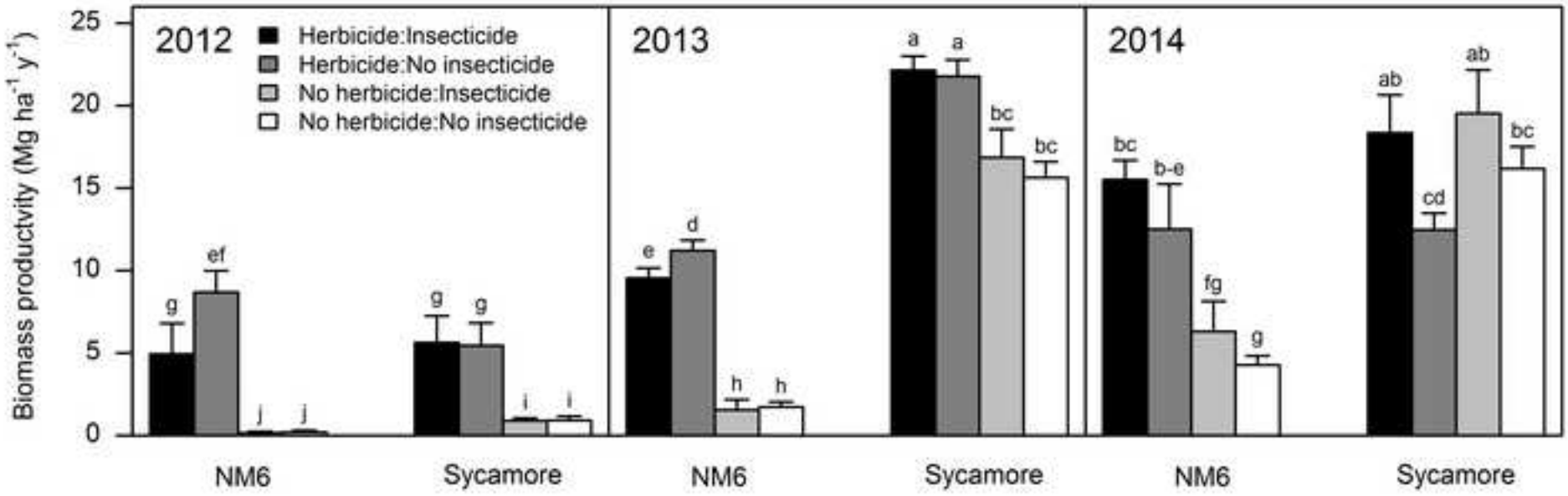

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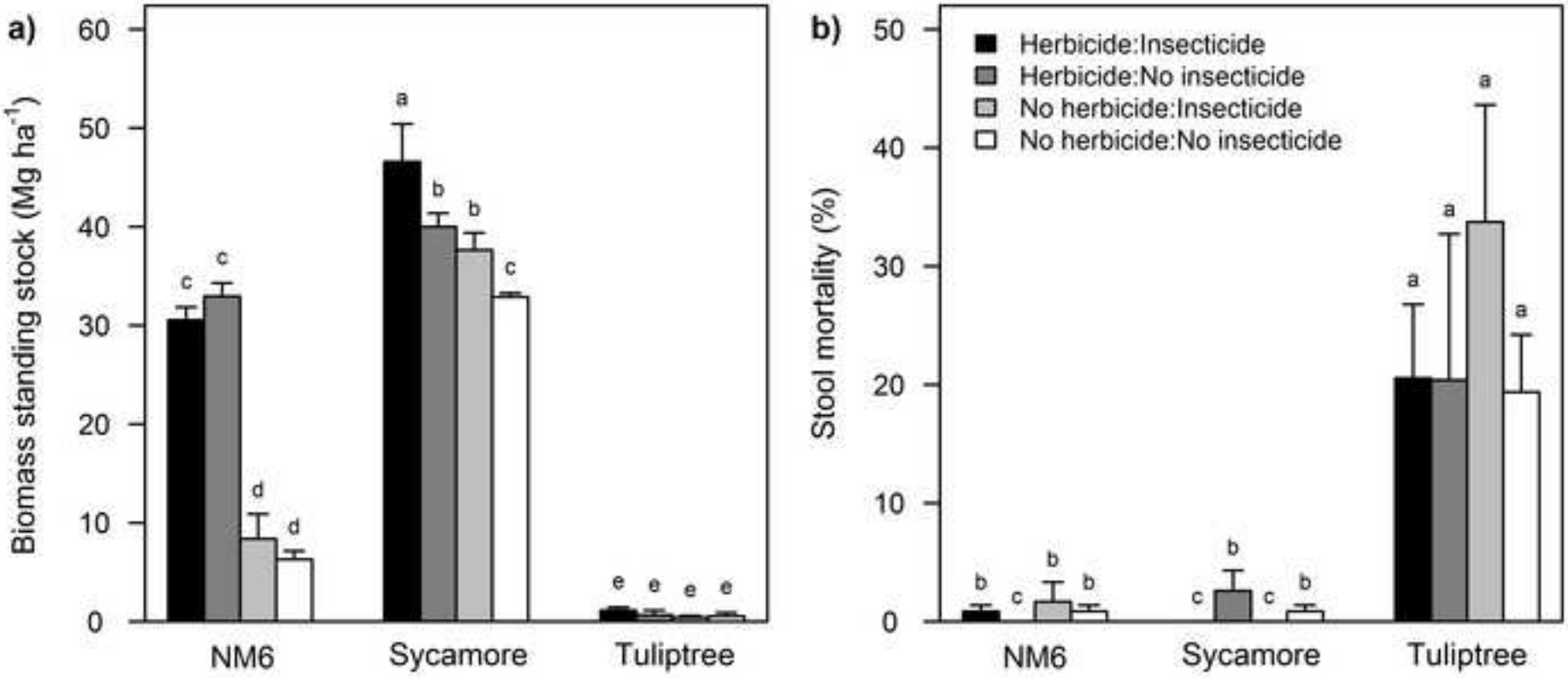
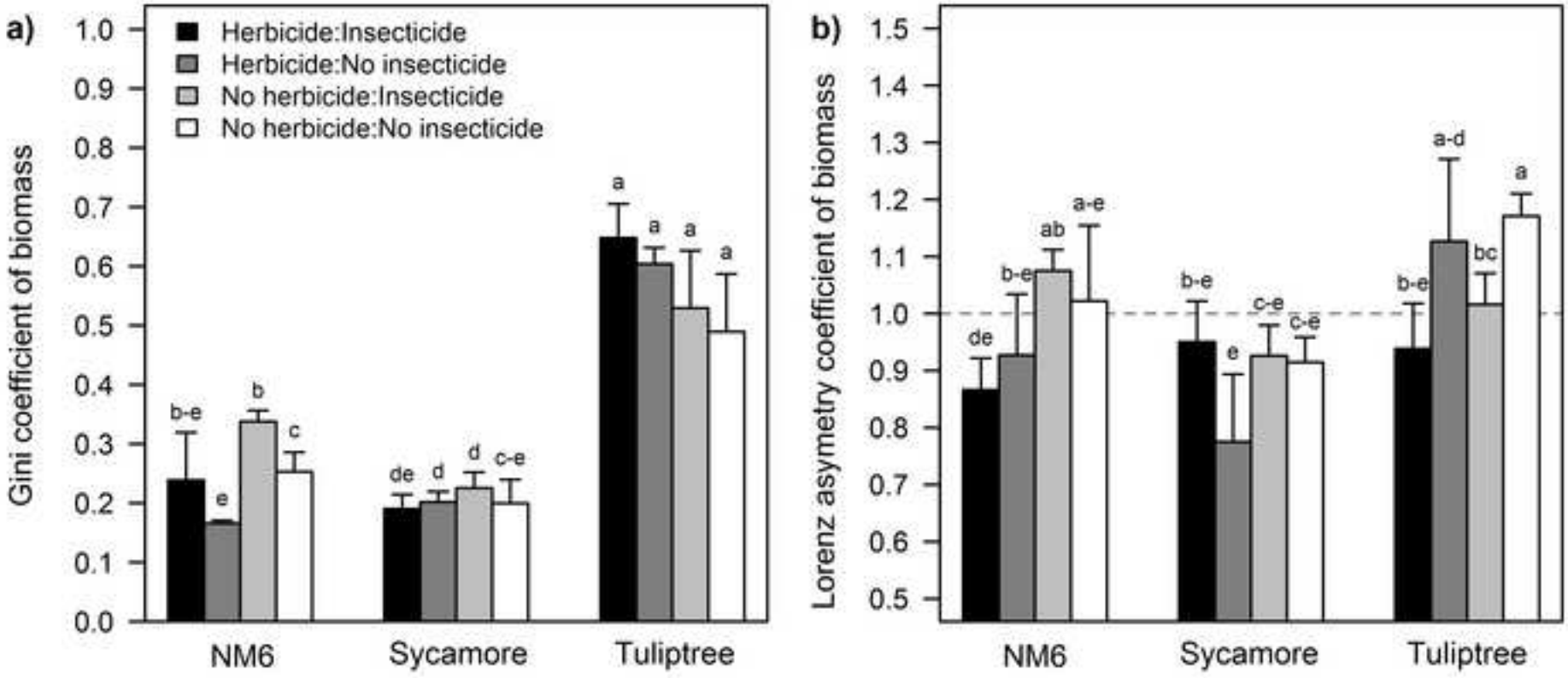
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