agronomy

MDPI

Article

Preliminary Results on the Effects of Initial Stand Density and Supplemental Irrigation on Biomass of *Eucalyptus camaldulensis* Dehn. Grown as a Short Rotation Woody Crop under Semi-Arid Conditions

Yiftach Vaknin * and Leonid Korol

Department of Natural Resources, Institute of Plant Sciences, Agricultural Research Organization, The Volcani Center, HaMaccabim Road 68, P.O. Box 15159, Rishon LeZion 7505101, Israel; vckorol@volcani.agri.gov.il
* Correspondence: yiftachv@volcani.agri.gov.il; Tel.: +972-3-9683486

Abstract: Most short rotation coppice (SRC) plantations are grown in temperate, subtropical, and tropical areas where land availability is limited. Very little is known about the potential biomass yield of *Eucalyptus camaldulensis* grown as SRC under semi-arid conditions with supplemental irrigation. Our objective was to maximize biomass production of *E. camaldulensis* under semi-arid conditions as a feedstock for biofuels by optimizing initial stem density (ISD) and irrigation amount. We tested the effects of four densities of 2500, 10,000, 40,000, and 160,000 stems per hectare, and supplemental irrigation of 100% or 200% of potential evapotranspiration on tree growth and biomass production. Our results showed that under semi-arid conditions and supplemental irrigation, trees grew rapidly and accumulated biomass at a rate equal to or exceeding that in tropical regions. As ISD increased, individual trees grew slightly taller, became much narrower, and had fewer stems. We concluded that competition for resources such as light and nutrients increased with ISD, resulting in significantly lower biomass accumulation by individual trees. However, the significantly greater number of individuals with increasing ISD was responsible for the higher biomass production per hectare, allowing us to achieve exceptionally high annual yields of eucalypt biomass under semi-arid conditions after three annual coppicing cycles.

Keywords: biomass production; *Eucalyptus camaldulensis*; initial stem density; semi-arid conditions; short rotation coppice

check for updates

Citation: Vaknin, Y.; Korol, L. Preliminary Results on the Effects of Initial Stand Density and Supplemental Irrigation on Biomass of *Eucalyptus camaldulensis* Dehn. Grown as a Short Rotation Woody Crop under Semi-Arid Conditions. *Agronomy* **2023**, *13*, 1216. https://doi.org/10.3390/agronomy13051216

Academic Editor: Pierluigi Paris

Received: 22 March 2023
Revised: 16 April 2023
Accepted: 23 April 2023
Published: 25 April 2023

1. Introduction

The world is actively seeking ways to harness the energy of plants as feedstock for biofuels. First-generation biofuels are based on commercially available feedstocks, most of which are edible and fiber-based, the supply of which is limited. More advanced biofuels address the sustainability issues of conventional biofuels by using biomass such as lignocellulose from agricultural and forestry wastes, municipal organic waste, perennial grasses, and short rotation coppice on marginal, non-arable land. The conversion of these biomass resources into biofuels is currently being developed and demonstrated in small-scale operating plants as well as large-scale plants being built or planned around the world.

Growing dedicated energy crops such as short rotation coppice (SRC) on marginal and degraded land would provide a sustainable biomass source for biofuel production without directly competing with food and fiber production. However, globally, most SRC is grown in temperate, sub-tropical, and tropical areas, which have limited availability and often require the clearing of large regions of pristine natural forests to obtain land for biomass production [1]. At the same time, semi-arid and arid regions around the world are expanding rapidly due to global warming and are potentially available for biomass production [2]. In 2021, according to the International Energy Agency, global demand for biofuels is projected to grow by 28% over the period of 2021–2026 [3]. However, depending on the availability of agricultural and forestry residues, food production, and dedicated crops, the area used for energy crops could increase from 30 million ha in 2013 to 100–160 million ha in 2050. The highest annual biomass yields worldwide come from dedicated crops, mainly perennial grasses such as switchgrass in North America (5–38 Mg d.m. $ha^{-1}y^{-1}$; [4–6]) and fast-growing trees such as poplar and Salix in Europe and North America (3–19 Mg d.m. $ha^{-1}y^{-1}$; [7–9]) and eucalyptus species (eucalypts) in Australia, southern Europe, South Africa, and Brazil (10–42 Mg d.m. $ha^{-1}y^{-1}$; [10–13]).

Eucalyptus trees are the most widespread hardwood, with an acreage of over 19.3×10^6 hectares, and are among the fastest growing deciduous trees. Most of the literature on eucalyptus trees focuses on their use as a source of pulp for the production of high quality paper and fabric [14–16]. They account for about 8% of all productive planted forests because of their ability to grow rapidly and their tolerance of harsh environments, including characteristics such as indeterminate growth, coppicing, resistance to drought, fire, and insects, and tolerance to soil acidity and low fertility [17–19]. Eucalyptus trees are particularly well suited for biofuel production because their biomass is converted into various energy and chemical products, including gaseous and liquid fuels and electricity [20]. Thus, there is considerable interest in the potential market opportunities and environmental benefits of producing biofuels and renewable electricity from eucalyptus biomass [21]. In particular, eucalyptus has been studied as a source of charcoal for the production of "green steel" [22–24] and ethanol production after pretreatment and enzymatic hydrolysis [25–28].

Eucalyptus trees are successfully grown in tropical and subtropical regions of Asia, Australia, Africa, and South America, as well as temperate regions of Europe, South and North America, and Africa [29]. Under semi-arid and arid conditions, in Israel, there is more than 50 years of experience in research and development of Eucalyptus for biomass [30–35], as well as analyses of phenotypic and genetic variation [36,37]. Numerous morphological and genetic variations have been observed in *E. camaldulensis* worldwide [38–40]. Acclimation of *E. camaldulensis* provenances in Israel set the stage for the emergence of local putative ecotypes. In the absence of reproductive barriers, many provenances have resulted from hybridization between taxa [31,36,41], providing considerable genetic potential for selection of superior genotypes for biomass production. A previous study has shown that due to the increased water use uptake of *E. camaldulensis*, it was not suitable for planting under arid conditions without supplementary irrigation [42]. When grown in India under arid conditions, without supplementary irrigation, the maximal biomass yield of *Eucalyptus camaldulensis* trees of age six years was calculated as 22 Mg $ha^{-1}y^{-1}$ [43], which is significantly lower than recorded biomass yields under tropical conditions.

However, very little is known about the successful management and potential biomass yield of *E. camaldulensis* grown under semi-arid conditions with supplemental irrigation. The objective of this research was to maximize the production of *E. camaldulensis* biomass under semi-arid conditions as a feedstock for biofuels by optimizing cultivation technologies, including initial stem density (ISD), irrigation amount, and SRC management.

2. Materials and Methods

The effects of ISD and supplemental irrigation on tree growth and biomass production under semi-arid conditions were tested. In July 2014, *E. camaldulensis* seedlings of a locally bred superior genetic line ("ARO1") were planted at the Volcani Center research institute in Rishon-LeZion (31°59′ N, 34°49′ E). The Mediterranean climatic conditions were hot and dry summers and cool and wet winters with 524 mm annual precipitation (Israel Meteorological Service). There were no frosts during the winter months, and the low temperatures in January ranged from 1 °C to 22 °C. The experiment was conducted in mid-Israel, classified as hot-summer Mediterranean climate according to the updated Köppen–Geiger climate map [44]. Seedlings at four months of age and at a height of about 50 cm were planted in a random block design with four blocks. Each block was divided into two halves, each consisting of four random 4 × 4 m plots with four densities: 2 × 2, 1 × 1, 0.5 × 0.5, and 0.25 × 0.25 m, i.e., 2500, 10,000, 40,000, and 160,000 trees per hectare (TPH), respectively (Figure 1). Due to the high water requirements of *E. camaldulensis* [32,35], during summer and early fall, each half-block was drip irrigated (June to October) with one of two irrigation amounts: 100% or 200% of potential evapotranspiration (ETp) (Figure 1). ETp was calculated from meteorological data from a neighboring station using a modified Penman–Monteith equation [45] and multiplied by a coverage factor. Since the water requirements of trees in both irrigation treatments were fully met, we actually tested the response to excess water rather than water stress.

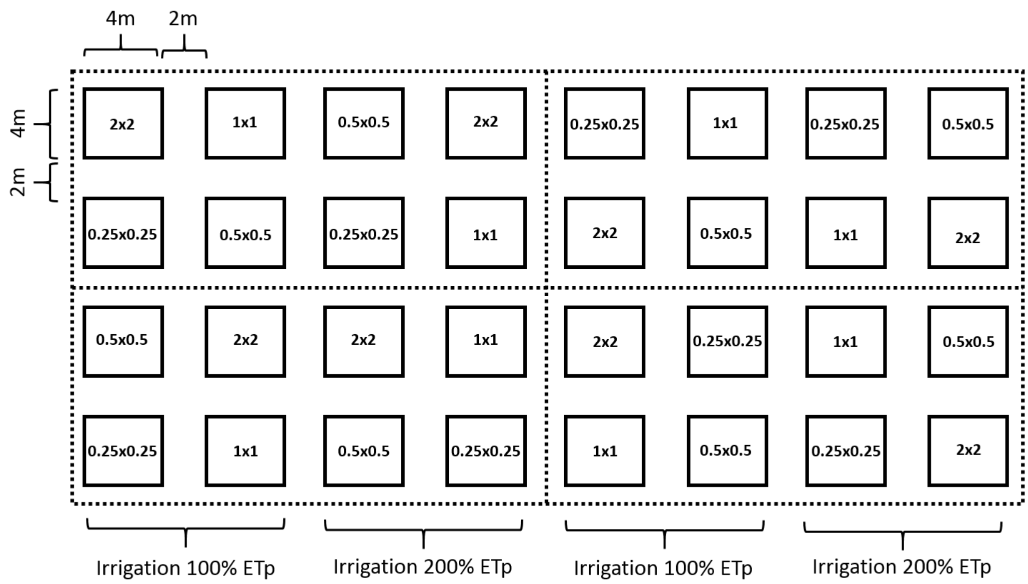

Figure 1. Experimental design with stem density (2 × 2, 1 × 1, 0.5 × 0.5, and 0.25 × 0.25 m) and irrigation amount (100% of ETp or 200% of ETp), arranged in four random blocks.

First, in each 4 × 4 plot, resources allocation to either the stem or the leaves were checked for each random tree. We randomly sampled 10-15 individual trees/stems across the diametrical classes of all 4 × 4 plots while in the peripheral ones, the trees from marginal rows were excluded from sampling. In spring 2015, immediately after first felling, the dry weight of leaves and stems was measured. In fall 2014, tree height from ground level to maximum height and stem diameter at 50 cm were measured. In winter and early spring 2015, two additional measurements were taken. Beginning in March 2015 and every 12 months through 2017, trees were cut to 50 cm and the following characteristics were measured:

(1) Tree height (cm);
(2) Stem diameter (cm) at 50 cm;
(3) Number of stems counted at 50 cm height;
(4) Dry weight (%)—measured on one random tree per 4 × 4 m plot;
(5) Dry weight per hectare—Fresh 200–500 g samples of stems and leaves were oven-dried at 60 °C for 48 h, and dry weight per hectare was calculated using average green biomass per hectare and percentage dry biomass.

A three-way analysis (ANOVA) of tree height, stem diameter, and number of stems was performed for the averages per sub-plots of three factors "density", "irrigation", and "block". Percent dry weight and total dry weight of biomass produced per hectare were calculated based on one measurement per 4 × 4 m plot. A three-way analysis (ANOVA) of percent dry weight and dry weight was also performed for three factors: "density", "irrigation", and "block". Since the lack of perimeter border trees posed a concern regarding edge effect bias, a three-way analysis (ANOVA) of dry weight per hectare was also performed for three factors: "density", "irrigation", and 4 × 4 plot location (peripheral or interior). Post hoc Tukey HSD was performed separately for each year on averages of tree height, stem diameter, number of stems per tree, tree biomass, and calculated biomass per hectare.

3. Results

3.1. Vegetative Growth and Biomass Production

3.1.1. Establishment and Acclimation (Year I)

We planted the young seedlings in the field in the summer of 2014 (July). In the first six months, the trees more than tripled in size, and their stems grew taller and wider, even during the colder winter months (January–February 2015; Figure 2). During this period, the young seedlings grew on a single stem with side branches and a canopy, and their growth rate was significantly affected by ISD.

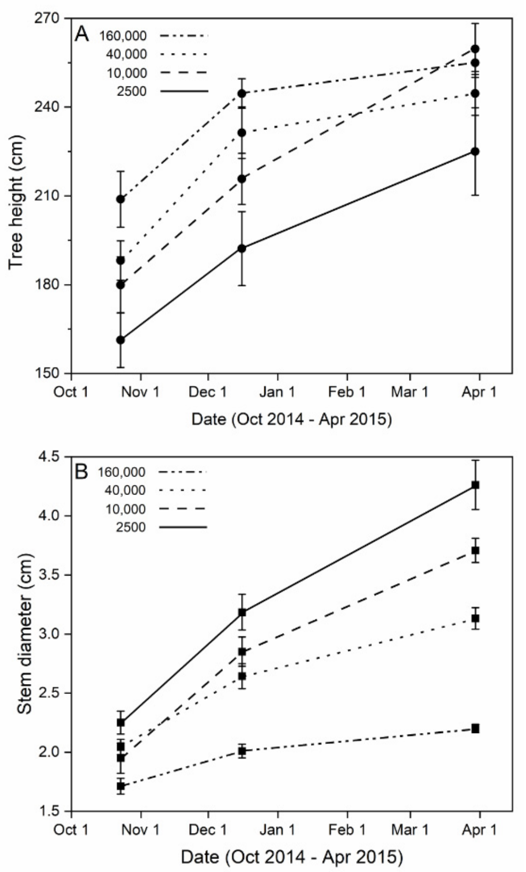

Figure 2. Growth rates of young seedlings measured as tree height (**A**) and stem diameter (**B**) during the winter months of the first year of acclimation and establishment. Trees were planted at four ISD levels: 2500, 10,000, 40,000, and 160,000 TPH.

Tree height measurements in October 2014, just before the first felling, were positively associated with ISD, with the tallest trees at the highest density (160,000 TPH) and the shortest at the lowest density (2500 TPH) (Figure 2A). During the winter and at all densities, trees grew relatively moderately in height, from 161 to 209 cm in fall 2014 to 225 to 260 cm in spring 2015, except at the density of 10,000 TPH, which grew significantly faster, almost identical to the rate measured in the summer.

Stem diameter measurements in October 2014 were negatively associated with ISD, with the widest stems (2.3 cm) measured at 2500 TPH and the narrowest (1.7 cm) at 160,000 TPH (Figure 2B). During winter, stems became wider at all ISDs, with a moderate growth rate measured at 160,000 TPH (2.2 cm) and progressively higher rates when ISD was reduced, from 40,000 to 10,000 and 2500 TPH, reaching 3.1, 3.7, and 4.3 cm, respectively (Figure 2B).

3.1.2. SRC Effects on Vegetative Growth and Biomass Production

Starting in March 2015, trees were felled every 12 months, and height, stem diameter, number of stems, percentage dry weight, and dry biomass were measured each time.

Tree Height

In the first year, trees at ISDs of 160,000, 40,000, and 10,000 TPH reached relatively similar heights of 255, 245, and 260 cm, respectively, whereas trees at the lowest density of 2500 TPH were slightly shorter, reaching 225 cm (Figure 3A). In the second year, trees grew much taller, reaching maximum heights of 578 to 706 cm (Figure 4). The tallest trees (706 cm) grew at the highest density of 160,000 TPH, whereas tree height was relatively similar at all other densities, ranging from 565 to 610 cm. In the third year, the tallest trees grew at density 40,000 TPH to 692 cm, while tree height was relatively similar at all other densities, ranging from 627 to 648 cm (Figure 3A).

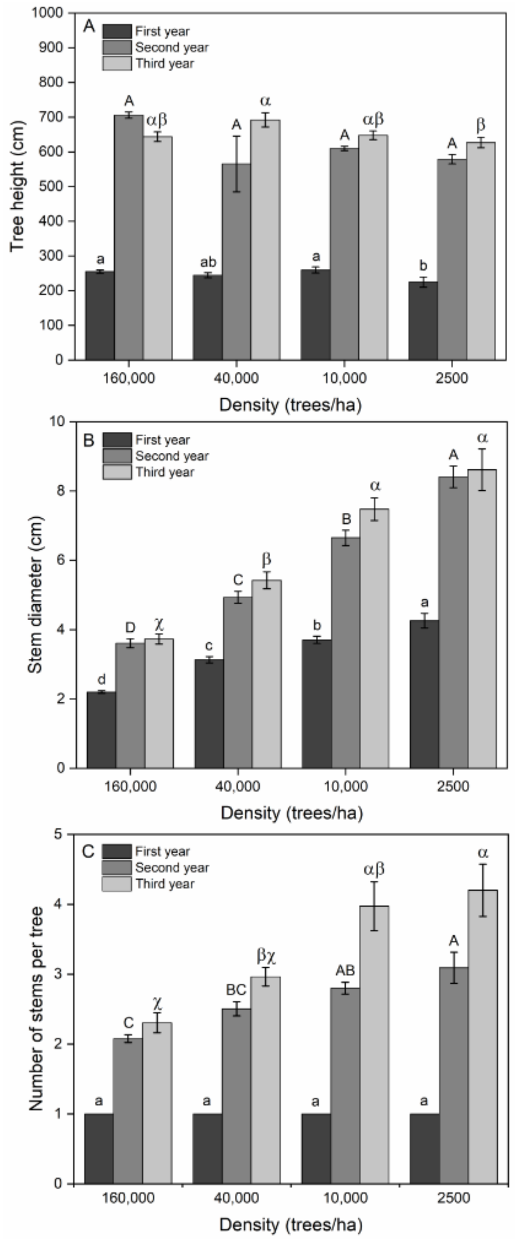

Figure 3. Effects of ISD on tree height (**A**), stem diameter (**B**), and number of stems (**C**) in the first, second, and third years after planting. Three-way ANOVA and Tukey HSD was performed separately for each year. Different letters represent statistical significance at $p < 0.05$.

Figure 4. Vegetative regrowth in the experimental plot, six months after first felling.

In the first year, tree height was non-significantly affected by ISD ($p = 0.0818$), irrigation ($p = 0.8285$), and the block ($p = 0.1671$) (ANOVA, $F_{(10,31)} = 1.4950$, $p = 0.2096$). In the second year, tree height was non-significantly affected by ISD ($p = 0.1121$), irrigation ($p = 0.7134$), and by the block location ($p = 0.4095$) (ANOVA, $F_{(10,31)} = 1.2318$, $p = 0.3277$). In the third year, tree height was significantly affected by ISD ($p = 0.0174$) and influenced by the block location ($p = 0.0086$) (ANOVA, $F_{(10,31)} = 3.0128$, $p = 0.0159$). Our results show that tree height, although relatively similar for all ISDs, was statistically affected by ISD and block location from the second year onward.

Stem Diameter

Stem diameter was negatively correlated with ISD, showing a significant increase from the first to the second year and a smaller increase from the second to the third year for all ISDs (Figure 3B). In the first year, stem diameter was significantly affected by ISD ($p < 0.0001$) (ANOVA, $F_{(10,31)} = 15.3728$, $p < 0.0001$) (Figure 3B). Stem diameter was also significantly affected by ISD in the second year ($p < 0.0001$) (ANOVA, $F_{(10,31)} = 50.1291$, $p < 0.0001$) and influenced by the block location ($p = 0.0321$), and a significant interaction between ISD and irrigation was found ($p = 0.0053$). In the third year, stem diameter was significantly affected by ISD ($p < 0.0001$) and influenced by the block location ($p = 0.0084$) (ANOVA, $F_{(10,31)} = 23.1901$, $p < 0.0001$), and a significant interaction was found between ISD and irrigation ($p < 0.0084$), indicating a differential effect of density, as a function of irrigation.

Number of Stems per Tree

Initially, all trees grew only an elongated stem. In the second and third years, after the trees were felled for the first and second time, respectively, the number of stems per tree increased significantly with decreasing ISD (Figure 3C). Comparative analysis of densities for the second and third years showed that the number of stems produced was negatively correlated with ISD, in 2016 (3.1, 2.8, 2.5, and 2.1 stems for 160,000, 40,000, 10,000, and 2500 TPH, respectively) and 2017 (4.2, 4.0, 3.0, and 2.3 stems for 160,000, 40,000, 10,000, and 2500 TPH, respectively) (Figure 3C).

In the second year, the number of sprouting stems was significantly affected by ISD ($p < 0.0001$) and irrigation amount ($p = 0.0242$) (ANOVA, $F_{(10,31)} = 5.2443$, $p = 0.0007$) (Figure 3C). In the third year, the number of sprouting stems was significantly affected by ISD ($p < 0.0001$) (ANOVA, $F_{(10,31)} = 4.6161$, $p = 0.0015$) (Figure 3C).

Biomass Production

Stem biomass of individual trees measured at the end of the first year was significantly affected by ISD ($p = 0.0006$) (ANOVA, $F_{(22,9)} = 3.5722$, $p = 0.0265$), with biomass produced per tree higher at 2500 TPH than at all other densities (Figure 5). Leaf biomass was also significantly affected by ISD ($p = 0.0006$) (ANOVA, $F_{(22,9)} = 3.2145$, $p = 0.0371$), with biomass significantly higher at 2500 TPH than at all other densities (Figure 5). Both stem and leaf biomass of a single tree were not significantly affected by irrigation amount or block.

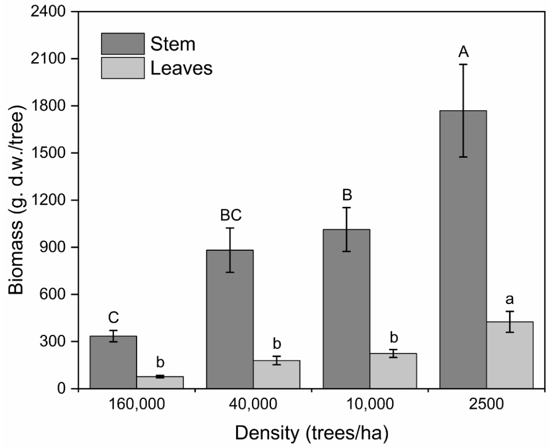

Figure 5. Effects of ISD on stem and leaf dry weight of a single tree in the first year. Three-way ANOVA and Tukey HSD was performed. Different letters represent statistical significance at $p < 0.05$.

Comparative analysis revealed that total biomass production per hectare was positively correlated with ISDs of 160,000, 40,000, 10,000, and 2500 TPH in 2015 (49,215, 39,184, 18,923, and 9745 kKg, respectively), 2016 (97,966, 92,142, 69,077 and 52,7049 kKg, respectively), and in 2017 (99,821, 95,191, 76,074 and 68,349 kg, respectively) (Figure 5). In the first year, biomass production was significantly affected by ISD ($p < 0.0001$) (ANOVA, $F_{(22,9)} = 5.2113$, $p = 0.0073$), with significantly higher biomass production for 160,000, 40,000 TPH compared with 10,000 and 2500 (Figure 6). In the second year, biomass production was significantly affected by ISD ($p < 0.0001$) (ANOVA, $F_{(22,9)} = 2.8447$, $p = 0.05$), with significantly higher biomass production for 160,000 and 40,000 TPH compared to 2500. Biomass production was about double for 160,000 and 40,000 TPH compared to the first year, while it increased three-fold and five-fold for 10,000 and 2500 TPH, respectively (Figure 6). In the third year, although average biomass production increased with increasing ISD, as described above, the differences between production levels were not statistically significant (ANOVA, $F_{(22,9)} = 1.9536$, $p = 0.1498$) (Figure 6). Comparative analysis revealed that during the three years of research, total biomass production per hectare was not statistically affected by 4×4 plot location ($p = 0.7402$, 0.2290, and 0.281 in 2015, 2016, and 2017, respectively).

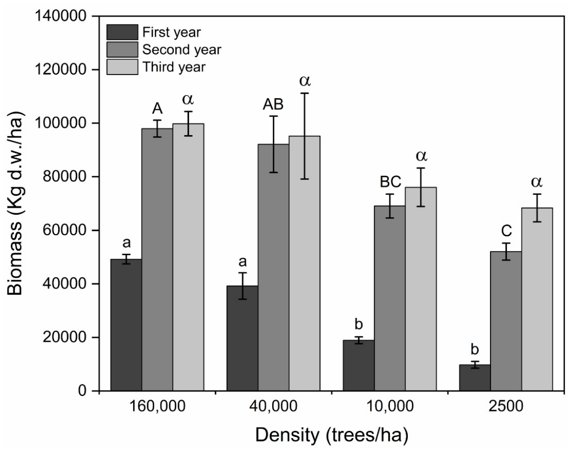

Figure 6. Effects of ISD on annual above ground biomass, including leaves, in the first, second, and third years after planting. Three-Way ANOVA and Tukey HSD were performed separately for each year. Different letters represent statistical significance at $p < 0.05$.

4. Discussion

In this study, we attempted to maximize biomass production of *E. camaldulensis* for energy purposes by altering conventional concepts of ISD, climatic region, water availability, and duration of harvesting cycles:

1. We grew *Eucalyptus* trees under Mediterranean semi-arid conditions.
2. We planted *Eucalyptus* trees at extremely high densities starting at 2500 and reaching 160,000 TPH.
3. We provided supplemental irrigation during the dry summer months.
4. We cut down the trees at extremely short rotations of once a year.

Globally, eucalyptus trees are conventionally grown for bioenergy as SRC at stem densities of 1000 to 3000 TPH, with natural precipitation as the only source of water [46]. Typical yields from SRC plantations of 10 to 24 Mg d.m. $ha^{-1}y^{-1}$ have been reported under warm temperate conditions [47–49], while biomass yields ranging from 48.7 to 53.3 Mg d.m. $ha^{-1}y^{-1}$ have been reported under tropical conditions, with the highest yields measured for the highest ISD [50]. Harvest cycles were, in most cases, at least once every three years or longer. An early study of ISD in eucalypt plantations found that understanding the forces controlling stand development was essential to maximizing the economic value of the plantation [51]. Our results were in full support of this claim.

4.1. Year I—Establishment and Acclimation

It is well known that a tree growing under low irradiance can maximize its light absorption through strong vertical growth [52] at the expense of its trunk diameter [53]. Our results also showed that the stems of the young trees became taller with increasing ISD and wider with decreasing ISD (Figure 2). In addition, as ISD increased, the total canopy area per hectare also increased; thus, more photosynthates were produced, resulting in greater biomass accumulation per hectare, as noted later in our study (Figure 6).

As is typical for most perennial plants under Mediterranean conditions, tree growth and biomass production were reduced in the first year due to the cold winter months. However, to our surprise, young trees at a low ISD of 2500 TPH, and especially at 10,000 TPH, grew almost as fast in the winter as in the summer months. This demonstrates that eucalyptus trees can maintain continuous growth and biomass accumulation under Mediterranean winter conditions.

4.2. SRC Effects on Vegetative Growth and Biomass Production

4.2.1. Tree Height

Our results showed that tree height, although relatively similar for all ISDs, was statistically affected by ISD and block location starting in the second year. Because our experimental blocks were relatively small and distributed throughout the experiment, we suspect that differences in factors such as direct irradiance and degree of shading may have played a role in our results. However, these differences were relatively small and likely the least significant in their contribution to biomass production per hectare. Similarly, in *E. globulus*, Henskens et al. [54] found that in block planting, the middle canopy and the southern side had the greatest leaf area, suggesting an importance of block location directly related to light interception.

The effect of ISD on the height of eucalyptus trees varies greatly depending on species, planting location, and growth stage [55]. Studies have shown that tree height of *E. nitens* was not affected by ISD [56]. However, in *E. urophylla* [54], *E. pilularis*, *E. grandis* [57], and *E. camaldulensis* [58] height decreased significantly with increasing ISD. This reported decrease in height with increasing ISD was explained by the increased competition for light and the resulting decreased photosynthesis of the trees [55]. However, the trees were not measured in the first year, and were exposed to water stress in addition to the increased competition for light. Furthermore, in *E. camaldulensis*, the mortality rate at 5 years of age was an incredible 80% with an ISD of 40,000 TPH [58]. In contrast, our trees received supplemental irrigation during the dry summer, and we measured tree height no later than

12 months after the stems were cut and regrowth occurred. Thus, the high ISD levels of our young trees (40,000, and 160,000 TPH) did not impede height growth as much during the rapid growth phase, until shading became the primary limiting factor.

4.2.2. Stem Diameter

In contrast to tree height, stem diameter was significantly and inversely affected by ISD, especially in the second and third years (Figure 3). This increase in stem diameter with reduced ISD is likely due to reduced competition for light, water and nutrient resources [53,56,59] and is considered the primary cause for our results. Our results showed a significant interaction between ISD and irrigation, suggesting that irrigation contributed differently to stem diameter at different ISD levels. Nevertheless, the most important factor affecting stem diameter was ISD while irrigation and block had little effect. In addition, the large increase in stem diameter in the second year and the smaller increase from the second to the third year could be related to the fact that trees transitioned from one to multiple stems after initial felling, thus, developing a significantly larger canopy. This growth pattern likely allowed trees, especially at low ISD levels, to receive more sunlight with less competition for resources, and therefore, accumulate more photosynthates, resulting in wider trunks.

4.2.3. Number of Stems per Tree

After the first felling, the number of sprouting stems was negatively associated with ISD, suggesting that trees compensated for lower competition for water and light resources by producing more stems. Alcorn et al. [53] indicated that establishing stands with higher ISD might limit the undesirable development of branches so that more energy is allocated to stems. However, the most important factor affecting the number of stems was ISD. In addition, both irrigation and block appeared to have some synergetic effect, suggesting that they should be further investigated in future experiments.

4.2.4. Biomass Production

Biomass production per hectare is the result of numerous factors, some of which have been described here previously, including tree height, stem diameter, and number of stems per tree. In our study, we found that biomass per hectare was significantly affected by ISD. As ISD increased, competition for resources such as light, water, and nutrients increased, resulting in individual trees accumulating significantly less biomass. However, the significantly greater number of individuals with increasing ISD was responsible for the higher biomass production per hectare associated with ISD, which offsets the lower biomass accumulated per individual tree. In many cases, high ISD produces the greatest stem biomass per hectare, and is the best choice in silvicultural practice [55].

Our results were supported by biomass production studies of *Eucalyptus* trees, which showed that tree height was generally insensitive to spacing. Reported increases in tree biomass with greater spacing in *E. globulus* and *E. nitens* [54,59] were driven by increased expansion of stem diameter, suggesting that stem diameter is the primary determinant of individual tree biomass.

In our study, we also tested the response to excess water rather than water stress, as water requirements were fully met in both irrigation treatments. Our results showed neither negative nor positive effects of excess water on growth and biomass accumulation. Therefore, during the long summer months, the provision of water beyond 100% replenishment of evaporation was not necessary under semi-arid conditions.

5. Conclusions

Under semi-arid conditions, with supplemental irrigation, we could reach some of the highest-ever recorded annual yields of eucalyptus biomass. Under these conditions, the trees grew extremely fast and accumulated biomass at a rate equal to or even higher than in tropical regions. We found that the most significant factor in determining biomass accumulation per hectare was ISD, with a positive correlation between ISD and biomass per hectare. Our results indicated that growing euclypts for biomass under semi-arid conditions required supplementary irigation during the long hot and dry summer months. With increasing ISD, the individual trees grew slightly taller and significantly narrower and produced less bioamss than with decreasing ISD. However, given their vast numbers in high ISDs, they collectively accumulated more biomass per hectare under low ISDs.

Because of the relatively small scale of this preliminary study, we plan to scale it up for future research, focusing on densities of 10,000 and 2500 trees per hectare, because densities of 160,000 and 40,000 trees are not economically viable and did not produce statistically higher biomass yields in the third year. However, we plan to add fertilizer to the soil to replenish the nitrogen removed by the small stems, having a high bark to wood ratio, thus removing important plant nutrients from the soil [60].

Author Contributions: Conceptualization, Y.V. and L.K.; methodology, Y.V. and L.K.; formal analysis, Y.V. and L.K.; investigation, Y.V. and L.K.; data curation, Y.V.; writing—original draft preparation, Y.V.; writing—review and editing, Y.V. and L.K.; project administration, Y.V.; funding acquisition, Y.V. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially funded by the Fuel Choices Initiative at the Israeli Prime Minister's office.

Data Availability Statement: Original data will be provided upon request.

Acknowledgments: The authors wish to thank Leonid Murkhovsky for his assistance in the fieldwork.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Chakravarty, S.; Ghosh, S.K.; Suresh, C.P.; Dey, A.N.; Shukla, G. Deforestation: Causes, effects and control strategies. In *Global Perspectives on Sustainable Forest Management*; Okia, C.A., Ed.; InTech: Rang-Du-Fliers, France, 2012; Volume 1, pp. 1–26, ISBN 978-953-51-0569-5. Available online: http://www.intechopen.com/books/globalperspectives-on-sustainable-forest-management/deforestation-causes-effects-and-control-strategies (accessed on 1 March 2023).
2. Huang, J.; Ji, M.; Xie, Y.; Wang, S.; He, Y.; Ran, J. Global semi-arid climate change over last 60 years. *Clim. Dynam.* **2016**, *46*, 1131–1150. [CrossRef]
3. IEA. *Analysis and Forecast to 2026*; International Energy Agency: Paris, France, 2021. Available online: https://iea.blob.core.windows.net/assets/5ae32253-7409-4f9a-a91d-1493ffb9777a/Renewables2021-Analysisandforecastto2026.pdf (accessed on 16 April 2023).
4. Vogel, K.P.; Brejda, J.J.; Walters, D.T.; Buxton, D.R. Switchgrass biomass production in the Midwest USA. *Agron. J.* **2002**, *94*, 413–420. [CrossRef]
5. Adler, P.R.; Sanderson, M.A.; Boateng, A.A.; Weimer, P.J.; Jung, H.J.G. Biomass yield and biofuel quality of switchgrass harvested in fall or spring. *Agron. J.* **2006**, *98*, 1518–1525. [CrossRef]
6. Lemus, R.; Brummer, E.C.; Burras, C.L.; Moore, K.J.; Barker, M.F.; Molstad, N.E. Effects of nitrogen fertilization on biomass yield and quality in large fields of established switchgrass in southern Iowa, USA. *Biomass Bioenergy* **2008**, *32*, 1187–1194. [CrossRef]
7. 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 Bioenergy* **2003**, *24*, 411–427. [CrossRef]
8. Amichev, B.Y.; Johnston, M.; Van Rees, K.C. Hybrid poplar growth in bioenergy production systems: Biomass prediction with a simple process-based model (3PG). *Biomass Bioenergy* **2010**, *34*, 687–702. [CrossRef]
9. Krzyżaniak, M.; Stolarski, M.J.; Waliszewska, B.; Szczukowski, S.; Tworkowski, J.; Załuski, D.; Śnieg, M. Willow biomass as feedstock for an integrated multi-product biorefinery. *Ind. Crop. Prod.* **2014**, *58*, 230–237. [CrossRef]
10. Eastham, J.; Scott, P.R.; Steckis, R.A.; Barton, A.F.M.; Hunter, L.J.; Sudmeyer, R.J. Survival, growth and productivity of tree species under evaluation for agroforestry to control salinity in the Western Australian wheatbelt. *Agrofor. Syst.* **1993**, *21*, 223–237. [CrossRef]
11. Du Toit, B. Effects of site management on growth, biomass partitioning and light use efficiency in a young stand of *Eucalyptus grandis* in South Africa. *For. Ecol. Manag.* **2008**, *255*, 2324–2336. [CrossRef]
12. Stape, J.L.; Binkley, D.; Ryan, M.G.; Fonseca, S.; Loos, R.A.; Takahashi, E.N.; Claudio, R.S.; Sergio, R.S.; Rodrigo, E.H.; Ferreira, J.M.D.A.; et al. The Brazil Eucalyptus Potential Productivity Project: Influence of water, nutrients and stand uniformity on wood production. *For. Ecol. Manag.* **2010**, *259*, 1684–1694. [CrossRef]

13. Barreiro, S.; Tomé, M. Analysis of the impact of the use of eucalyptus biomass for energy on wood availability for eucalyptus forest in Portugal: A simulation study. *Ecol. Soc.* **2012**, *17*, 14. Available online: https://www.jstor.org/stable/26269037 (accessed on 1 March 2023). [CrossRef]
14. Borralho, N.M.G.; Cotterill, P.P.; Kanowski, P.J. Breeding objectives for pulp production Of *Eucalyptus globulus* under different industrial cost structures. *Can. J. For. Res.* **1993**, *23*, 648–656. [CrossRef]
15. Raymond, C.A.; Schimleck, L.R.; Muneri, A.; Michell, A.J. Genetic parameters and genotype-by-environment interactions for pulp-yield predicted using near infrared reflectance analysis and pulp productivity in *Eucalyptus globulus*. *For. Genet.* **2001**, *8*, 213–224.
16. Almeida, A.C.; Soares, J.V.; Landsberg, J.J.; Rezende, G.D. Growth and water balance of *Eucalyptus grandis* hybrid plantations in Brazil during a rotation for pulp production. *For. Ecol. Manag.* **2007**, *251*, 10–21. [CrossRef]
17. Eldridge, K.; Davidson, J.; Harwood, C.; VanWyk, G. *Eucalypt Domestication and Breeding*; Clarendon Press: Oxford, UK, 1993.
18. Niknam, S.R.; McComb, J. Salt tolerance screening of selected Australian woody species—A review. *For. Ecol. Manag.* **2000**, *139*, 1–19. [CrossRef]
19. Zohar, Y.; Gafni, A.; Morris, J.; Shalhevet, S. Eucalyptus plantations in Israel: An assessment of economic and environmental viability. *New For.* **2008**, *36*, 135–157. [CrossRef]
20. Kheshgi, H.S.; Prince, R.C.; Marland, G. The potential of biomass fuels in the context of global climate change: Focus on transportation fuels. *Annu. Rev. Energy Environ.* **2000**, *25*, 199–244. [CrossRef]
21. Harper, R.J.; Sochacki, S.J.; Smettem, K.R.J.; Robinson, N. Bioenergy feedstock potential from short-rotation woody crops in a dryland environment. *Energy Fuels* **2010**, *24*, 225–231. [CrossRef]
22. Antal, M.J.; Croiset, E.; Dai, X.; DeAlmeida, C.; Mok, W.S.L.; Norberg, N.; Al Majthoub, M. High-yield biomass charcoal. *Energy Fuels* **1996**, *10*, 652–658. [CrossRef]
23. Norgate, T.; Langberg, D. Environmental and economic aspects of charcoal use in steelmaking. *ISIJ Int.* **2009**, *49*, 587–595. [CrossRef]
24. Piketty, M.G.; Wichert, M.; Fallot, A.; Aimola, L. Assessing land availability to produce biomass for energy: The case of Brazilian charcoal for steel making. *Biomass Bioenergy* **2009**, *33*, 180–190. [CrossRef]
25. Inoue, H.; Yano, S.; Endo, T.; Sakaki, T.; Sawayama, S. Combining hot compressed water and ball milling pretreatments to improve the efficiency of the enzymatic hydrolysis of eucalyptus. *Biotechnol. Biofuels* **2008**, *1*, 2. [CrossRef] [PubMed]
26. Kaida, R.; Kaku, T.; Baba, K.; Oyadomari, M.; Watanabe, T. Enzymatic saccharification and ethanol production of *Acacia mangium* and *Paraserianthes falcataria* wood, and *Elaeis guineensis* trunk. *J. Wood Sci.* **2009**, *55*, 381–386. [CrossRef]
27. Yu, Q.; Zhuang, X.; Yuan, Z.; Wang, Q.; Qi, W. Two-step liquid hot water pretreatment of *Eucalyptus grandis* to enhance sugar recovery and enzymatic digestibility of cellulose. *Bioresour. Technol.* **2010**, *101*, 4895–4899. [CrossRef] [PubMed]
28. Magalhães, W.L.; Helm, C.; Silva, P.; Lima, E.; Hoffman, K. Pretreatment of Eucalypts biomass towards enzymatic saccharification. *BMC Proc.* **2011**, *5*, P116. [CrossRef]
29. Shepherd, M.; Bartle, J.; Lee, D.J.; Brawner, J.; Bush, D. Eucalypts as a biofuel feedstock. *Biofuels* **2011**, *2*, 639–657. [CrossRef]
30. Karschon, R. *The Effect of Irrigation Upon the Growth of Eucalyptus camaldulensis Dehn: Report to 4th Session, Committee on Mediterranean Forest Research, Ankara*; FAO: Rome, Italy, 1970; p. 4.
31. Grunwald, C.; Karschon, R. Variation of *Eucalyptus camaldulensis* from north Australia grown in Israel. *Silvae Genet.* **1983**, *5*, 165–173.
32. Zohar, Y. Biomass production of short rotation *Eucalyptus camaldulensis* Dehn. stands growing on peat soil under a high water table in Israel. *S. Afr. For. J.* **1989**, *149*, 54–57. [CrossRef]
33. Zohar, Y.; Karschon, R. Above-ground biomass of *Eucalyptus camaldulensis* Dehn. in Israel. *S. Afr. For. J.* **1984**, *128*, 26–29. [CrossRef]
34. Zohar, Y.; Moreshet, S. Provenances of *Eucalyptus occidentalis* in the arid zone of Israel. *For. Ecol. Manag.* **1987**, *22*, 71–77. [CrossRef]
35. Zohar, Y.; Schiller, G. Growth and water use by selected seed sources of eucalyptus under high water table and saline conditions. *Agric. Ecosyst. Environ.* **1998**, *69*, 265–277. [CrossRef]
36. Korol, L.E.; Atzmon, N.; Shkliar, G.; Moshe, Y. *Genetic Characterization of Basic Eucalyptus Species in Israel*; KKL: Jerusalem, Israel, 2010.
37. Korol, L.E.; Riev, Y.; Shkliar, G.; Moshe, Y.; Sitbon, R. *Genetic Diversity in the River Red Gum (Eucalyptus camaldulensis) Growing in Israel*; KKL: Jerusalem, Israel, 2012.
38. Prober, S.J.; Bell, C.; Moran, G. A phylogenetic and allozyme approach to understanding rarity in three "green ash" eucalypts (*Myrtaceae*). *Plant Syst. Evol.* **1990**, *172*, 99–118. [CrossRef]
39. Brooker, M.I.H.; Kleinig, D.A. *Field Guide to Eucalypts: Vol. 1. South-Western and Southern Australia*, Revised ed.; Bloomings Books: Melbourne, Australia, 1999.
40. Butcher, P.A.; McDonald, M.W. Congruence between environmental parameters, morphology and genetic structure in Australia's most widely distributed eucalypt, *Eucalyptus camaldulensis*. *Tree Genet. Genomes* **2009**, *5*, 189–210. [CrossRef]
41. Potts, B.M.; Wiltshire, R.J.E. Eucalypt genetics and genecology. In *Eucalypt Ecology: Individuals to Ecosystems*; Williams, J., Woinarski, J., Eds.; Cambridge University Press: Cambridge, UK, 1997; pp. 56–91.
42. Zahid, D.M.; Shah, F.U.R.; Majeed, A. Planting *Eucalyptus camaldulensis* in arid environment—Is it useful species under water deficit system. *Pak. J. Bot.* **2010**, *42*, 1733–1744.
43. Nagar, B.; Rawat, S.; Rathiesh, P.; Sekar, I. Impact of initial spacing on growth and yield of *Eucalyptus camaldulensis* in arid region of India. *World Appl. Sci. J.* **2015**, *33*, 1362–1368.

44. Beck, H.; Zimmermann, N.; McVicar, T.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef]
45. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements*; FAO Irrigation and Drainage Paper 56; Food and Agriculture Organization of the United Nations: Rome, Italy, 1998; p. 15.
46. Venendaal, R.; Jørgensen, U.; Foster, C.A. European energy crops: A synthesis. *Biomass Bioenergy* **1997**, *13*, 147–185. [CrossRef]
47. Sims, R.E.; Handford, P.A.; Bell, T. *Wood Fuel Supply and Utilization from Short Rotation Energy Plantations*; Agronomy Department, Massey University: Palmerston North, New Zealand, 1990.
48. Rockwood, D.; Rudie, A.; Ralph, S.; Zhu, J.; Winandy, J. Energy product options for Eucalyptus species grown as short rotation woody crops. *Int. J. Mol. Sci.* **2008**, *9*, 1361–1378. [CrossRef]
49. Gabrielle, B.; Nguyen The, N.; Maupu, P.; Vial, E. Life cycle assessment of eucalyptus short rotation coppices for bioenergy production in southern France. *Gcb Bioenergy* **2013**, *5*, 30–42. [CrossRef]
50. Bernardo, A.L.; Reis, M.G.; Reis, G.G.; Harrison, R.B.; Firme, D.J. Effect of spacing on growth and biomass distribution in *Eucalyptus camaldulensis*, *E. pellita* and *E. urophylla* plantations in southeastern Brazil. *For. Ecol. Manag.* **1998**, *104*, 1–13. [CrossRef]
51. Schönau, A.P.G.; Coetzee, J. Initial spacing, stand density and thinning in eucalypt plantations. *For. Ecol. Manag.* **1989**, *29*, 245–266. [CrossRef]
52. King, D.A. The adaptive significance of tree height. *Am. Nat.* **1990**, *135*, 809–828. [CrossRef]
53. Alcorn, P.J.; Pyttel, P.; Bauhus, J.; Smith, R.G.B.; Thomas, D.; James, R.; Nicotra, A. Effects of initial planting density on branch development in 4-year-old plantation grown *Eucalyptus pilularis* and *Eucalyptus cloeziana* trees. *For. Ecol. Manag.* **2007**, *252*, 41–51. [CrossRef]
54. Henskens, F.L.; Battaglia, M.; Cherry, M.L.; Beadle, C.L. Physiological basis of spacing effects on tree growth and form in *Eucalyptus globulus*. *Trees* **2001**, *15*, 365–377. [CrossRef]
55. Xue, L.; Pan, L.; Zhang, R.; Xu, P.B. Density effects on the growth of self-thinning *Eucalyptus urophylla* stands. *Trees* **2011**, *25*, 1021–1031. [CrossRef]
56. Pinkard, E.A.; Neilsen, W.A. Crown and stand characteristics of *Eucalyptus nitens* in response to initial spacing: Implications for thinning. *For. Ecol. Manag.* **2003**, *172*, 215–227. [CrossRef]
57. Kearney, D.; James, R.; Montagu, K.; Smith, R.G.B. The effect of initial planting density on branching characteristics of *Eucalyptus pilularis* and *E. grandis*. *Aust. For.* **2007**, *70*, 262–268. [CrossRef]
58. Thoranisorn, S.; Sahunalu, P.; Yoda, K. Density effects and self-thinning in even-aged pure stands of *Eucalyptus camaldulensis* Dehn. *Bot. Mag.* **1990**, *103*, 283–295. [CrossRef]
59. Neilsen, W.A.; Gerrand, A.M. Growth and branching habit of *Eucalyptus nitens* at different spacing and the effect on final crop selection. *For. Ecol. Manag.* **1999**, *123*, 217–229. [CrossRef]
60. Paris, P.; Mareschi, L.; Sabatti, M.; Tosi, L.; Scarascia-Mugnozza, G. Nitrogen removal and its determinants in hybrid Populus clones for bioenergy plantations after two biennial rotations in two temperate sites in northern Italy. *iFor.-Biogeosci. For.* **2015**, *8*, 668. [CrossRef]