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Growth Rates of Giant Miscanthus (*Miscanthus* × *giganteus*) and Giant Reed (*Arundo donax*) in a Low-Input System in Arkansas, USA

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Abstract

The US Department of Energy is currently building strategies for the expansion of clean and renewable energy sources, and tall, rapidly-growing grasses such as giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax*) are two of the many of species that could fill this renewable energy niche. The objective was to compare stalk growth components of giant miscanthus and giant reed, in a low-input system (no irrigation and no fertilizer use) in Arkansas, USA. Due to the potential invasiveness of giant reed, our study was conducted on an upland site to minimize escape. Plant height and dry weight per stalk were measured every week for two consecutive growing seasons in 2012 and 2013. Leaf area index (LAI) was measured every two weeks from May to September in 2012. A significant species × day interaction occurred for plant height and dry weight per stalk, due to the relatively greater height and weight of giant reed compared to giant miscanthus after May. Stalk elongation rate was greater for giant reed than giant miscanthus (1.85 and 1.11 cm day^{-1}, respectively). Leaf area index differed between species, giant reed (10.4 m^2 m^{-2}) > giant miscanthus (4.4 m^2 m^{-2}). We showed that giant reed produced taller, heavier stalks, and had a greater stalk elongation rate, compared to giant miscanthus. For sustainable bioenergy production from giant reed in Arkansas, further studies should be performed to determine ideal number of harvests per year and associated production cost.

Keywords

Miscanthus × *giganteus*, *Arundo donax*, Growth, Stalk Elongation Rate, Dry Weight per Stalk

1. Introduction

In the US alone, total transport fuel consumption is 195 billion gallons per year, with fossil fuels contributing nearly 93% of the total [1]. Carbon dioxide released from the combustion of fossil fuels in turn increases atmospheric CO_2, and the associated rise in atmospheric CO_2 has contributed to the increase in global temperature [2]. The CO_2 produced by combustion of biofuels, however is partially compensated by CO_2 fixed during plant growth [3] [4]. Therefore, replacing fossil fuels with biofuels could mitigate global temperature increases.

Maize is a major source of biofuel in the US and globally [5] [6]. In recent years the focus has shifted toward using prairie grasses instead of maize because total maize grain produced in US per year can meet only 12% of the biofuel demand, and maize requires intensive fertilization, resulting in a small net positive carbon balance [7].

Giant miscanthus (*Miscanthus* × *giganteus* Greef & Deuter ex Hodkinson & Renvoize) is a rhizomatous C_4 perennial grass [8] [9] which requires little fertilizer and pesticides [10], is capable to grow under a variety of environmental conditions, and has high nitrogen-use efficiency [11] [12]. It requires little soil management and use of fossil fuels during establishment, and reduces soil erosion once established [13]. In addition to rhizome propagation, micropropagation is possible; thus, large numbers of plants can be rapidly produced in a short time [14]. The mature plant can grow up to 4 m-tall with roots penetrating to 1.8 m [15]. If giant miscanthus was grown on 9.3% of current US cropland, it could provide 20% of current gasoline needs [6].

Giant reed (*Arundo donax* L.) is able to grow in a range of soils [16], becomes drought tolerant after one year of establishment [16], and can survive in saline and metal-contaminated soils [17] [18]. Its vegetative growth potential and propagation efficacy make giant reed a highly-competitive plant [16]. Furthermore, giant reed stems and leaves contain phytochemicals that protect the plant from insect and animal predation [19]. A sterile triploid, giant reed propagates by agamic reproduction through rhizomes, shoots, and stem nodes [20]. A single rhizome can form a dense bunch of stems and eventually propagate across a large land area [16]. Under optimal conditions, rhizomes can grow up to 50 cm and fibrous roots can penetrate to 5 m soil depth [21]. Giant reed can attain a height of 8 m, growing at a rate of 4 - 7 cm day^{-1} [17]. Although giant reed has C_3 physiology, its photosynthetic potential is comparable to that of a C_4 species [22]. Giant reed is capable of producing high net energy yields [8].

Studies have shown that fraction of intercepted photosynthetically active radiation (FIPAR) absorbed by photosynthesizing tissue can be used to estimate vegetative productivity and yield in the absence of destructive sampling technique or harvest data [23]. The FIPAR provides information about the effectiveness with which a plant intercepts light and can be used to calculate the leaf area index (LAI) using Beer's law without direct measurement of leaf area [24] [25] [26] [27] [28].

Giant miscanthus and giant reed both have a high stalk elongation rate and biomass yield from low inputs [16], and can be used as biofuels by direct combustion, anaerobic digestion, or alcoholic fermentation [29] [30]. Stalk elongation rate of giant miscanthus and giant reed varies depending on water table, temperature, photoperiod, and soil nutrient status [8] [31]. The aim of this study was to compare stalk elongation rate and dry weight per stalk of giant miscanthus and giant reed under a low-input system in Arkansas, USA.

2. Materials and Methods

2.1. Site Description

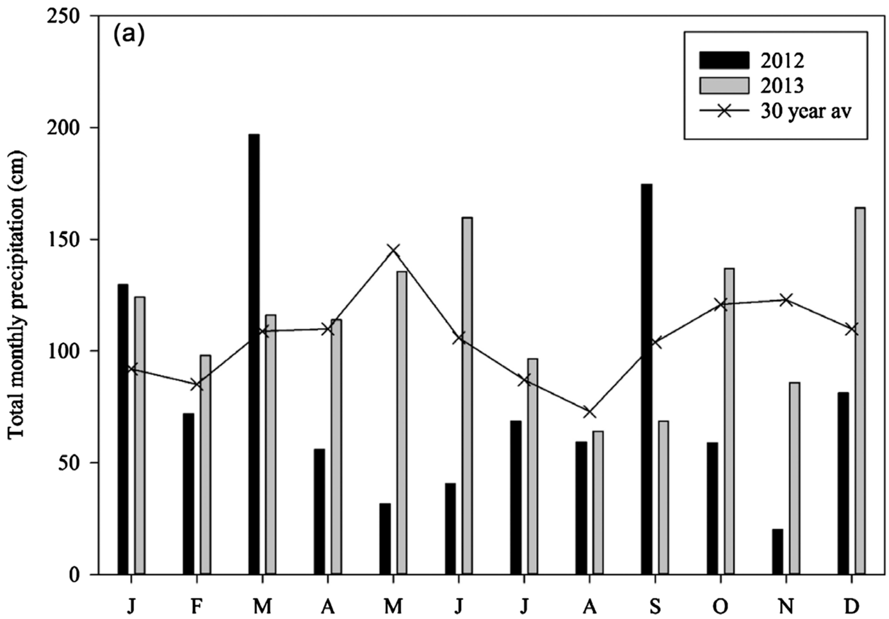
This study was conducted near Booneville, Arkansas (35.08˚N, 93.98˚W). The soil at the experimental site was a Leadvale silt loam (fine-silty, siliceous, semiactive, thermic Typic Fragiudults), with water movement and plant rooting limited by a fragipan at a depth of 0.15 to 1.0 m [32]. During late winter and early spring, the fragipan layer severely restricts water movement in the soil profile, and a perched water table is common at a depth of 61 to 91 cm or more [32]. The site received 99 cm rainfall in 2012 and 135 cm in 2013, with the 30-year (1981 to 2010) mean annual precipitation of 127 cm (**Figure 1(a)**) [33]. Mean annual temperatures in 2012 and 2013 were 18.2˚C and 15.6˚C, respectively. The 30-year mean annual temperature was 15.5˚C, with a winter minimum of 10.6˚C and summer maximum of 32.3˚C (**Figure 1(b)**) [33].

2.2. Plant Establishment

Giant miscanthus rhizomes (proprietary clone Q42641, Biomass Industrial Crops, Ltd., Somerset, UK) and axillary internode buds of giant reed (obtained from a riparian area along the Little River near Temple, Texas) were transplanted to a greenhouse in fall 2006. Tubs containing rhizomes (giant miscanthus) or axillary internode buds (giant reed) were placed in a temperature-controlled greenhouse (22˚C - 27˚C) under natural light (12 - 14 h daylight per day). Detailed information on these origins of the plant material can be found in previous publications [34] [35] [36]. In March 2007, greenhouse clones of 5 clones per species were planted in a split-plot arrangement with four replicates. In each split-plot five clones of one of the two species were arranged in single row at 1 m spacing. Rows of split-plots were spaced at 2.5 m. To ensure successful establishment, plots were irrigated occasionally during the first two years (2006 and 2007), but were not irrigated thereafter. Each spring, prior to regrowth, plants were cut to a 15 cm stubble height. Chemical weed suppressors, fertilizer, and soil amendments were not applied during the entire study period.

2.3. Measurement of Plant Height and Biomass Yield

Plant height and dry weight per stalk were measured every week from March through September in 2012 and 2013. A 0.3 m × 0.3 m PVC pipe frame was permanently placed in each plot to mark plot locations. In each split-plot there



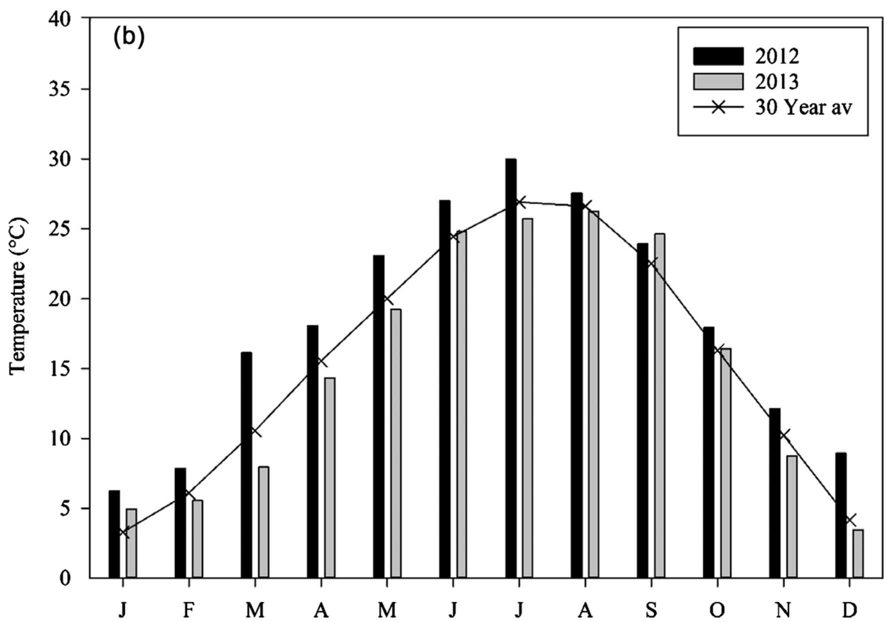


Figure 1. (a) Total monthly precipitation and (b) mean monthly temperature in Booneville, AR in 2012 and 2013. Total monthly precipitation and temperature (1981-2010) were obtained from NOAA (2010).

were five plants per PVC frame, and four replicates per species. Four individual stalks within each frame were tagged and labeled for repeated measurements of height. Plant height was initially measured using a meter stick, then two meter sticks, and then a tree measurement pole. To assess dry weight per stalk, 4 plants were cut at 15 cm stubble height from similarly-sized stalks adjacent to the repeatedly measured stalks, but not so close as to affect growth of the plants being measured for height. One plant per plot with a total of four replicates per treatment were sampled. Stalks were cut into small sections, dried in a forced-air draft oven at 60˚C for 48 h, and weighed to determine dry mass.

2.4. Calculation of Leaf Area Index (LAI)

Photosynthetic active radiation (PAR) was measured with a 0.8 m long Sunfleck Ceptometer PAR light bar sensor (Decagon Devices Inc., Pullman, WA) twice per month from May through September in 2012. Changes in personnel prevented us from conducting measurements in 2013. In each plot, five measurements of PAR were taken below the canopy and five above, between 11 a.m. and 1 p.m. local time. The fraction of incident PAR intercepted by the canopy (FIPAR) was calculated by subtracting the ratio of PAR below the canopy to that above the canopy from 1.0 [37]. We used Beer's law [24] to calculate LAI according to the formula:

$$\text{LAI} = \left[\ln\left(1 - \text{FIPAR}\right)\right] / k,$$

where k is the light extinction coefficient. The value of k was assumed to be constant over the growing period [38], and k = 0.6 for giant miscanthus [10] [39] [40] [41] and k = 0.29 for giant reed [42] [43].

2.5. Statistical Analysis

The experimental design was a randomized complete block design with four blocks per treatment. Treatments were grass species and sampling day. Species, day, and the species × day interaction were considered fixed effects, and year and replication were considered random effects. Analysis of variance was conducted using the PROC MIXED procedure of SAS [44]. Residuals were normally-distributed using the Shapiro-Wilk test- and homogeneity of variance was confirmed using Levene's F-test. When mean squares were significant ($P \leq 0.05$), pairwise post-hoc comparisons of the least square means were conducted using LSD ($P \leq 0.05$). Means separations were performed by the SAS macro "pdmix800" [45] with Fisher's Type-1 error rate of 5%.

3. Results

3.1. Plant Height and Dry Weight per Stalk

Plant height was significantly ($P < 0.0001$; **Table 1**) affected by the species × day interaction which was due to the greater height of giant reed than giant miscanthus after May (**Figure 2**). Before May, height of both species was similar ($P >$ 0.05); however, after May giant reed was taller compared with giant miscanthus and remained taller till the end of the study in September ($P < 0.0001$). Giant miscanthus and giant reed had mean plant heights of 223 and 358 cm, respectively, in August (**Figure 2**). Dry weight also was significantly ($P < 0.001$) affected by the species × day interaction, which was due to the greater weight of giant reed than giant miscanthus after May (**Figure 3**). The greatest dry weight per stalk for giant miscanthus and giant reed was observed in August, when measurements were 36.3 and 192.5 g, respectively.

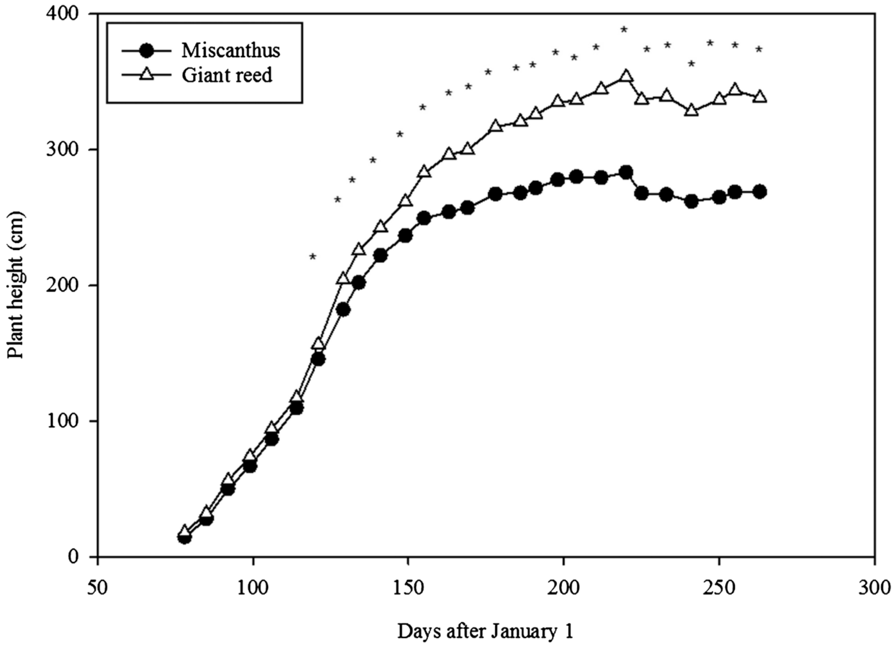


Figure 2. Effect of species [giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax* L.)] on plant height measured weekly during the growing season in 2012 and 2013 in Booneville, Arkansas, USA. Asterisks above the sampled day indicate significant differences in plant height between species (Post hoc test; $P < 0.05$).

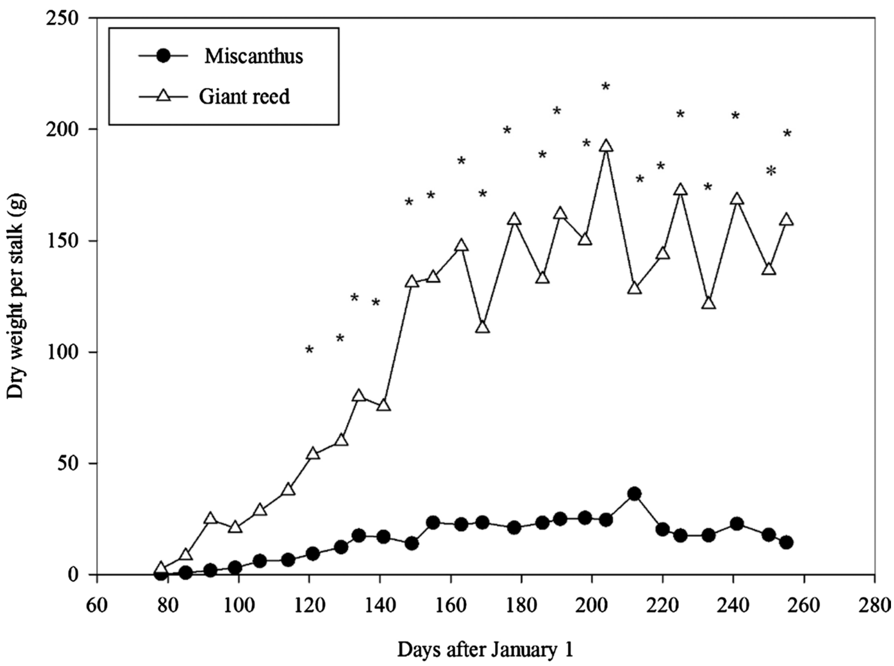


Figure 3. Effect of species [giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax* L.)] on dry weight per stalk measured weekly during the growing season in 2012 and 2013 in Booneville, Arkansas, USA. Asterisks above the sampled day indicate significant differences in dry weight per stalk between species (Post-hoc test; $P < 0.05$).

3.2. Stalk Elongation Rate

Stalk elongation rate had significant species and day responses ($P \leq 0.004$; Table

1; Figure 4), but the species × day interaction was not significant (P = 0.74). Stalk elongation rate was greater for giant reed than giant miscanthus (1.85 and 1.11 cm day^{-1} respectively; P = 0.003).

Table 1. Analysis of variance results for giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax* L.) sampled weekly during the growing season in 2012 and 2013 in Booneville, AR.

Fixed effect	Fixed effect	Num DF	Den DF	F Value	*Pr* > F
Plant height	Species	1	1442	2209.56	<0.0001
	Day	26	1442	462.62	<0.0001
	Species × day	26	1442	34.01	<0.0001
Stalk elongation rate	Species	1	39	9.40	<0.0039
	Day	25	39	7.62	<0.0001
	Species × day	25	39	0.78	0.7443
Dry weight per stalk	Species	1	317	926.62	<0.0001
	Day	25	317	21.50	<0.0001
	Species × day	25	317	12.50	<0.0001
Leaf area index[a]	Species	1	51	175.88	<0.0001
	Day	8	51	2.49	0.0229
	Species × day	8	51	1.28	0.2748

[a]Leaf area index was measured every two weeks from May to September in 2012.

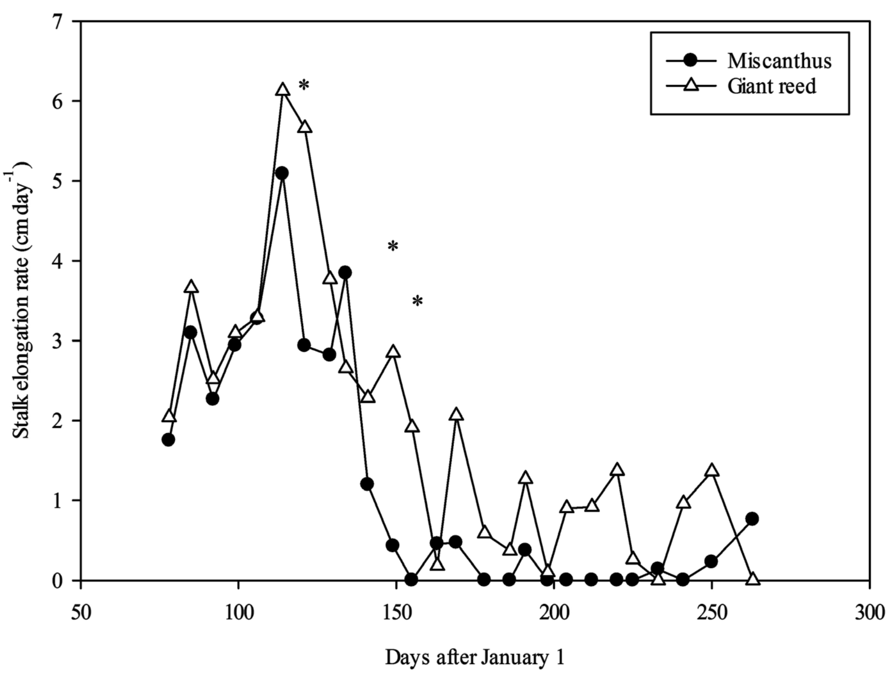


Figure 4. Effect of species [giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax* L.)] on growth rate per day measured weekly during the growing season in 2012 and 2013 in Booneville, Arkansas, USA. Asterisks above the sampled day indicate significant differences in stalk elongation rate between species (Post-hoc test; $P < 0.05$).

3.3. Leaf Area Index

The species × day interaction was not significant for LAI ($P = 0.27$; **Figure 5**), and LAI was greater for giant reed than giant miscanthus at any sampling day. Species means were 4.4 and 10.4 $m^2 m^{-2}$ for giant miscanthus and giant reed, respectively (data not shown).

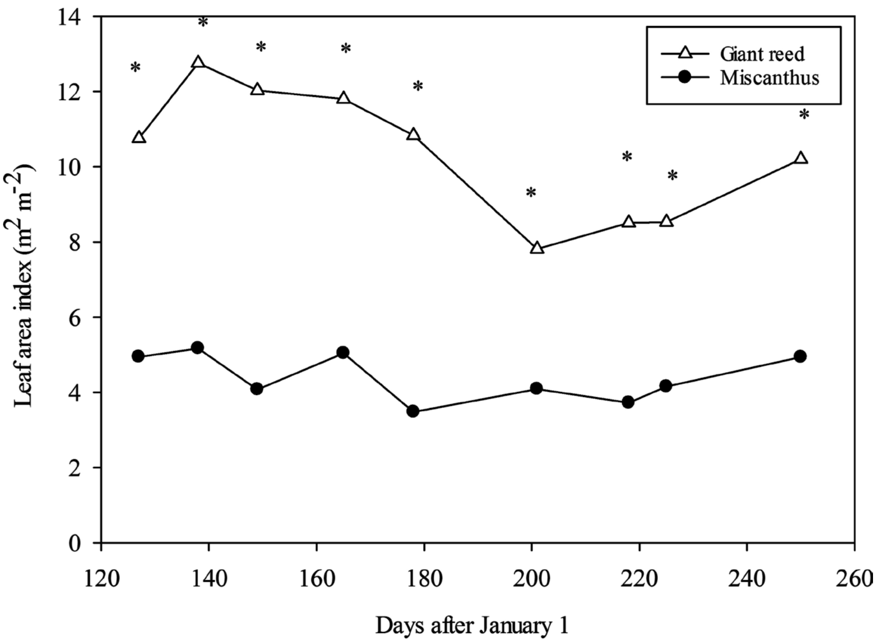


Figure 5. Effect of species [giant miscanthus (*Miscanthus* × *giganteus*) and giant reed (*Arundo donax* L.)] on leaf area index measured every two weeks from May to September in 2012 in Booneville, Arkansas, USA. Asterisks above the sampled day indicate significant differences in leaf area index between species (Post-hoc test; $P < 0.05$).

4. Discussion

In the current study, both giant miscanthus and giant reed grew relatively well under this low-input system. Giant reed was taller, had greater dry weight per stalk, stalk elongation rate, and LAI than giant miscanthus. Consistent with our study, Angelini *et al.* [8] also reported that giant miscanthus was shorter than giant reed central Italy. However, plant heights of giant miscanthus and giant reed measured in our study were shorter than in central Italy [8]. Site differences in water availability, fertilization, weed control, solar radiation, and air and soil temperatures, and clonal differences, could have caused location differences [8]. A previous, more intensively-managed study of these plants showed that mean heights of giant miscanthus and giant reed were 230 and 410 cm, respectively [35], which are comparable to plant heights in the present study and in other studies conducted in Europe and USA [46] [47]. Nitrogen fertilization and irrigation alone had no effect on aboveground biomass production [12] [35] [48] [49], but N fertilization with irrigation increased total biomass production of giant miscanthus [8] [50] [51]. For giant reed, application of N alone [52] or N and irrigation increased production [53]. In contrast to our study, research on a coastal area of Italy characterized by high solar radiation and nutrient rich soils with a shallow water table showed that giant miscanthus was taller and had greater dry weight per stem than giant reed [31].

Dry weight per stalk of giant miscanthus and giant reed were similar until the first week of April, quite early in the growing season, after which giant reed was heavier throughout the study period. Similar results were reported from our previous study, and in an Italian study [8] [35]. Rhizomes of giant miscanthus are impacted by drought condition more than giant reed, but adequate soil moisture is needed by both species during establishment [54]. We showed previously that irrigation increased dry matter yield of plant-cane and first ratoon crops of giant reed, but did not affect giant miscanthus [35]. Irrigation did not significantly affect second ratoon yields of either species [36]. After establishment, giant miscanthus roots can penetrate to 3 m-depth in alluvial soil [55]. Normal growth is achieved with rainfall > 5 cm mo^{-1} during summer, and adequate soil nutrient availability [8].

Stalk elongation rate of giant miscanthus and giant reed is affected by soil nutrient status, solar radiation, fertilization, and soil moisture [56] [57] [58]. Giant miscanthus grew at a rate of 2 cm day^{-1} during July, reaching only 120 cm-height, due to the short summers at a northern site in Lithuania [55]. In a Mediterranean climate, giant miscanthus can grow at a rate of 3.5 cm day^{-1} for two months reaching 334 cm by November [31]. In another Mediterranean study [56], giant reed had a maximum stalk elongation rate of 2 - 3 cm day^{-1} in June, with plants reaching 250 - 300 cm by September. In California, the stalk elongation rate of giant reed was 6.25 cm day^{-1} for the first 40 days of growth, 2.3 cm day^{-1} for the first 150 days, and plants ultimately attained a height of 400 cm [54]. Giant reed can potentially grow at 4.2 - 10 cm day^{-1} under ideal conditions achieve a plant height of 500 cm [17].

Leaf area index is the fundamental factor driving plant growth as it critically influences the amount of light intercepted [59]. At the time of measurement initiation in May, giant miscanthus and giant reed had already reached maximum or near maximum LAI. Giant reed LAI in this study was within the range reported for plants grown in a semi-arid Mediterranean environment during June but greater than that reported a Mediterranean coastal area [31] [53]. We found that LAI of giant miscanthus was lower than that reported in a Mediterranean coastal area in Greece and in Italy, which could be due to shorter height of giant miscanthus in the current study [31] [60]. Nitrogen fertilization and irrigation resulted in greater LAI and increased aboveground biomass production in giant reed and giant miscanthus [51] [53]. In our study, neither irrigation nor fertilizer were applied, which likely decreased maximum LAI of giant miscanthus. Interestingly, LAI of giant reed was greater than that reported by Cosentino *et al.* [53] despite our low input practice.

5. Conclusion

Giant reed was taller, and had greater dry weight per stalk, stalk elongation rate and LAI than giant miscanthus. In this minimal input practice with summer rainfall ≥ 5 cm per month and no additional input of fertilizers and herbicide, giant reed grew to 358 cm and produced stalk dry weights of 192 g per stalk with a production cycle of at least 7 years. Growth and yield of both species need to be studied across a range of sites and management inputs before either is recommended for on-farm production.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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