





Article

Influence of Irrigation on Biomass Partitioning in Above- and Belowground Organs of Trees Planted in Desert Sites of Mongolia

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Abstract: Planting trees is considered a crucial factor in mitigating the increase in carbon emissions in the atmosphere by generating plant biomass. In addition to advancing our understanding of how tree biomass is allocated in desert environments, we explore potential variations in biomass partitioning based on the irrigation regimes (4, 8, and 12 L h⁻¹) supporting the growth of these trees. Specifically, this study compares the pattern of biomass distribution between above-ground and belowground organs of 11-year-old trees (*U. pumila*, *E. moorcroftii*, and *T. ramosissima*) planted in a desert site in Mongolia. An interesting result of this study is the demonstration that biomass partitioning among roots of different diameter classes differs between the tree species tested, suggesting that each tree species establishes its own type of root/soil interaction. The differences in biomass partitioning in roots could determine specificity in the strength of anchorage and efficiency of nutrition for the trees. We also demonstrate that the presence of plantations influences certain chemical properties of the desert soil, with differences depending on the tree species planted. In addition to presenting a method for planting trees in desert sites, this study underscores that a reliable evaluation of atmospheric carbon sequestration in trees must necessarily include root excavation to obtain an accurate measurement of biomass stored in belowground structures. Assessing the overall biomass produced by these trees allows us to determine the potential for carbon sequestration achievable through plantations established in desert sites.

Keywords: irrigation; biomass; arid area; carbon sequestration; tree carbon



Citation: Byambadorj, S.-O.; Park, B.B.; Lkhagvasuren, S.; Tsedensodnom, E.; Byambasuren, O.; Khajid, A.; Chiatante, D.; Nyam-Osor, B. Influence of Irrigation on Biomass Partitioning in Above- and Belowground Organs of Trees Planted in Desert Sites of Mongolia. *Forests* **2024**, *15*, 46. <https://doi.org/10.3390/f15010046>

Academic Editors: Andrzej Węgiel and Adrian Lukowski

Received: 30 November 2023

Revised: 19 December 2023

Accepted: 21 December 2023

Published: 25 December 2023



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1. Introduction

The worsening effects of global changes (i.e., a continuous reduction of precipitations and an increase in the frequency of heat waves) are leading to land degradation and desertification. Human behaviour maintains irresponsibly high levels of grazing on natural grasslands [1–3]. Moreover, there is no need to stress the negative effect of land abandonment on areas prone to desertification [4]. In this scenario, it is not surprising that there is a surge of initiatives [5–9] aimed at planting trees in arid and semiarid regions as a measure to counteract the effects of global changes [10].

The average air temperature in Mongolia has risen by 2.25 °C in the last 80 years and the number of hot days has increased considerably [11] while average precipitation is

decreasing by a value of 7.3%. Therefore, it is not surprising that the assessment establishes that nearly 76.9% (i.e., 120.3 m/ha) of the total Mongolian lands are already in a condition of extreme degradation tending towards desertification [12]. As a consequence of this scenario, the implementation in Mongolia of well-managed plantations is considered to be the only means to counteract urgently this situation [2].

In analogy to strategies adopted worldwide to arrest desertification of arid lands through the construction of green wall [5], in Mongolia a tree planting initiative named “Green Belt” has been launched jointly by the Mongolian and South Korean Governments. The objectives of this initiative are: (1) protecting the soil from further degradation; (2) sequestering carbon within the construction of the tree biomass; (3) increasing carbon concentration in the soil [13]; (4) associating forestry with the development of agricultural activities by taking advantage of the irrigation systems used for the plantations [14].

Under this Green Belt initiative, a total of 1,079,663 trees have already been planted for a total of 2520 hectares, located both in Mongolia’s semiarid steppe and in the Gobi Desert [15]. Hence, after 11 years from planting time, it is necessary to assess the performance of the tree species to select the best candidate to be suggested for future plantations. For this purpose, our laboratories have been involved in evaluating the performance of the new plantations, and the results of these studies are summarized in several papers [2,16–22]. In these studies, the kinetics of growth and development of three tree species (*Ulmus pumila* L., *Tamarix ramosissima* Ldb., and *Elaeagnus moorcroftii* Wall. ex Schlecht.) has been investigated. The choice of testing the growth performance of *Ulmus pumila* L. was based on the fact that this tree species is widespread through Mongolia’s lands and shows good tolerance to conditions of water/nutrient shortages [19]. In the case of *Tamarix ramosissima* Ldb., the choice was based on its capacity to live well in dry and semi-arid habitats with a high tolerance to abiotic stress (drought, salinity, and high temperature) [23]. In the case, of *Elaeagnus moorcroftii* Wall. ex Schlecht the choice was based upon its capacity to live in degraded soil affected by strong winds [18] which are very frequent in the desert sites considered here. During growth, these plantations have been supported by different irrigation regimes (“drip irrigation”). This type of irrigation has been used because it provides the occurrence of regular moisture in the soil, and it accelerates root growth resulting in an increase in nutrient availability with a related increase in tree growth [24].

Investigations regarding the performance of tree plantations [25] have focused mainly on measuring the morphological traits of aboveground organs (stem, branches, and leaves), whereas the analysis of how roots grow and develop after planting has remained completely ignored. This gap in knowledge represents a bias not only for a correct evaluation of the plantation performance but also because it affects the possibility of measuring correctly the carbon sequestration potential of this type of environmental restoration initiative. The present work is aimed at eliminating this gap with *Ulmus pumila* L., *Tamarix ramosissima* Ldb., and *Elaeagnus moorcroftii* Wall. (ex Schlecht) trees planted in a desert site. In particular, here we analyze accurately the growth in both above- and belowground organs, with a particular focus on carbon partitioning among plant organs. For this reason, we have excavated the trees and measured their morphological traits (stem height, root collar diameter, and root length) and the amount of biomass allocated in both aboveground and belowground organs (i.e., carbon pools) [26]. In addition, we have also investigated if/how biomass partitioning is affected by the amount of water made available in the soil when plantations are supported by three different irrigation regimes (4, 8, and 12 L h⁻¹) [25]. Investigation about the effect of irrigation regimes is necessary, as it is known that the amount of water in the soil affects the functional equilibrium that regulates the amount of carbon that must be distributed between the different organs (i.e., the carbon sink) to ensure an optimal growth rate [27]. Moreover, it has been shown that plants growing under drought conditions prefer to invest in the construction of root biomass and surfaces to maximize exchange with the soil and increase water and nutrient uptake [28]. On the contrary, it has been shown that leaf area increases when water is abundant to enable a higher level of carbon fixation [29].

In addition, investigating biomass partitioning to different plant organ pools, this work also analyzes how the presence of trees affects the chemical properties of the soil in the first 0–20 cm of depth. In fact, it is known that the chemical and physical properties change when the soil is prepared and managed for tree-planting initiatives [30].

An interesting aspect of this work derives also from the fact that we show a methodological approach for measuring correctly the overall biomass (i.e., carbon from the atmosphere) produced by plantations established in desert sites. Moreover, this approach provides useful indications for planting trees and supporting their growth and development by irrigation in biomes characterized by limited water resources.

2. Materials and Methods

2.1. Study Site Description

This study regards the plantation implemented in Dalanzadgad soum (43°36′12.74″ N, 104°21′22.25″ E), Umnugobi province, Mongolia (Figure 1).

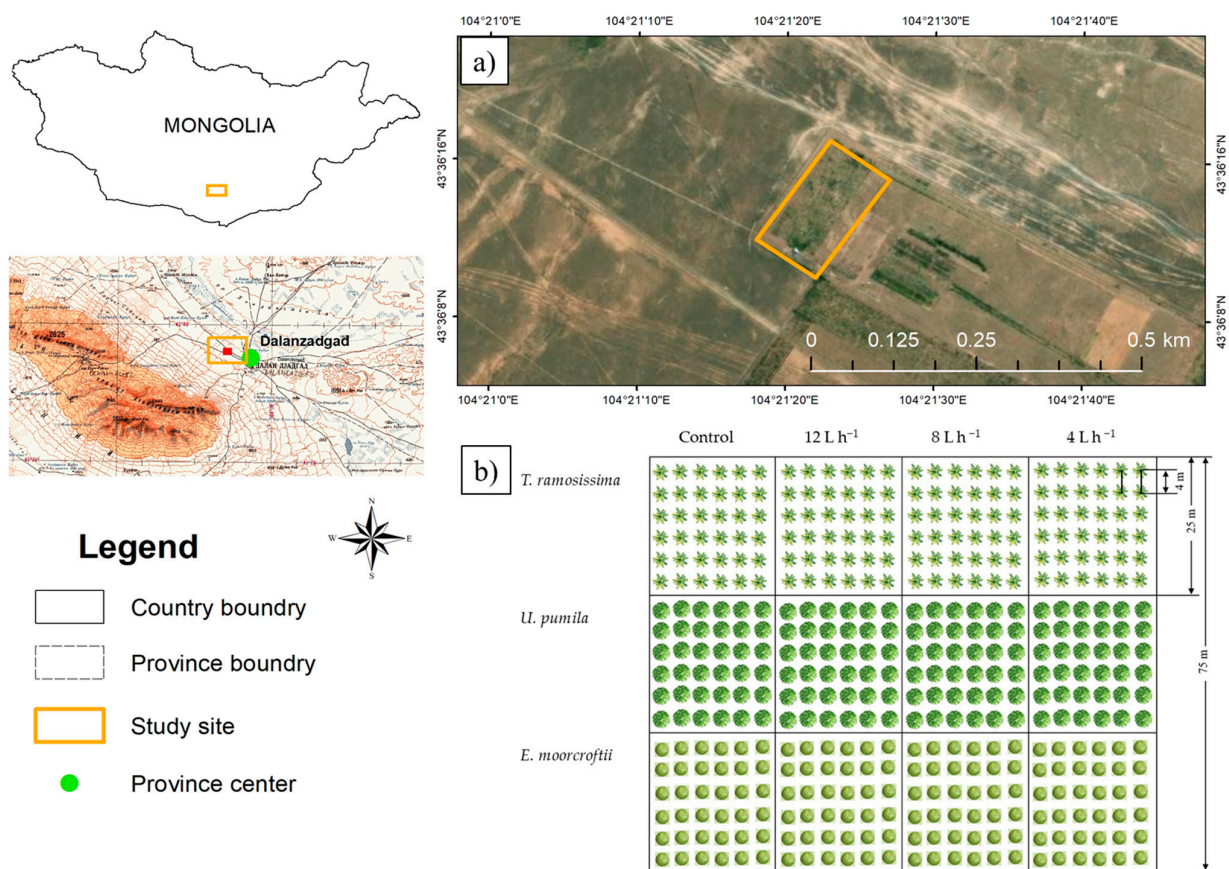


Figure 1. (a) Location and (b) Planting scheme of the study site. Each plot (25 m × 25 m) refers to one of three tree species tested and to a different irrigation regime. Each plot included 36 seedlings of the experimental site within the Green belt plantation in Dalanzadgad soum, Umnugobi province, Mongolia.

This site is classifiable as Desert-steppe and is characterized by grassland plains or mainly feather grass-onion communities with pea shrubs [18,31]. The dominant species (i.e., 59.7%) includes *Oxytropis aciphylla* Ldb., *Convolvulus ammannii* Desr., *Peganium nigellastrum* Bge, and annual plants, such as *Artemisia pectinata* Pall., *Chenopodium aristatum* L., *Eragrostis minor* Host., *Enneapogon desvauxii* P. Beauv. [32,33]. These species are associated with *Allium polyrrhizum* Turcz. ex Rgl, *A. mongolicum* Rgl, *Stipa gobica* Roshev., and *S. glareosa* P. Smirn. The vegetative season is very short starting in May and ending in September) when the first frost events occur. The temperature and precipitation are reported in Figure 2 [34].

The soil is classifiable as Gobi brown soil (Calcisol), which is generally, stony, sandy loamy, with high carbonate content and low organic matter [35].

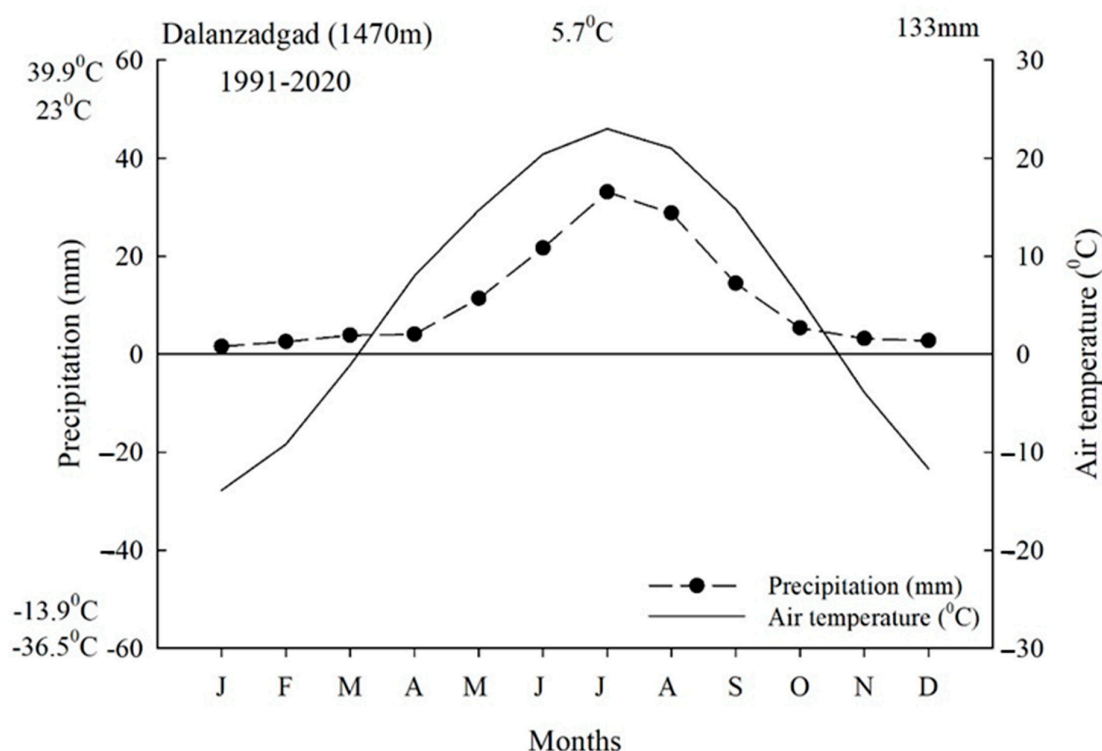


Figure 2. Mean annual temperature (solid line) and rainfall (broken, dotted line) in the experimental site are obtained from the period of January–December (1991–2020).

2.2. Planting Scheme and Sampling Design

Two-year-old seedlings (grown in the nursery) (*Ulmus pumila* L., *Tamarix ramosissima* Ldb., *Elaeagnus moorcroftii* Wall. ex Schlecht) are transplanted in 2009 and grown with the support of drip irrigation treatments. Four different irrigation regimes are tested (rainfall as control, rainfall + 84 mm tree⁻¹ yr⁻¹ (corresponding to 4 L h⁻¹ with a field capacity of 30%), rainfall + 168 mm tree⁻¹ yr⁻¹ (corresponding to 8 L h⁻¹ with a field capacity of 50%), rainfall + 252 mm tree⁻¹ yr⁻¹ (corresponding to 12 L h⁻¹ with a field capacity of 70%). Irrigation (5 h) is repeated twice a week for the entire vegetative season (May to mid-September). Samples are collected from 12 plots (each measuring 25 × 25 m), where trees are planted at a 4 m distance between rows, for a total of 36 seedlings planted in each plot (Figure 1). Seedlings are planted in 60–70 cm deep holes having a 50–60 cm diameter. For easy establishment, seedlings are daily irrigated with the same amount of water for one month.

2.3. Measurement of Morphological Traits and Allocation of Biomass to Above and Below-Ground Organs

To measure the growth performance five trees × 3 species × 3 treatments are selected and excavated by hand 11 years (August, 2020) after their planting. As indicators of growth performance, traits such as stem height, Root Collar Diameter (RCD), and root length are measured by using a digital Vernier calliper [36] and ruler (Basic aluminium Staff TS5-5MD, Republic of Korea). Root length is obtained by summing the root length obtained from each root class as described below.

Regarding biomass, we measured separately the dry weight of above- and below-ground organs. In the case of above-ground organs, we have measured separately each component (i.e., stem, branches, and leaves) and for this purpose subsamples of each component were collected and dried in an oven for 72 h at 105 °C (stem, branches, and

roots) or 70 °C (leaves) in the oven (Forced Convection Oven-OF-21E, Lab Comp., Seoul, Republic of Korea). SB indicates stem biomass; BB indicates branch biomass; LB indicates leaf biomass.

In the case of belowground organs, we used a digital calliper to segregate the roots into different classes based on their diameter according to the classification first suggested by [37] and later modified by [38]. The roots with a diameter below 2 mm are named Fine Root (FR). All the roots characterized by a diameter above 2 mm are divided into four categories (i.e., classes) as follows: Small Root (SR) with a diameter of 2–5 mm); Medium R (MR) with a diameter of 5–10 mm; Large Root (LR) with a diameter of 10–20 mm; and Very Large Root (VLR) with a diameter > 20 mm). Moreover, the Main Root or tap root (TR) is measured separately from all the other lateral roots. Biomass of each root class is obtained by measuring the dry weight of the subsamples after treatment in the oven at 105 °C until constant weight is achieved. An electronic balance (Discovery Semi-Micro and Analytical Balance-DVG215CD, Ohaus Corp., Parsippany, NJ, United States America) is used and biomass of each root class is named: FRB, SRB, MRB, LRB, VLRB, and TRB.

The biomass of aboveground organs (AG) is obtained by summing the biomass of each component and in analogy the biomass of belowground organs (named BG) was obtained by summing the biomass of each single root class. The sum of AG or BG is named the total tree biomass (ToTB) of the tree.

Total carbon (TC) stock per hectare (Mg ha^{-1}) is calculated by summing up the carbon stock of AG and BG of all the trees present in the hectare [39]. The carbon content in AG and BG is calculated by multiplying the dry weight values by a conversion factor of 0.5 [40–43]. The amount of CO_2 sequestered is estimated by multiplying AG and BG carbon content by a 3.67 factor [44].

2.4. Soil Sampling and Chemical Analyses

Regarding the evaluation of the effects of the presence of trees on the chemical properties of the soil, three replicates of soil samples are collected from the plots representing the three tree species tested and the four irrigation regime treatments (control + 3 irrigation regimes). Soil samples referred to two different layers (0–10 and 10–20 cm depth) are collected at 40 cm distance from the stem. Soil samples are air-dried and passed through a 2 mm sieve. Soil organic matter (SOM) is measured by the $\text{K}_2\text{CrO}_7\text{-H}_2\text{SO}_4$ oxidation method of Walkley and Black [45]. Calcium carbon content is determined by the volumetric method [46]. The pH is determined for a 1:2.5 air-dried soil/distilled water mixture using a glass electrode pH meter [47]. The electrical conductivity (EC) is determined for a 1:5 air-dried soil/distilled water mixture using a platinum electrode. Available phosphorus (P_2O_5) is measured by molybdenum blue colourimetric after $(\text{NH}_4)_2\text{CO}_3$ digestion [48]. Nitrate-nitrogen ($\text{NO}_2\text{-N}$) is determined by using CH_3COONa digestion and a spectropolarimeter. Potassium (K_2O) is analyzed by flame spectrometry methods [49].

2.5. Statistical Analysis

All the statistical analyses are performed by using the Statistical Analysis Software (SAS) package v.9.4 [50]. Two-way ANOVA is run for each species to determine the effects of different irrigation treatments on the parameters measured. Duncan's multiple range test (DMRT) is used to evaluate multiple comparisons among the treatments. For the ratio between each morphological parameter, principal component analysis (PCA) is performed by using the Paleontological Statistics (PAST) program [51]. All parameters are visualized by a heat map function. The heat map was built using the Display R program package [52] and grouped both rows and columns. The numeric differences in the heat map are highlighted by a colour scale where dark blue and light blue colours indicate the increase and the decrease of each parameter, respectively. The graphs are produced using the Sigma Plot 12.5 software [53].

3. Results

3.1. Effect of Irrigation Regimes on Morphological Traits of Above- and Below-Ground Organs of the Trees

The growth performance of the trees in the presence or absence of irrigation was evaluated by measuring separately the morphological traits of above- or below-ground organs. Seedlings of the three species growing without irrigation (control samples) did not survive after planting (not shown), contrary to the seedlings treated with irrigation showing a good growth performance (stem height, RCD, and root length) also at the lowest irrigation regime (Figure 3; Table S1). In *U. pumila* treated with 12 L h⁻¹ (Figure 3) stem height presented values higher than the trees treated with 8 and 4 L h⁻¹. Instead, in *T. ramosissima* and *E. moorcroftii* stem height showed similar values with 12 or 8 L h⁻¹ which were higher than 4 L h⁻¹. In the case of RCD, both *E. moorcroftii* and *U. pumila* treated with 8 and 12 L h⁻¹ showed similar values higher than 4 L h⁻¹ whereas in *T. ramosissima*, the highest value was found in 8 L h⁻¹. Root length values in *U. pumila* and *T. ramosissima* were similar in all irrigation regimes, contrary to *E. moorcroftii* which showed the highest value with 12 L h⁻¹ whereas the other two watering regimes did not show significant differences.

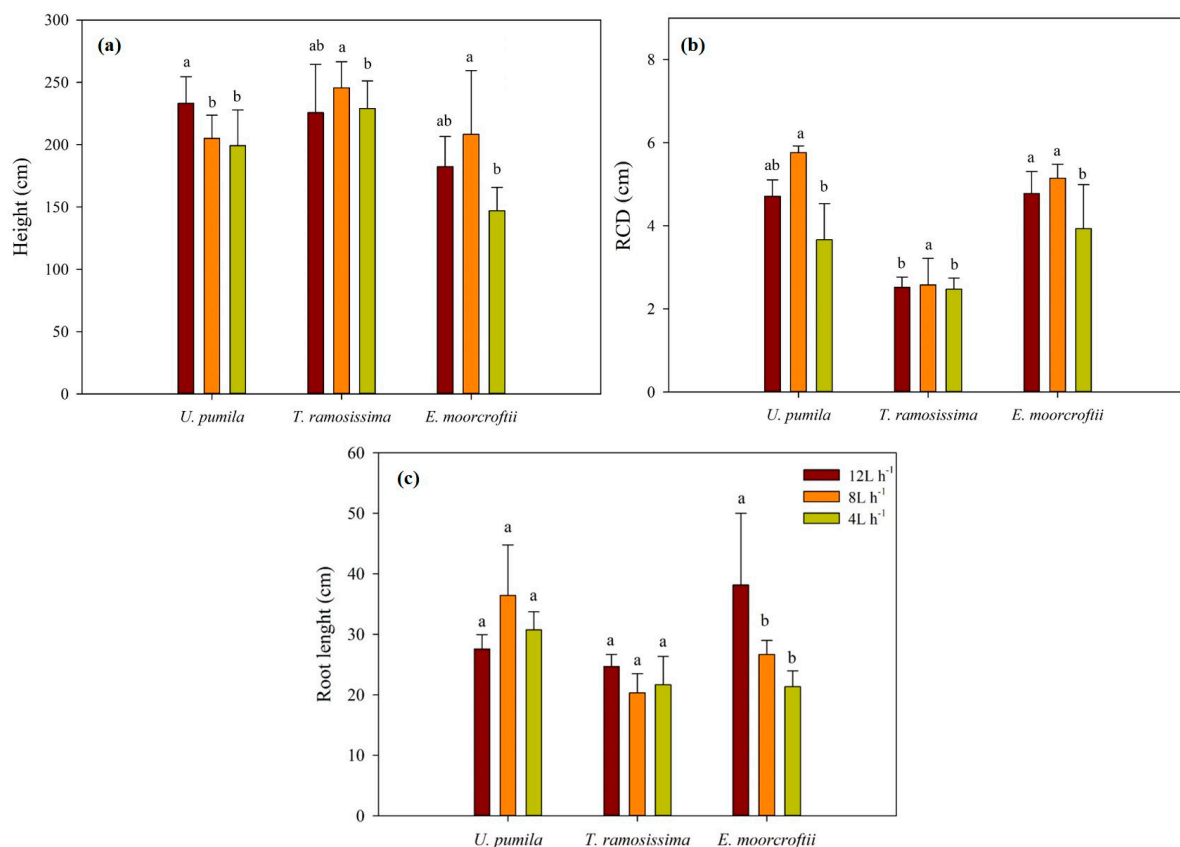


Figure 3. Plant height (cm) (a), root collar diameter (RCD, cm) (b) and root length (cm) (c) of *U. pumila*, *T. ramosissima* and *E. moorcroftii* measured during the last growing season (2020) on trees grown at different irrigation regimes (12 L h⁻¹, 8 L h⁻¹ and 4 L h⁻¹) ($n = 5 \pm SE$). Different letters indicate significant differences ($p < 0.05$) between treatments for each species.

3.2. Irrigation and Biomass Partitioning

In the case of TB, our data showed (Figure 4a) that in *U. pumila* there were no differences between the irrigation regime applied contrary to both *T. ramosissima* and *E. moorcroftii*. In *E. moorcroftii*, TB values were almost similar to those reported for *U. pumila* in 12 L h⁻¹ and 8 L h⁻¹ whereas the values in 4 L h⁻¹ were significantly lower. In *T. ramosissima* the TB values in 12 L h⁻¹ were considerably lower than in *U. pumila* or *E. moorcroftii* (Figure 4a; Table S2) with the lowest value found in 8 L h⁻¹.

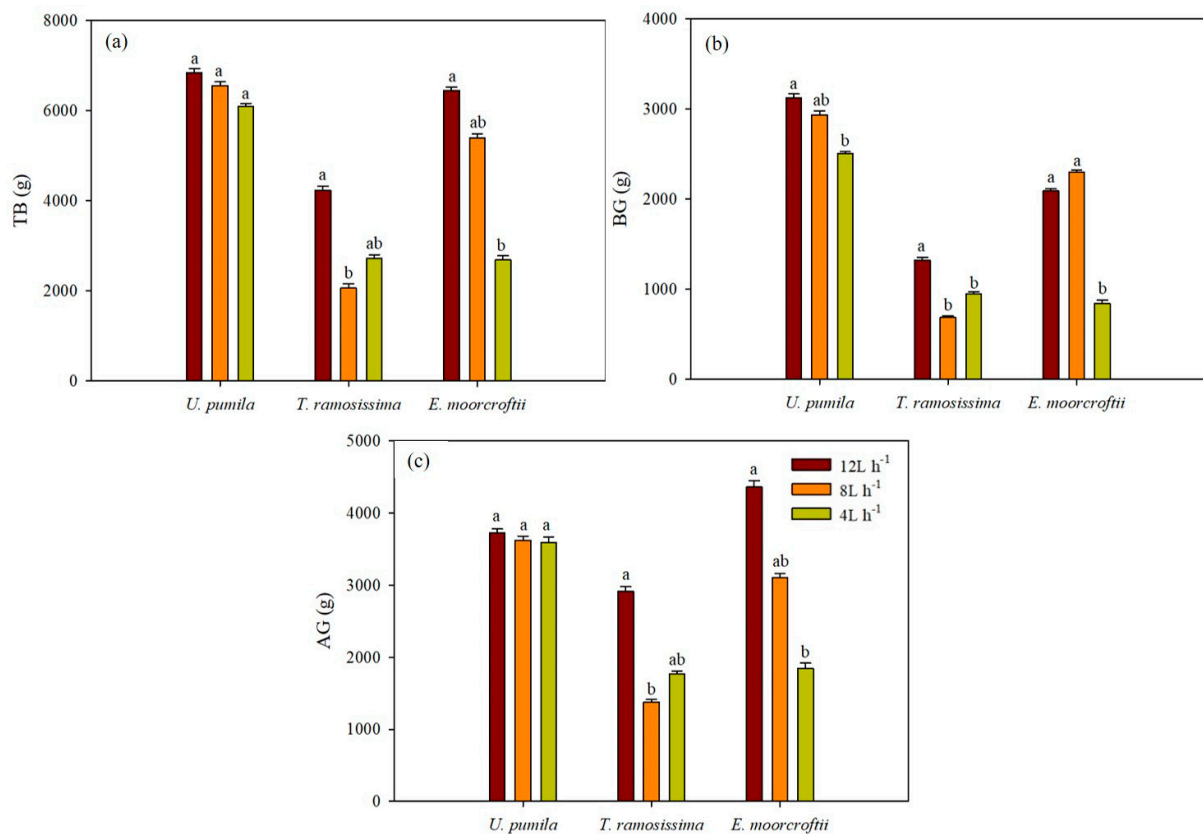


Figure 4. TB (a), BG (b) and AG (c) for *U. pumila*, *T. ramosissima* and *E. moorcroftii* in different irrigation regimes (12 L h⁻¹, 8 L h⁻¹ and 4 L h⁻¹) ($n = 5 \pm \text{SE}$). Different letters indicate significant differences ($p < 0.05$) between treatments for each species.

In the case of BG (i.e., TRB) in *U. pumila*, 4 L h⁻¹ induced a lower value concerning the other two irrigation regimes (Figure 4b). The same pattern of BG variations was observed in *T. ramosissima* and *E. moorcroftii* even though the 8 L h⁻¹ induced in *E. moorcroftii* values were similar to those measured in 12 L h⁻¹ (Figure 4b).

When we measured AG biomass (Figure 4c) *U. pumila* showed similar values which were independent of irrigation regimes. Higher were the values in *T. ramosissima* and *E. moorcroftii* when irrigation was 12 L h⁻¹.

It was interesting to investigate if/how the different irrigation regimes affected the partitioning of biomass among the different components of the AG or BG.

Regarding AG, we found that LB, except for 8 L h⁻¹ in *U. pumila*, was not affected by the irrigation regime used. The lowest value was observed in *T. ramosissima* (Figure 5a; Table S2). Also in the case of SB, our data showed a lack of difference between the irrigation regimes except for *E. moorcroftii* trees, where a significant reduction of stem biomass were observed with the lowest irrigation regime (Figure 5b). In analogy, also regarding BB (Figure 5c), the only difference was found in *E. moorcroftii* trees, with the lowest value found in 4 L h⁻¹.

Regarding the biomass investment in the different root classes (described in Materials and Methods), our data showed that in *U. pumila* the irrigation regimes did not induce variations in TR, VLR and MR classes, whereas significant reductions were observed in FR, SR, and LR classes but only in 12 L h⁻¹ (Figure 6a–f). In *T. ramosissima*, biomass investments in MR, LR, and VLR classes were reduced with lower irrigation regimes (i.e., 8 and 4 L h⁻¹), whereas they were completely arrested in the FR class. (Figure 6a–f). In the case of *E. moorcroftii*, our data showed that biomass investments in FR and SR classes were insensitive to irrigation regimes whereas increased in MR, LR, VLR, and TR classes with higher irrigation regimes (Figure 6a–f).

To better understand how the irrigation regimes altered the partitioning of biomass in the AG components (SB, BB, and LB) or BG, we investigated the ratio between the biomass present in each AG component or BG and the total biomass measured in the tree species studied (ToTB) (Table 1). According to the data collected, we found that in *U. pumila*, more than half of TB (54%–58%) are located in AG, compared to a little more than 40% (41%–45%) found in RB. Slightly higher (65%–68%) was the percentage of biomass found in AG organs of *T. ramosissima* and *E. moorcroftii* concerning ToTB. Regarding the BG, we found that the percentage of biomass decreased from 41%–45% in *U. pumila* to 31%–42% in the other two tree species.

Table 1. The ratio between LB, BB, SB, BG, and AG against Total Tree Biomass (ToTB) total biomass of *U. pumila*, *T. ramosissima*, and *E. moorcroftii* grown with different irrigation regimes (12 L h⁻¹, 8 L h⁻¹, and 4 L h⁻¹) ($n = 5 \pm SE$).

Plant Species	Treatments	%, LB/ToTB	%, BB/ToTB	%, SB/ToTB	%, AG/ToTB	%, BG/ToTB
<i>U. pumila</i>	12 L h ⁻¹	11.49 ± 1.29 ^a	24.62 ± 1.58 ^b	18.2 ± 1.43 ^{a,b}	54.32 ± 5.05 ^a	45.67 ± 3.45 ^a
	8 L h ⁻¹	8.23 ± 1.13 ^b	24.94 ± 1.65 ^b	22.05 ± 1.44 ^a	55.24 ± 5.12 ^a	44.75 ± 3.48 ^a
	4 L h ⁻¹	11.5 ± 1.25 ^a	31.5 ± 1.72 ^a	15.86 ± 1.38 ^b	58.87 ± 5.35 ^a	41.12 ± 3.21 ^a
<i>T. ramosissima</i>	12 L h ⁻¹	6.47 ± 0.98 ^b	49.74 ± 2.58 ^a	12.5 ± 1.12 ^b	68.72 ± 5.14 ^a	31.27 ± 2.24 ^a
	8 L h ⁻¹	8.43 ± 1.25 ^a	35.95 ± 2.85 ^b	22.29 ± 1.25 ^a	66.68 ± 6.12 ^a	33.31 ± 2.35 ^a
	4 L h ⁻¹	8.12 ± 1.21 ^a	40.17 ± 1.89 ^{a,b}	16.82 ± 1.24 ^{a,b}	65.11 ± 5.12 ^a	34.88 ± 2.65 ^a
<i>E. moorcroftii</i>	12 L h ⁻¹	8.24 ± 1.28 ^b	44.42 ± 5.42 ^a	14.9 ± 2.85 ^a	67.56 ± 6.87 ^a	32.43 ± 3.18 ^a
	8 L h ⁻¹	9.49 ± 1.56 ^b	29.26 ± 3.48 ^b	18.63 ± 2.47 ^a	57.39 ± 6.49 ^b	42.6 ± 3.25 ^a
	4 L h ⁻¹	19.16 ± 2.36 ^a	33.82 ± 3.87 ^a	15.62 ± 2.34 ^a	68.61 ± 6.98 ^a	31.38 ± 2.98 ^a

Letters indicate significant differences ($p < 0.05$) among actors for each species.

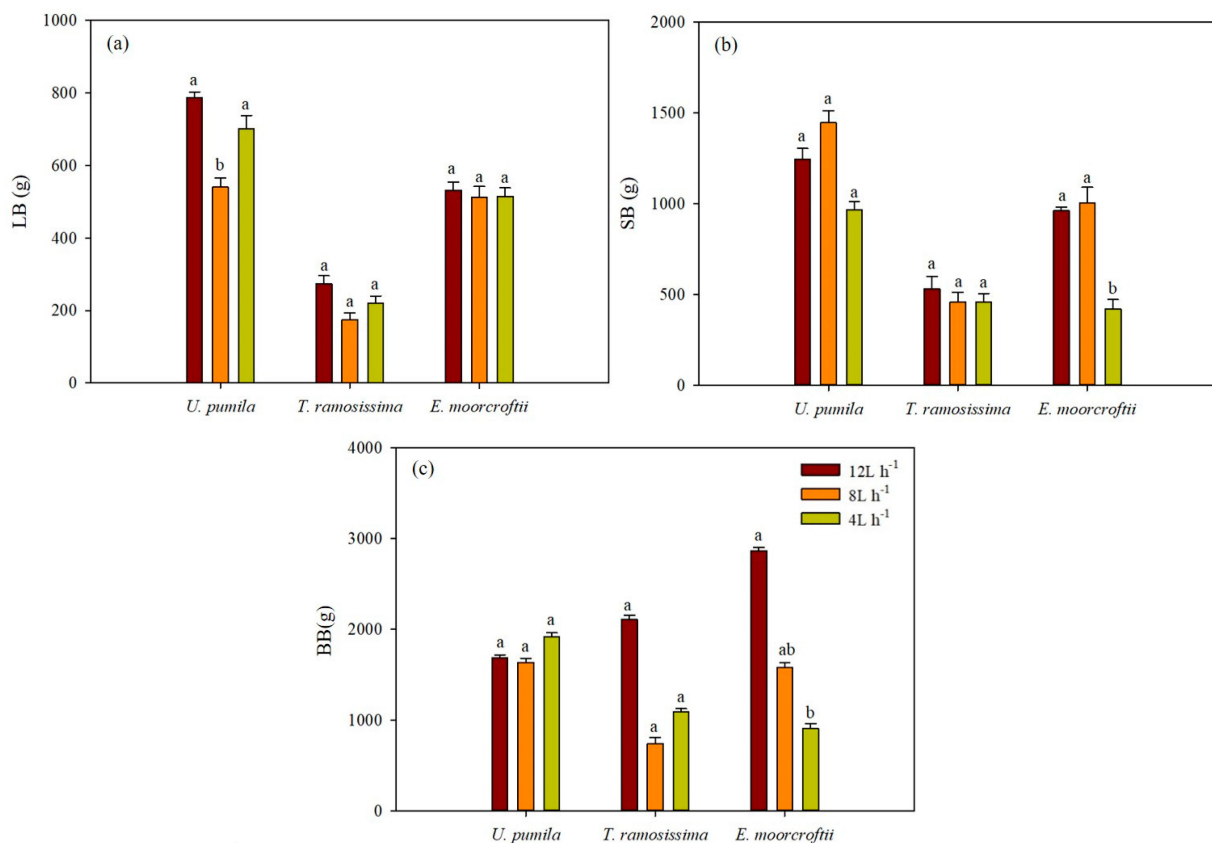


Figure 5. LB (a); SB (b), and BB (c) in *U. pumila*, *T. ramosissima* and *E. moorcroftii* grown with different irrigation regimes (12 L h⁻¹, 8 L h⁻¹ and 4 L h⁻¹) ($n = 5 \pm SE$). Different letters indicate significant differences ($p < 0.05$) between treatments for each species.

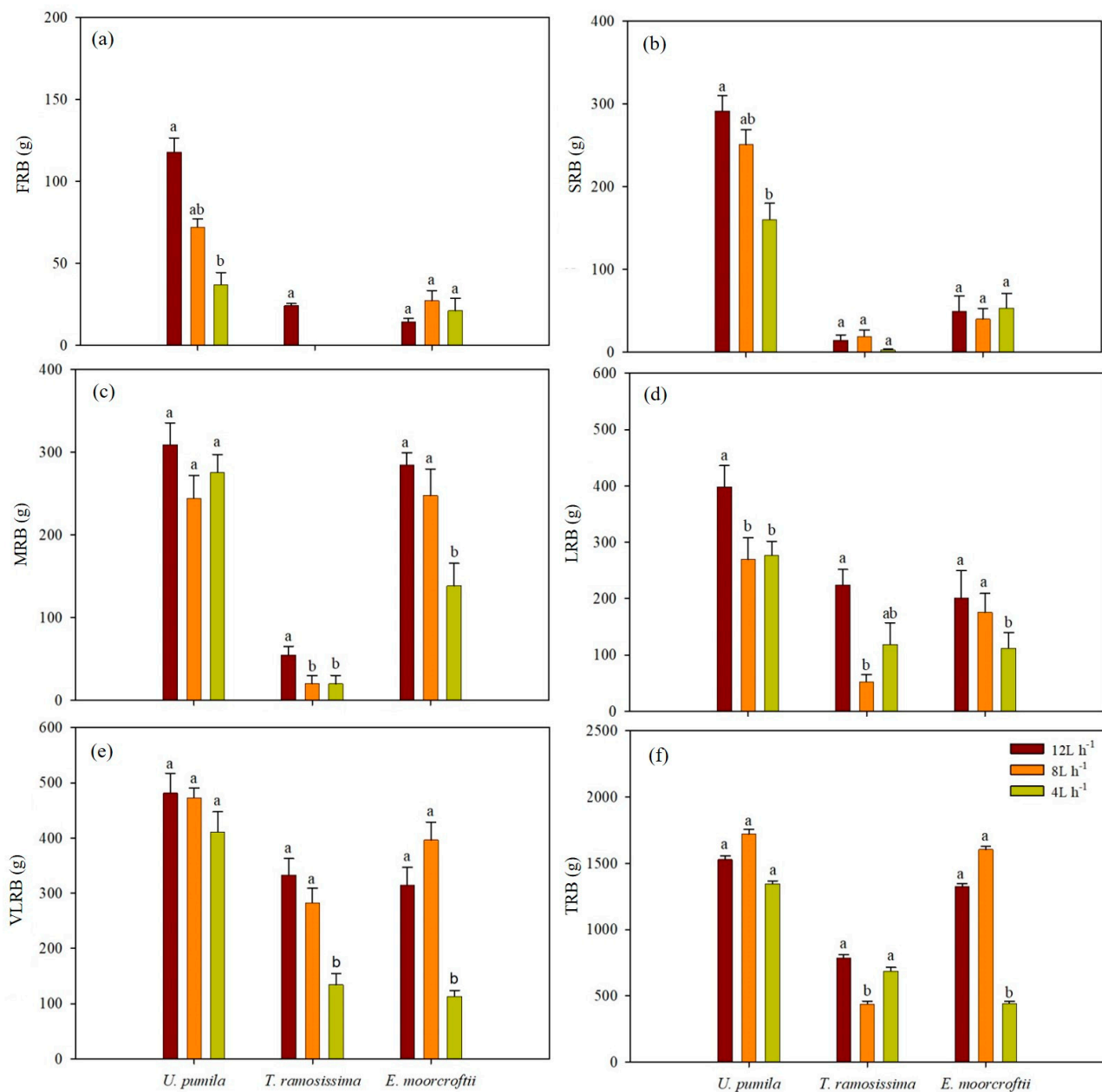


Figure 6. Measurement of root biomass divided into categories. FRB (a); SRB (b); MRB (c); LRB (d); VLR (e); TRB (f) of *U. pumila*, *T. ramosissima*, and *E. moorcroftii* treated with different irrigation treatments (12 L h⁻¹, 8 L h⁻¹, and 4 L h⁻¹) ($n = 5 \pm SE$). Different letters indicate significant differences ($p < 0.05$) between irrigation treatments for each species.

With the same purpose, we decided to analyze (Table 2) how biomass investments belowground were partitioned among each root class in the three tree species. In this case, it is evident that TRB of *U. pumila* presented nearly half (48%–58%) of BG and this partitioning was not affected by variations of the irrigation regimes. Moreover, our data showed that biomass partitioning was not sensitive to variation of irrigation regime in TR but also MR, and VLR. On the contrary, significant variations of biomass in response to irrigation regimes were found in FR, SR, and LR with higher values observed with the highest level of irrigation.

Table 2. The ratio between the biomass of a specific root class against the biomass of the total root biomass (BG) in tree species (*U. pumila*, *T. ramosissima* and *E. moorcroftii*) grown with different irrigation regimes (12 L h⁻¹, 8 L h⁻¹ and 4 L h⁻¹) ($n = 5 \pm SE$). TRB = TapRoot Biomass; FRB = Fine Root Biomass; SRB = Small Root Biomass; MRB = Medium Root Biomass; LRB = Large Root Biomass; VLRB = Very Large Root Biomass.

Plant Species	Treatments	%, TRB/BG	%, FRB/BG	%, SRB/BG	%, MRB/BG	%, LRB/BG	%, VLRB/BG
<i>U. pumila</i>	12 L h ⁻¹	48.87 ± 4.03 ^a	3.76 ± 1.14 ^a	9.32 ± 1.59 ^a	9.89 ± 1.64 ^a	12.73 ± 1.54 ^a	15.39 ± 2.25 ^a
	8 L h ⁻¹	58.61 ± 4.65 ^a	2.45 ± 1.08 ^{ab}	8.53 ± 1.48 ^{ab}	8.32 ± 1.58 ^a	9.18 ± 1.39 ^b	16.1 ± 2.37 ^a
	4 L h ⁻¹	53.67 ± 4.69 ^a	1.47 ± 0.98 ^b	6.39 ± 1.35 ^b	10.99 ± 1.72 ^a	11.06 ± 1.42 ^a	16.38 ± 2.39 ^a
<i>T. ramosissima</i>	12 L h ⁻¹	59.11 ± 4.12 ^b	1.82 ± 0	1.08 ± 0.12 ^{ab}	4.15 ± 0.85 ^a	16.93 ± 2.45 ^a	25.13 ± 2.24 ^{ab}
	8 L h ⁻¹	63.76 ± 4.54 ^{ab}	-	2.7 ± 0.01 ^a	2.9 ± 0.02 ^{ab}	7.63 ± 1.11 ^b	31.13 ± 2.35 ^a
	4 L h ⁻¹	72.35 ± 5.51 ^a	-	0.28 ± 0.01 ^b	2.11 ± 0.02 ^b	12.54 ± 1.45 ^a	14.19 ± 2.14 ^b
<i>E. moorcroftii</i>	12 L h ⁻¹	63.22 ± 7.01 ^{ab}	0.68 ± 0.01 ^b	2.35 ± 1.01 ^b	13.61 ± 1.25 ^a	9.6 ± 2.11 ^b	15.05 ± 2.14 ^a
	8 L h ⁻¹	69.73 ± 6.52 ^a	1.18 ± 0.02 ^b	1.72 ± 0.98 ^b	10.76 ± 1.12 ^a	7.63 ± 1.85 ^b	17.23 ± 2.16 ^a
	4 L h ⁻¹	52.54 ± 6.12 ^b	2.5 ± 0.02 ^a	6.3 ± 1.25 ^a	16.42 ± 1.36 ^a	13.25 ± 1.26 ^a	13.42 ± 2.05 ^a

Letters indicate significant differences ($p < 0.05$) among actors for each species.

Biomass partitioning between the root classes of *T. ramosissima* showed that in the root apparatus of this tree, the TR (Table 2) accounted for more than 50% of total root biomass (59%–72%). Significant differences were observed with variations of irrigation regime with the highest value found at lower levels of irrigation. In all the other root classes (SRB, MRB, LRB, VLRB) the highest percentages were observed with the highest level of irrigation.

The data regarding the partitioning of root biomass in *E. moorcroftii* (Table 2), showed that 52%–69% of biomass was allocated to the TR class with higher values with 8–12 L h⁻¹. The biomass allocated to MR and VLR classes lacked significant variations with the irrigation regimes whereas LRB decreased significantly its percentage with the the increase of the level of irrigation.

3.3. Statistical Analysis of the Variation of Biomass Partitioning between Above and Below-Ground Organs of Each Tree Species in Response to Different Irrigation Regimes

According to our PCA analysis, it was particularly evident that variation in biomass partitioning was positively correlated with the increase of irrigation regime. In particular, 8 and 12 L h⁻¹ irrigation regimes accounted for 77.14% of data variance (PCA 1 58.83%, PCA 2 18.31%) (Figure 7a). Moreover, when we used the heat map approach we obtained a clear indication that in all three tree species tested, ToTB showed variations that depended on the irrigation regime. Regarding biomass partitioning, it became evident (Figure 7b–d) that in BG the amount of biomass allocated to root classes with low diameters did not change (or change very little) with the variation of the irrigation regime. Different was the response of the taproot showing variations already when trees were treated with the lowest 4 L h⁻¹ level of irrigation (Figure 7b–d).

Regarding AG partitioning, the Heath Map showed that variations depending on the irrigation regime of AG in *U. pumila* were absent compared with *T. ramosissima* and *E. moorcroftii*. In particular, biomass accumulation in the leaves and non-significant variation were not observed in irrigation in all three tree species tested.

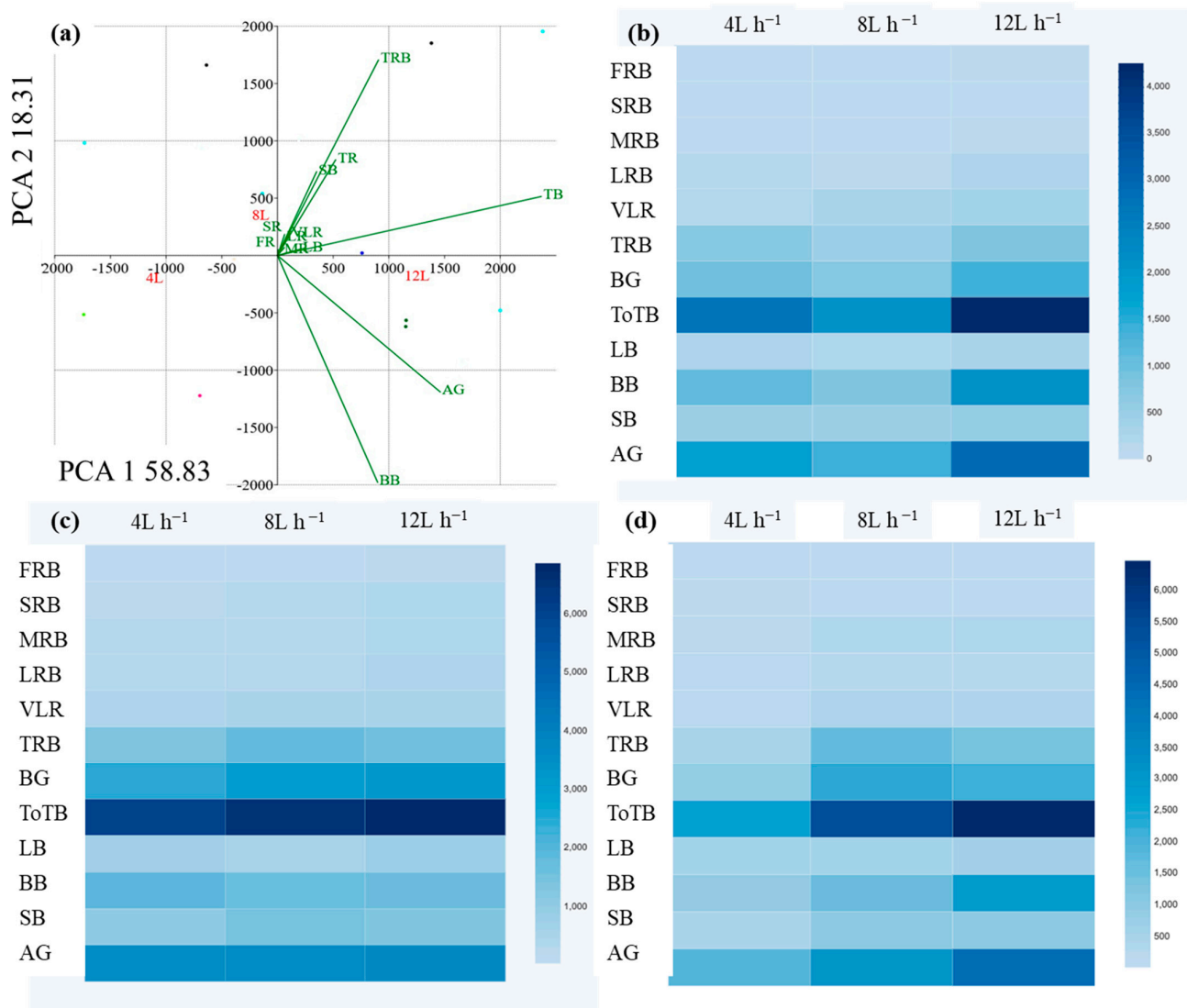


Figure 7. Principal component analysis and heatmap for morphological parameters under different irrigation treatments (12 L h^{-1} , 8 L h^{-1} , and 4 L h^{-1}). (a) PCA biplot of all individual samples for PCA 1 and PCA 2. The data shows three species with three watering regimes and four replicates. FRB (Fine Roots Biomass), SRB (Small Roots Biomass), MRB (Medium Roots Biomass), LRB (Large Root Biomass), VLR (Very Large Roots), TRB (Taproot Biomass), BG (Below-Ground Biomass), ToTB (Total Tree Biomass), LB (Leaf Biomass), BB (Branch Biomass), SB (Stem Biomass), AG (Above-Ground Biomass). (b) Heat-map of *T. ramosissima*; (c) Heat-map of *U. pumila*; (d) Heat-map of *E. moorcroftii*.

3.4. Carbon Content in the Tree

By summing AG and BG, we have estimated (according to what is described in the Materials and Methods section): (1) the mean amount of plant biomass produced per hectare; (2) the amount of carbon sequestered in the tree biomass per hectare; and (3) the amount of carbon sequestered by the plantation per hectare (Figure 8). The data indicated that *U. pumila* trees presented the highest values of all three parameters, whereas *T. ramosissima* showed the lowest values.

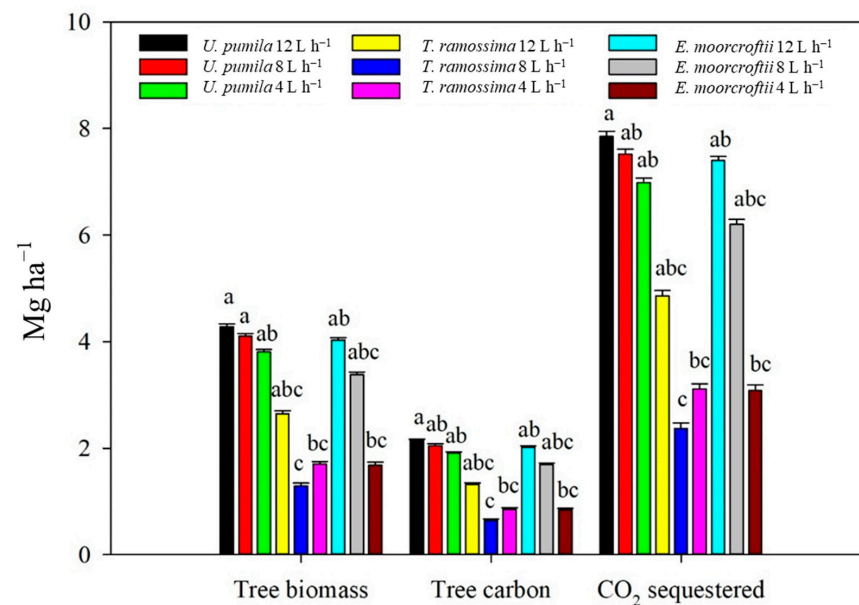


Figure 8. Total biomass found in the trees present per hectare, total carbon sequestered by the trees (i.e., TC stock) present per hectare, and total CO₂ sequestered in the plantation per hectare. Lowercase letters indicate significant differences ($p < 0.05$) between treatments and species. ($n = 5 \pm SE$).

3.5. Soil Chemical Properties

When we compared the chemical properties of soil where plantations with the selected tree species had been established with the pH of control soil (i.e., soil without plantations) (Table 3), we did not find significant differences. In the case of calcium carbonate (CaCO₃), the data indicated that the soil planted with *U. pumila* or *T. ramosissima* showed a considerable decrease in concentration that was correlated to higher irrigation regimes (8 and 12 L h⁻¹). Completely different was the result obtained with soil where *E. moorcroftii* had been planted as in this case the lowest concentration of calcium carbonate was observed with the highest level of irrigation (Table 3). The percentage of organic matter (%) remained constant with different watering regimes independently from the tree plantation considered. Regarding the Nitrate-Nitrogen concentration in the soil, we found a rapid decrease related to an increase in the level of the irrigation regime in the soil where *U. pumila* and *T. ramosissima* had been growing. In the case of soil with *E. moorcroftii*, we observed that despite the decrease of concentration related to an increase in the irrigation level, all Nitrate-Nitrogen concentrations were considerably higher than the control soil independent from the level of irrigation considered (Table 3). EC in soil with *T. ramosissima* showed close values with different levels of irrigation, while decreased in *U. pumila* and *E. moorcroftii* with irrigation higher than 4 L h⁻¹. Regarding phosphorous we found that by excluding the soil where *U. pumila* trees were irrigated with 12 L h⁻¹, all the other soils showed decreasing values related to an increase of the level of irrigation. In the case of potassium (K₂O), our data showed that by increasing the level of irrigation the concentration of potassium, except in soil with *E. moorcroftii* (Table 3).

Table 3. Changes in soil chemical properties in different irrigation regimes (12 L h⁻¹, 8 L h⁻¹ and 4 L h⁻¹) for *U. pumila*, *T. ramosissima* and *E. moorcroftii* values represent the mean of soil depth.

Plant Species	Treatments	pH	CaCO ₃	Organic Matter	EC _{2.5}	Nitrate-Nitrogen	P ₂ O ₅	K ₂ O
			%	%	dS/m	mg kg ⁻¹	mg/100 g	
<i>U. pumila</i>	12 L h ⁻¹	8.14 ± 0.03 ^a	4.25 ± 0.13 ^b	1.27 ± 0.03 ^b	0.109 ± 0.007 ^b	0.66 ± 0.03 ^c	4.39 ± 0.08 ^a	9.2 ± 0.11 ^a
	8 L h ⁻¹	8.09 ± 0.05 ^a	7.28 ± 0.04 ^{ab}	1.32 ± 0.03 ^{ab}	0.138 ± 0.008 ^{ab}	3.18 ± 0.06 ^a	1.08 ± 0.10 ^b	8.0 ± 0.05 ^a
	4 L h ⁻¹	8.42 ± 0.13 ^a	9.67 ± 0.17 ^a	1.41 ± 0.03 ^a	0.241 ± 0.04 ^a	1.35 ± 0.05 ^b	1.66 ± 0.04 ^{ab}	7.4 ± 0.1 ^a

Table 3. Cont.

Plant Species	Treatments	pH	CaCO ₃	Organic Matter	EC _{2.5}	Nitrate-Nitrogen	P ₂ O ₅	K ₂ O
			%	%	dS/m	mg kg ⁻¹	mg/100 g	
<i>T. ramosissima</i>	12 L h ⁻¹	7.83 ± 0.03 ^a	5.45 ± 0.02 ^b	1.83 ± 0.06 ^a	0.163 ± 0.005 ^a	0.87 ± 0.05 ^c	1.39 ± 0.04 ^a	9.8 ± 0.39 ^a
	8 L h ⁻¹	8.11 ± 0.05 ^a	5.45 ± 0.12 ^b	1.25 ± 0.07 ^c	0.155 ± 0.02 ^b	1.28 ± 0.03 ^b	0.75 ± 0.07 ^a	9.8 ± 0.60 ^a
	4 L h ⁻¹	7.99 ± 0.05 ^a	10.91 ± 0.05 ^a	1.45 ± 0.02 ^b	0.163 ± 0.005 ^a	2.38 ± 0.03 ^a	2.24 ± 0.11 ^a	8.0 ± 0.20 ^a
<i>E. moorcroftii</i>	12 L h ⁻¹	8.14 ± 0.02 ^a	11.51 ± 0.28 ^a	1.23 ± 0.05 ^a	0.126 ± 0.01 ^a	3.58 ± 0.07 ^b	1.27 ± 0.03 ^{a,b}	6.2 ± 0.03 ^b
	8 L h ⁻¹	8.13 ± 0.08 ^a	7.88 ± 0.01 ^{a,b}	1.20 ± 0.05 ^a	0.106 ± 0.01 ^a	4.55 ± 0.12 ^c	0.17 ± 0.01 ^b	6.2 ± 0.23 ^b
	4 L h ⁻¹	8.03 ± 0.08 ^a	4.45 ± 0.24 ^b	1.78 ± 0.06 ^a	0.189 ± 0.01 ^a	6.92 ± 0.10 ^a	3.87 ± 0.03 ^a	11.2 ± 0.39 ^a
Control	-	8.02 ± 0.07	10.91 ± 0.20	1.49 ± 0.04	0.132 ± 0.02	2.85 ± 0.07	3.93 ± 0.12	10.5 ± 0.65

Letters indicate significant differences ($p < 0.05$) among actors for each species.

4. Discussion

During the last decade, the number of new forests planted worldwide has increased exponentially, and this fact is important as it leads to an attempt to mitigate the negative effect of global changes through sequestering carbon from the atmosphere into plant biomass. At the same time, FAO reports [54] that the number of failures of tree planting initiatives is increasing with seedling mortality after 10 years of growth that could reach 83% as a consequence of negative factors related to technical (i.e., management) and environmental variables acting on the plantations [55].

The danger of failure calls attention to the need to continuously monitor the performance of these plantations, even several years from their implementation, to preserve the possibility of adopting supporting measures if necessary. In particular, close monitoring is necessary during the first few years of growth of the seedlings, when they are more exposed to negative effects due to environmental factors [56]. Moreover, avoiding the failure of the planting initiative is necessary to prevent a decrease in political support for this type of environmental restoration action [55].

Our research group started more than 10 years ago a monitoring activity to assess the performances of plantations implemented in the arid and semiarid lands of Mongolia to mitigate the advancement of desertification [2,17,19–21]. These plantations are part of a broader project called the “Green Belt Project,” aimed not only to avoid the irreparable loss of degraded soil but also to improve the local level of livelihood [57]. Another ecosystem service expected from these plantations is the possibility of sequestering carbon from the atmosphere into plant biomass and soil [58]. In fact, it is known that forests represent one of the largest carbon sinks in the world, given that more than 80% of terrestrial biomass is represented by AG and BG components of forest trees [59,60].

In a previous paper [25], we reported that all the tree species tested in the Green Belt plantations are not able to survive the drought conditions of desert sites without the support of drip irrigation. However, in this first study, the knowledge of both growth and development parameters referring to below-ground organs was completely ignored. The importance of investigating carbon allocation derives from the fact that it has been predicted [61] that distribution to below-ground organs is normally preferred over above-ground organs (i.e., optimal partitioning theory) when constraints such as drought limit the growth and development of trees [62]. In fact, several models regarding carbon allocation have been published, but the strategies adopted to govern the variations of biomass partitioning remain unclear [63].

The present study sheds light on the growth and development of *U. pumila*, *T. ramosissima*, and *E. moorcroftii*, trees and investigates if/how biomass is partitioned in above- and below-ground organs in different tree species responds to variations of the irrigation regimes. The first important result emerging from this work is that, unlike other tree species [64,65], we demonstrate that *U. pumila*, *T. ramosissima*, and *E. moorcroftii* can grow and develop in the presence of a low irrigation regime such as 4 L h⁻¹. Despite the fact that in our experimental settings we have not included the inclusion of a barrier able to avoid the movement of water among soil parcels subjected to different irrigation regimes (i.e.,

the impossibility to correctly correlate the growth response of the trees with the amount of water available in the soil receiving a specific irrigation regime), we show that also the lowest irrigation regime is sufficient to ensure the full development of all their above- and belowground organs. Hence, our study agrees with other authors [66–68] that in desert sites, the implementation of forests is possible despite the fact that it is necessary to dig wells to enable tree growth and consequently good plantation performance.

The morphological effect of irrigation on tree branching observed carries little significance since the plantations examined by our work are not located in an urban context where trees play a recreational and landscape-depicting function [69]. More important are the considerations emerging from our comparative analysis of biomass production and its partitioning among above- and below-ground organs (i.e., AG and BG). In fact, knowing where carbon is allocated is an important indication regarding the possible duration of its storage in plant tissues. The length of this storage depends directly upon the lifetime (i.e., when the organ will be shed from the rest of the plant) of the organ where the tissues are located. In fact, when carbon is allocated to leaves or fine roots, we can assume, from the knowledge that these organs have a short mean lifetime, that the carbon stored in them will be returned rapidly to the environment. Different is the case of stems, branches, or MR, LR, and VLR [70,71] where the retention time could be as long as the long life of the tree.

According to the data presented here, *T. ramosissima* accumulates less biomass and, for this reason, should not be used when a plantation aims only to sequester carbon. At the same time, *U. pumila* emerges as a better carbon accumulator even when trees are irrigated with the lowest irrigation regime. We exclude from our evaluations the data referring to leaf biomass produced by the trees examined, given that this carbon sink presents a too short lifetime compared to all other plant organs. Moreover, the fact that the ratio of BG to ToTB in all the tree species remains constant despite increasing levels of irrigation confirms that the amount of 4 L h^{-1} satisfies all the needs of water. This fact explains well why trees arrest any investment of carbon for the production of more roots [72,73].

Interesting is the pattern emerging of how BG is partitioned among roots of different diameter classes, despite the unexplained increase in biomass investment for the production of roots with small diameters when higher irrigation is present. In fact, our result contrasts with what is reported in the literature, which suggests that more fine roots are produced when the water amount in the soil decreases and a larger volume of soil must be explored by the plant in the search for water [74]. Our result also contrasts with our observation that AG does not change with higher irrigation regimes. In the absence of a physiological need (i.e., a higher level of water uptake), one possible explanation could be that in the presence of a higher amount of water in the soil, the mean lifetime of roots with smaller diameters is longer than normal, which would explain why we find an increase in biomass in this root class.

It is known that anthropogenic activities modify soil properties [75], and our data confirm that a number of the chemical properties of desert soil are modified, whereas others remain unchanged after the implementation of our plantations. We show the occurrence of a leaching effect on CaCO_3H and Nitrate-Nitrogen [76,77], despite the unexplained reason why, in the case of some tree species, the highest concentration values are related to the highest irrigation support. Furthermore, the lack of variation in organic matter measurable in the soil even in the presence of a high level of biomass production suggests that, probably in the desert site, litter decomposition has a scarce influence on the organic matter stored in the soil (at least at the soil depth considered in our study).

However, the alteration of desert soil properties when plantations are implemented calls for a more thorough study. More so given that irrigation of desert lands paves the way to agroforestry activities that represent an additional economic turning point for the population living in these poor lands.

5. Conclusions

Our work shows how the implementation of plantations in desert sites needs a preliminary comparative analysis of the effects of different irrigation regimes to find the lowest and most sustainable level of irrigation sufficient to successfully support the growth and development of trees. Furthermore, our comparative analysis of tree growth and development proves to be a necessary step in selecting the tree species that better adapts to the environmental factors that characterize a desert site. The destructive approach (i.e., tree excavation) used in our comparative analysis is the only one that provides a reliable measurement of the amount (and plant's organ partitioning) of atmospheric carbon sequesterable per tree and per hectare of plantation. This knowledge is necessary for building models regarding the possible contribution of forests established worldwide on desert lands to increasing global change mitigation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f15010046/s1>, Table S1: Two-way ANOVA results for woody plant height, RCD and root length; Table S2: Two-way ANOVA results for Above-ground and below-ground biomass.

Author Contributions: Conceptualization, B.N.-O. and S.-O.B.; methodology, B.N.-O. and S.-O.B.; software and data analysis, S.-O.B.; data collection, S.-O.B., S.L., E.T., O.B. and A.K.; writing, reviewing and editing S.-O.B., D.C., B.N.-O. and B.B.P.; supervision, B.N.-O. and B.B.P.; funding acquisition, B.N.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by the Mongolia-Korea Joint “Green Belt” Plantation Project provided by the Korea Forest Service and Northeast Asian Forest Forum and Yuhan Kimberly Co., Ltd. (Republic of Korea).

Data Availability Statement: The data used is primarily reflected in the article. Other relevant data is available from the authors upon request.

Acknowledgments: We thank the members of the Laboratory of Forest Genetics and Ecophysiology, National University of Mongolia and Jonathan O. Hernandez (College of Forestry and Natural Resources, University of the Philippines) for their help in field survey and plant material collections.

Conflicts of Interest: The authors declare no conflict of interest.

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