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Article

Effects of soil moisture stress on water use and crop coefficient of *Pinus eldarica* and *Melia azedarach* at different growth stages in an arid region

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Abstract: Water scarcity, particularly in arid and semi-arid regions, is a critical issue affecting forest management. This study investigates the effects of drought stress on the water requirement and morphological characteristics of two important tree species Turkish pine and Chinaberry. Using a factorial design, the study examines the impact of three age stages (one-year-old, three-year-old, and five-year-old plants) and three levels of drought stress on these species. Microlysimeters of varying sizes were employed to simulate different drought conditions. Soil moisture was monitored to show the effect of the various irrigation schedules. The study also calculated reference crop evapotranspiration (ET_0) using the PMF-56 method and developed plant coefficients (Kc) for the species. Results showed that evapotranspiration increased with soil moisture, peaking during summer and decreasing in winter. Turkish pine exhibited higher plant ET than Chinaberry, particularly among one-year-old seedlings. Drought stress significantly reduced evapotranspiration and water uses for both species, highlighting the importance of efficient water management in afforestation projects. The findings underscore the necessity of selecting drought-resistant species and optimizing irrigation practices to enhance the sustainability of green spaces in arid regions. These insights are crucial for improving urban forestry management and mitigating the impacts of water scarcity in Iran and similar climates globally.

Keywords: water requirement; water efficiency; microlysimeter; urban forestry management

1. Introduction

Low forest cover countries (LFCCs) are nations with minimal forested areas relative to their total land area [1]. These countries often face unique challenges related to environmental sustainability, biodiversity, and climate change mitigation [2]. Iran is currently considered one of the poorest countries in terms of forest area, classified as an LFCC, with forests covering only about 7.5% of the country's total area [3,4]. As a result of low forest cover and rapid forest degradation, afforestation and forest restoration programs began in the early 1950s in cooperation with governmental and non-governmental organizations (NGO), institutions, and associations in Iran [5].

A brief historical overview of these programs reveals that numerous projects have not been successful [6]. The primary reasons for these failures include water scarcity, unsuitable selection of planted species, soil infertility, dust storms, and lack of participation from indigenous and local communities [7,8]. Among these factors, water shortage is particularly significant because water is crucial for forestry in arid and semi-arid lands and is very limited for tree growth and development in the tropics [9–11].

The water crisis profoundly affects food, economic, and agricultural security and has even taken on political and security dimensions [12,13]. The scarcity of water resources, arising from environmental phenomena such as recurring droughts, population growth, increased energy demands, and water use in arid and semi-arid regions, is becoming increasingly problematic [14]. With the impacts of climate change (CC), global warming (GW), and excessive plant ET, water will become even scarcer in most geographical zones worldwide [15]. Therefore, allocating water use in arid and semi-arid regions is a highly challenging issue [16].

In urban areas, vegetation requires dedicated water to reduce air and noise pollution, sequester carbon, increase relative humidity, absorb dust and pollutants, provide recreation, and reduce psychological and mental stress. Insufficient water supply may result in reduced annual tree growth (ATG), increased incidence of pests and diseases, and higher maintenance costs for urban irrigation systems [17–19].

Drought stress is a critical environmental factor that significantly influences the growth, development, and survival of plant species, particularly in arid and semi-arid regions. Understanding how different tree species respond to drought stress is essential for effective and sustainable forest management (SFM) and conservation strategies. This study focuses on the effects of drought stress on two economically and ecologically important tree species: *Pinus eldarica* Medw. (i.e., Turkish pine) and *Melia azedarach* L. (i.e., Chinaberry tree).

P. eldarica is widely planted in urban and suburban landscapes due to its drought tolerance and aesthetic appeal. Native to the Caucasus region, it has adapted to dry climates but still faces challenges under extreme drought conditions [20]. *M. azedarach*, commonly known as Chinaberry, is a fast-growing deciduous tree native to South Asia and Australia, known for its ornamental value and use in agroforestry. Despite its adaptability regarding water uses, the extent to which drought stress affects the plant's development and morphological characteristics across different growth stages is still underexplored [21].

Evapotranspiration, which causes water loss from water, soil, and vegetation surfaces, is a critical factor to consider in Iran's arid and semi-arid lands with low rainfall and limited water resources [22]. Understanding the water uses of trees used in green belts, green spaces, and afforestation is crucial [23]. There is a great necessity to increase knowledge about actual evapotranspiration (crop plant ET which relates to transpiration) to adopt strategies that enhance irrigation efficiency [24]. Monitoring soil moisture allows for irrigation scheduling tailored to species types, ages, planting locations, and specific root zones [25].

Irrigation scheduling helps achieve optimal irrigation with suitable efficiency. Water shortage is a serious challenge in regions with arid and semi-arid climates, while in other regions, water abundance is not a similarly vulnerable condition [26]. Over the past decades, research on water uses has focused on fruit trees [27–30] and crops [31] to reduce financial costs and obtain more revenue. However, in the 21st century, with water scarcity prevalent in most parts of the world, the importance of this issue has greatly increased. Estimating the reference crop evapotranspiration (ET_0) and then adjusting it using crop coefficients (K_C) for a given plant has been widely used for irrigation scheduling and reported by many authors [32]. The estimated crop evapotranspiration (ET_C) can be used to determine the amount of irrigation water required for crops or trees in different months throughout the year [33].

This study aims to investigate the effects of drought stress on the water uses and morphological characteristics of *P. eldarica* and *M. azedarach* at various ages. By examining these effects, we seek to provide insights into the drought resilience of these species, which can inform their management and utilization in landscapes prone to water scarcity. Specifically, we will assess the overall water use efficiency of young, mature, and old trees of both species.

Understanding these dynamics is crucial for selecting appropriate species for afforestation and reforestation projects, urban greening, and landscape restoration efforts. Additionally, our findings will contribute to broader knowledge on plant adaptation mechanisms to drought stress, aiding in developing more resilient forest ecosystems in the face of climate change.

2. Materials and methods

2.1. Site description

Robat Karim County is located in the southwest of Tehran Province and covers an area of 275 km^2, situated at a longitude of 51°4′ and a latitude of 35°28′. It is at an elevation of 1050 meters above sea level. The county is bordered to the north by Shahriar County and the city of Karaj (in Alborz Province), to the south by Ray and Eslamshahr counties, to the east by Baharestan County, and to the west by Saveh County (in Markazi Province) [34]; (**Figure 1**).

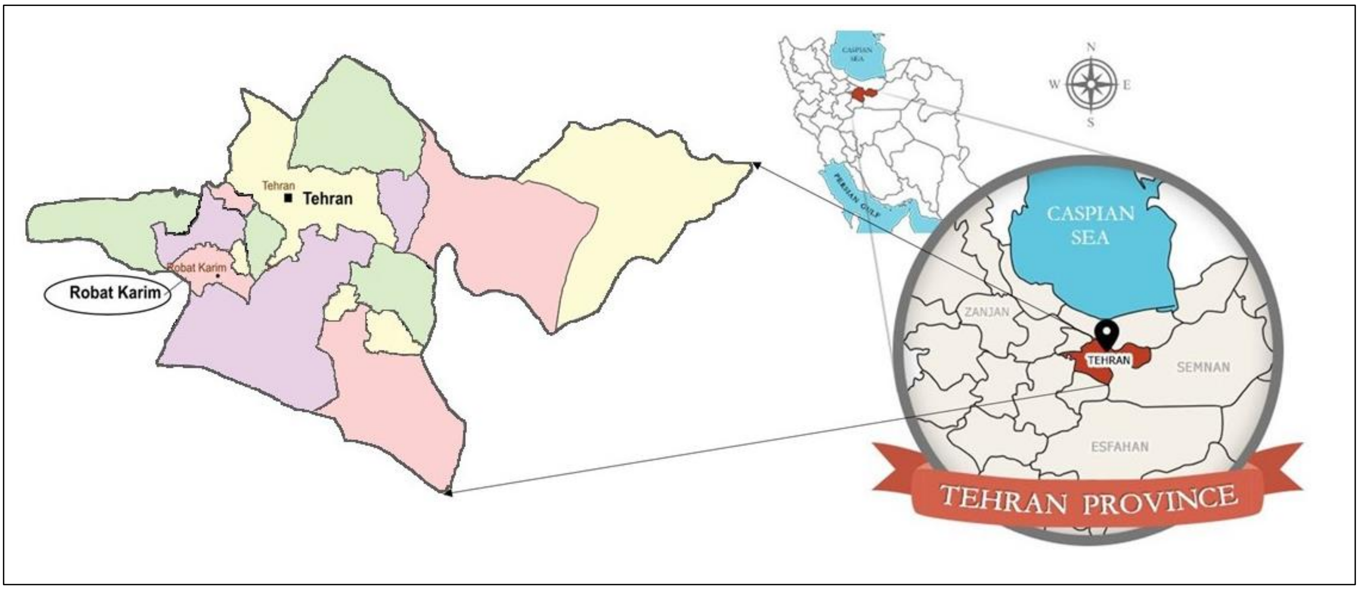


Figure 1. Location of the study area.

The study area experiences an arid climate, with an average annual rainfall of 140.2 mm and an average annual temperature of 17.8 ℃, according to the De Martonne aridity index.

2.2. Experimental design

The experiment follows a completely randomized design with a factorial arrangement of treatments. Each treatment combination (Plant Age × Drought × Day of the Year × Plant Type) is replicated 10 times, resulting in a total of 10 × 3 × 2 × 4 = 240 experimental units.

The factors considered were two plant species (Turkish pine and Chinaberry), three age stages (one-year-old, three-year-old, and five-year-old plants), and three levels of drought stress (low stress with MAD (Management Allowable Depletion) = 0.30, moderate stress with MAD = 0.50, and high stress with MAD = 0.70). Based on the root zone areas and maximum root depths of the one-year, three-year, and five-year-old saplings of Turkish pine and Chinaberry, the saplings were planted in microlysimeters considering the appropriate diameter and height for each species and age group (**Table 1**).

Table 1. Dimensions of used weighing microlysimeters.

Dimensions	**Small microlysimeter**	**Medium microlysimeter**	**Large microlysimeter**
Average diameter (cm)	17.5	23	26.5
Height (cm)	18	24	30
Area (cm^2)	240.4	415.26	551.26
Volume (cm^3)	4327.31	9966.36	16537.98

To analyze the effects of plant age, drought, day of the year, and plant types on our response variable, a multi-way ANOVA was used with 10 repetitions per treatment combination.

Three types of weighing microlysimeters of different sizes were used (**Figure 2**): small microlysimeters for one-year-old saplings, medium microlysimeters for three-year-old saplings, and large microlysimeters for five-year-old saplings. Weighing microlysimeters are not straight cylinders but are slightly shaped as cones. To facilitate drainage and increase hydraulic conductivity, the bottom of each weighing microlysimeter was covered with a one-centimeter layer of gravel. Considering the characteristics of both Turkish pine and Chinaberry, a sandy loam soil texture was used.

Figure 2. Shapes of used microlysimeters.

Out of the 240 repetitions, 120 were related to Turkish Pine, with 40 repetitions each for one-year-old, three-year-old, and five-year-old saplings. Similarly, 120 repetitions were related to Chinaberry, with 40 repetitions each for one-year-old, three-year-old, and five-year-old saplings.

Before planting the saplings, the initial morphological characteristics of all 24 treatments were measured. These characteristics included collar diameter (using a Caliper in mm), stem height (using a tape measure in cm), sapling canopy area (in cm^2), root length (longest root length), root volume (in cm^3), and the stem/root ratio. To establish the baseline status of the experimental saplings, 10 saplings were randomly selected. In addition to measuring the morphological parameters, the fresh and dry weights of the root and aboveground biomass were also measured.

Before planting the saplings, the physical and chemical properties of the soil were analyzed in the soil laboratory. The key physical and chemical parameters of the soil are summarized in **Table 2**.

Table 2. Soil physical and chemical properties.

Parameter	Unit	Measured value
Sand	%	62
Silt	%	19.8
Clay	%	18.2
Electrical Conductivity	$dS.m^{-1}$	5.62
pH	---	7.12
Bulk Density	$gr.cm^{-3}$	1.42
Field Capacity	%	23.3
Wilting Point	%	12.48

The current research was conducted in three distinct phases: estimation of water use, determination of plant coefficients, and investigation of the effects of drought stress on water use, plant coefficients, and morphological characteristics of the mentioned species.

2.3. First phase of study: Determining irrigation scheduling and water use

2.3.1. Step 1: Irrigation scheduling

After planting the seedlings in microlysimeters, a period of approximately 6 months (from December 2020 to June 2021) was allocated to acclimatize the seedlings to the new environment and mitigate environmental stresses without soil moisture monitoring. Soil moisture monitoring began in June 2021. Post-irrigation, soil moisture reached field capacity (FC) within 24 to 72 h. Daily soil moisture monitoring using TDR hygrometers (HH2 model) at specific morning times commenced to determine irrigation timing. The HH2 Moisture Meter is a versatile readout unit manufactured by Delta-T Devices, designed for use with various soil moisture sensors. Soil moisture levels at FC and permanent wilting point (PWP) were measured to establish management allowable depletion (MAD) levels for irrigation scheduling. Subsequently, irrigation was performed according to the scheduled plan, and soil moisture deficit (SMD) based on irrigation scheduling was replenished in the microlysimeters.

Field Capacity (FC) is a crucial parameter in soil science, representing the amount of water retained in the soil after excess water has drained away and the rate of downward movement has significantly decreased. Determining FC can be done through various methods, both in the laboratory and in situ. A common laboratory technique involves saturating a soil sample and then placing it on a pressure plate to apply a suction of approximately −1/3 atmosphere (or −100 hPa). This allows water to drain from larger pores while retaining water in smaller pores, which is considered the field capacity.

The volumetric water content at FC and PWP was calculated using Equation (1):

$$\theta_v = \frac{\forall_w}{\forall_t} = \frac{d_w * A}{d_t * A} = \frac{d_w}{d_t} \tag{1}$$

where θ_v is volumetric water content (%), $\forall_w$ is water volume, $\forall_t$ is total soil volume, A is microlysimeter's area (mm), d_w is water depth (mm) and d_t is total soil depth.

2.3.2. Step 2: Determining water use at four growth stages

Using the irrigation schedule and soil moisture data collected throughout the study period for all 18 treatments, evapotranspiration (ET) was calculated for four plant growth stages: initial, growth and development, intermediate, and final stages based on recorded microlysimeter data.

Evapotranspiration (ET) is a critical process in the water cycle, representing the sum of water evaporated from the soil and transpired by plants. Various methods have been developed to measure or estimate ET, each with its own advantages and applications. Direct measurement methods were used in this research.

In this method, Lysimeters are devices designed to measure the amount of water lost through evaporation and transpiration from plants. They consist of containers filled with soil that allow for the growth of crops under controlled conditions. Weighing Lysimeters measure changes in weight to determine water loss.

By measuring the weight of the lysimeter at regular intervals, researchers can directly assess how much water is lost due to ET. This method provides accurate data but requires careful control of environmental conditions to ensure that results reflect actual field conditions.

2.3.3. Second phase of study: Calculation of references crop evapotranspiration (ET_0)

Reference crop evapotranspiration (ET_0) was calculated using the PMF-56 method with ET_0 Calculator software, utilizing meteorological data from Imam Khomeini International Airport weather station, the nearest station to the study area during the research period.

The PMF-56 method refers to the Penman-Monteith FAO-56 model, a widely recognized standard for estimating reference crop evapotranspiration (ET_0). It is extensively used in agricultural, hydrological, and ecological studies due to its robust physical basis and accuracy in diverse climatic conditions.

Plant coefficients (Kc) for Turkish pine and Chinaberry were determined using Equation (2) since specific Kc values for these species in the study context were not previously known:

$$K_c = ET_c/ET_0 \tag{2}$$

where K_c is plant coefficient, ET_c is plant evapotranspiration and ET_0 is references crop evapotranspiration.

2.3.4. Third phase of study: Evaluation of the effects of different soil moisture stress

This phase involves evaluating how various levels of drought stress affect water use, plant coefficient (Kc), and morphological characteristics of Turkish pine and Chinaberry.

At various growth stages, morphological characteristics of saplings subjected to different levels of soil moisture stress were measured. The parameters evaluated included sapling height (cm), sapling diameter (mm), leaf condition (optimal, medium, pale), sapling health status (healthy, semi-healthy and infested), longest root length (mm), fresh and dry weights of roots (gr), and root volume (cm^3). Root parameters were measured at the beginning and end of the study period. Phenological data such as leafing time, full leafing time, leaf fall time, peak leaf fall time, and duration of leaflessness were also measured.

2.4. Data analysis

Data collection was managed using Microsoft Excel 2013. After ensuring data normality with the Kolmogorov–Smirnov test, a multivariate analysis of variance (MANOVA) was conducted at a 5% significance level using SPSS, R, and Python software. Additionally, all figures were generated using Microsoft Excel 2013.

The Kolmogorov–Smirnov (K-S) test is a nonparametric statistical method used to determine whether a sample follows a specific distribution or whether two samples originate from the same underlying distribution. It quantifies the maximum difference between cumulative distribution functions (CDFs) to assess the goodness of fit or the equality of distributions.

3. Results

At the beginning of the year (January), evapotranspiration starts at around 20–30 mm per 10 days. It gradually increases, reaching its peak between June and July, where values exceed 50 mm per 10 days, with some intervals approaching 60 mm. This peak corresponds to the warmest months, likely due to higher temperatures, increased solar radiation, and longer daylight hours. After July, evapotranspiration begins to decline, dropping to around 30–40 mm per 10 days in September and further decreasing to below 20 mm by November. The lowest values, around 10–15 mm per 10 days, occur in December and January (**Figure 3**).

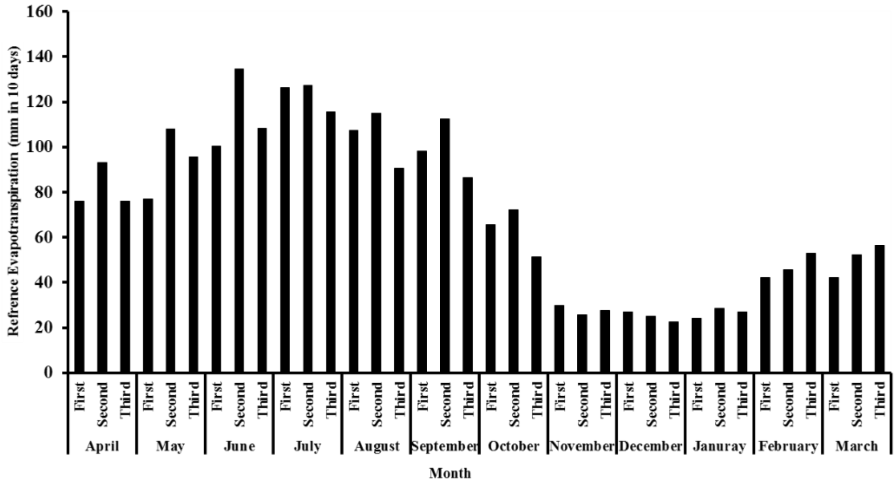
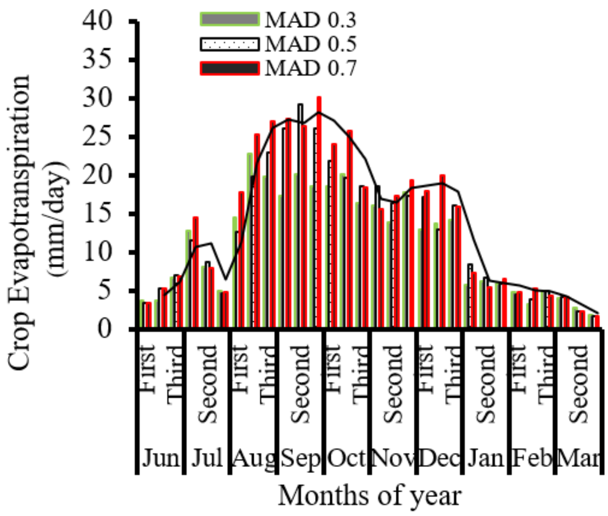
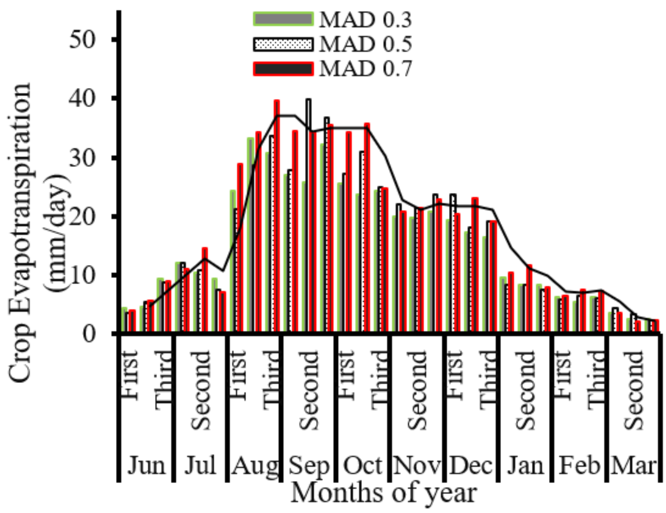


Figure 3. References crop evapotranspiration (ET_0).

During the observational period spanning April 2021 to March 2022, the crop evapotranspiration of pine was computed with respect to the magnitude of MAD and the corresponding age categories (**Figure 4**). The results indicated a maximum in pine water use during the summer season. Remarkably, the months of January and February exhibited the least demand for pine water across the 1-, 3-, and 5-year-old age groups, respectively. Furthermore, the manifestation of intensified water stress, denoted as MAD 0.7, exhibited a discernible increase during warm months and a concomitant reduction during cooler months across all age stages.



(a)



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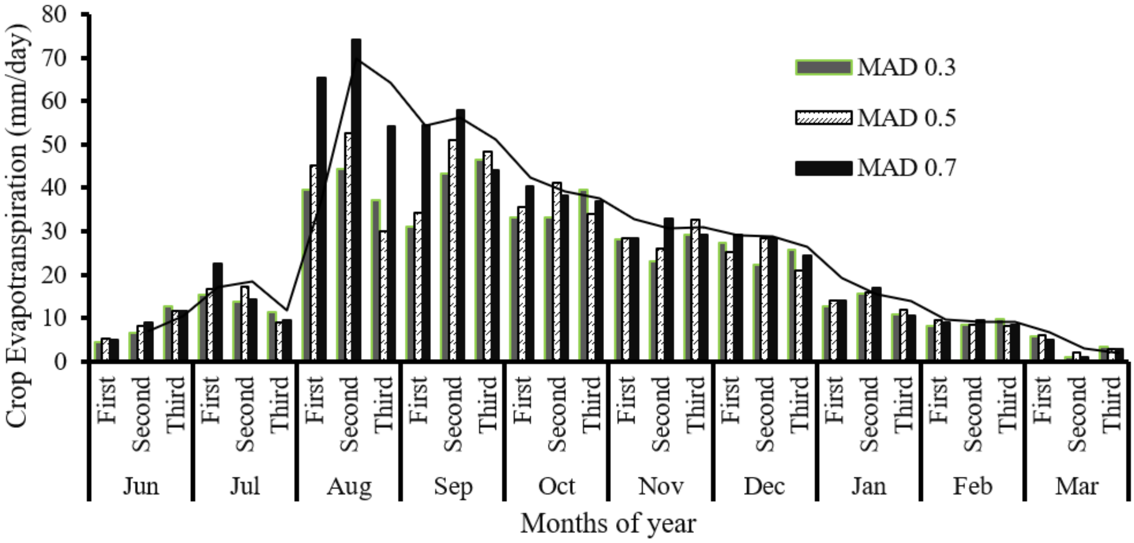
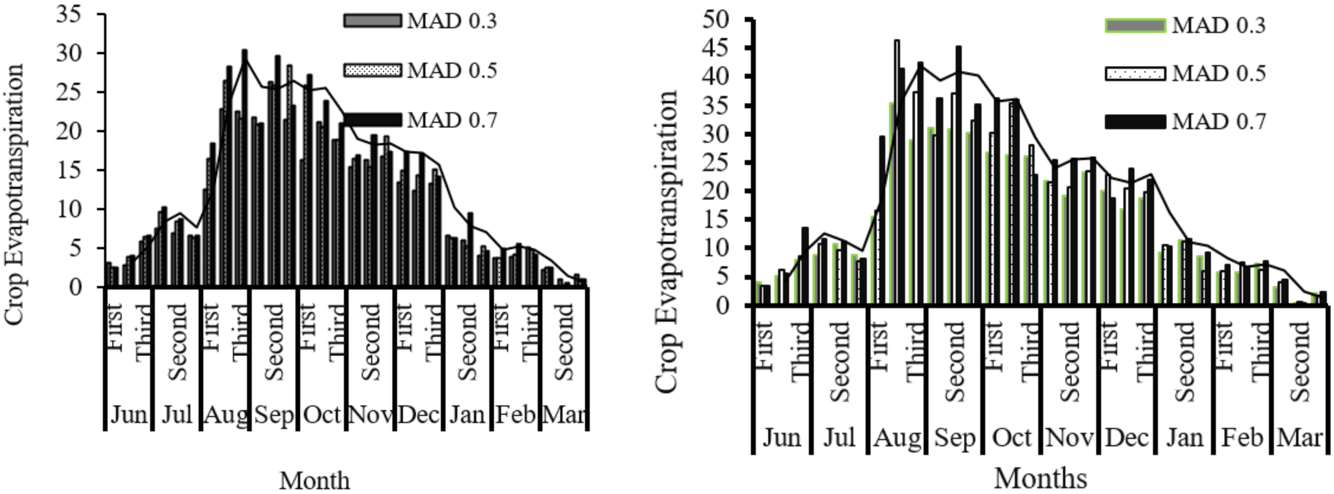


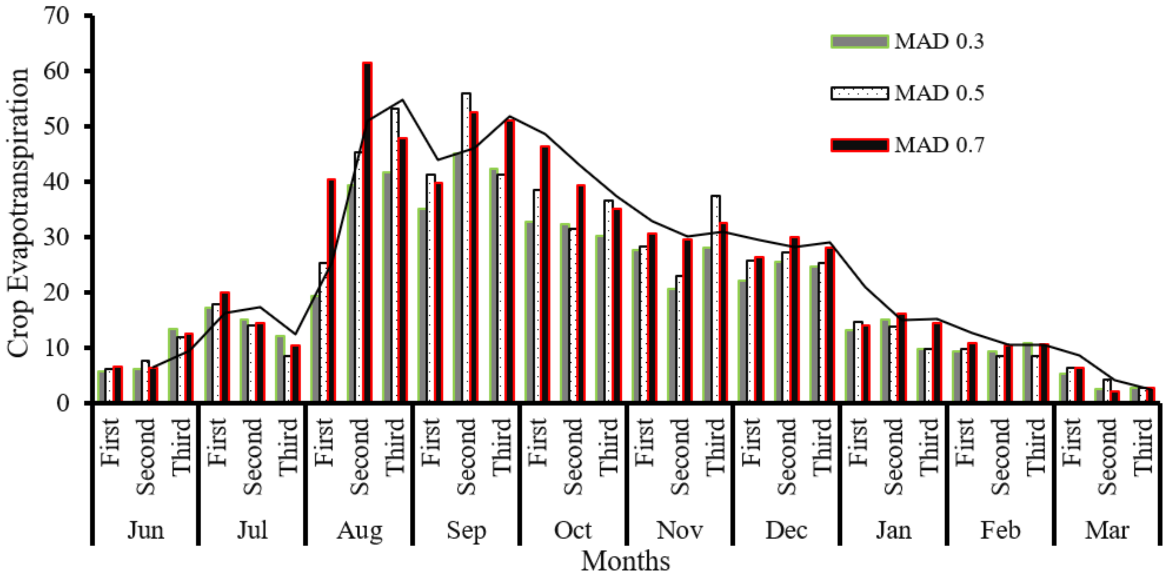
(c)

Figure 4. Turkish pine evapotranspiration in study period according to MAD and age.

Crop evapotranspiration (ETC) of chinaberry during the study period (April 2021–March 2022) according to the amount of MAD and the different ages was calculated (**Figure 5**). The results are the minimum and maximum in Chinaberry water uses during the summer season. Importantly, the months of February, February, and January depicted the least demand for pine water across the 1, 3, and 5 age groups, respectively. Furthermore, the manifestation of intensified water stress, denoted as MAD 0.7, exhibited discernible escalation during warm months and a concomitant reduction during cooler months across all age brackets (**Figure 5**).



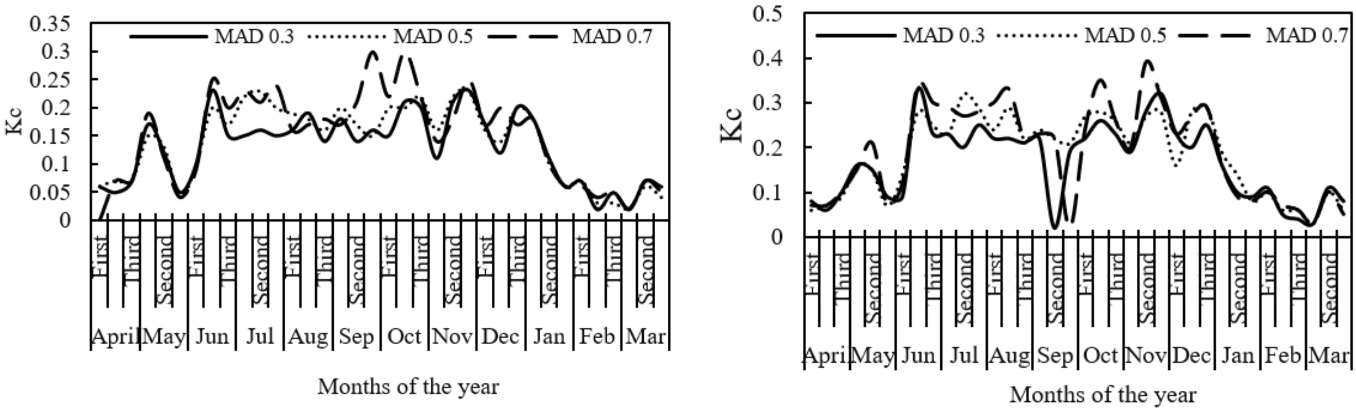
(a) **(b)**



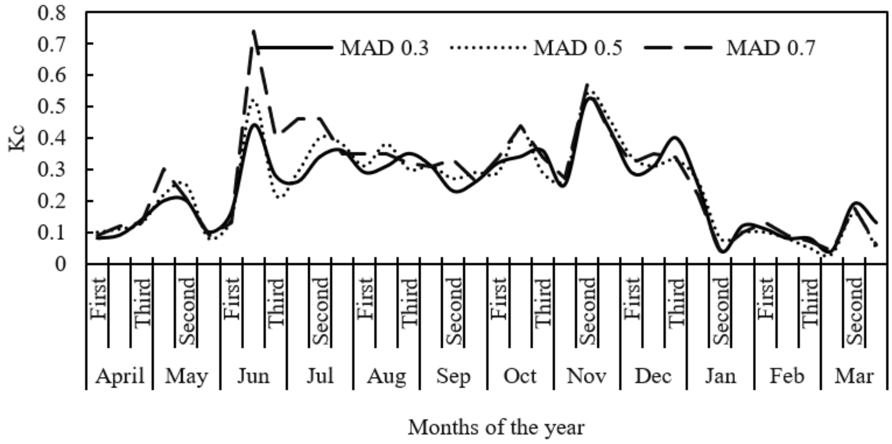
(c)

Figure 5. The chinaberry evapotranspiration in study period according to MAD and age.

Kc for Turkish pine at different MAD and ages was calculated (**Figure 6**). The vegetation coefficient of 1-year-old Turkish pine, experiencing drought stress, registers values of 0.3 MAD, 0.5 MAD, and 0.7 MAD from May to February, with the lowest values observed in March and April. The plant coefficient peaks at 0.23 (corresponding to the first decade of June and the third decade of November) when the stress level is at 0.3 MAD. Conversely, the lowest value of 0.02 is evident during the second decade of January and the first decade of March (**Figure 6a**).



(a) **(b)**



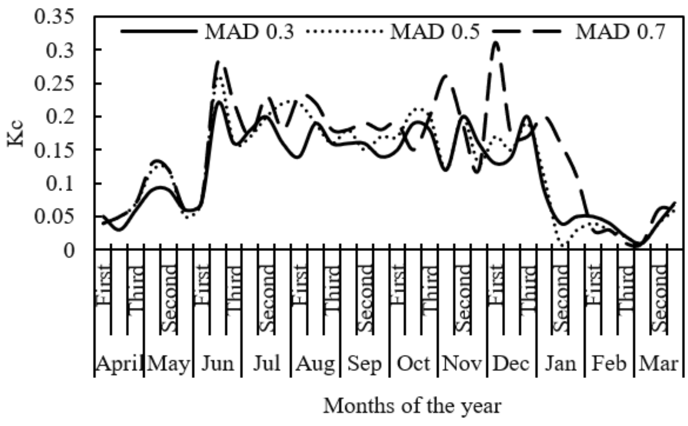
(c)

Figure 6. Plant coefficient for Turkish pine at different MAD and ages. **(a)** 1-year-old pine; **(b)** 3-year-old pine; **(c)** 5-year-old pine.

The vegetation coefficient of 3-year-old Turkish pine reaches its peak during drought stress conditions of 0.3 MAD, 0.5 MAD, and 0.7 MAD from May to January, while exhibiting its lowest value from February to April. Remarkably, the maximum value of the plant coefficient for the three-year-old Turkish pine under a drought stress level of MAD = 0.3 is observed in the second decade of June, at 0.33, whereas the minimum value is recorded in the first decade of March, at 0.03 (**Figure 6b**).

The vegetation coefficient for 5-year-old Turkish pine, under drought stresses of 0.3 MAD, 0.5 MAD, and 0.7 MAD, exhibits the highest values from May to December, and the lowest values from January to April. Specifically, the plant coefficient's highest value, at 0.52, is observed during the second decade of November under drought stress of MAD = 0.3. Conversely, the lowest value, at 0.04, is recorded during the second decade of January (**Figure 6c**).

The vegetation coefficient of a 1-year-old Chinaberry exhibits its highest values during drought stress periods of 0.3 MAD, 0.5 MAD, and 0.7 MAD from June to December. Conversely, the lowest values are observed from January to May. Specifically, the highest value of the plant coefficient in 1-year-old Chinaberry under drought stress is MAD = 0.3, occurring in the second decade of June, which is equal to 0.23. The lowest value, on the other hand, is recorded in the first decade of March, with a value of 0.1 (**Figure 7a**).



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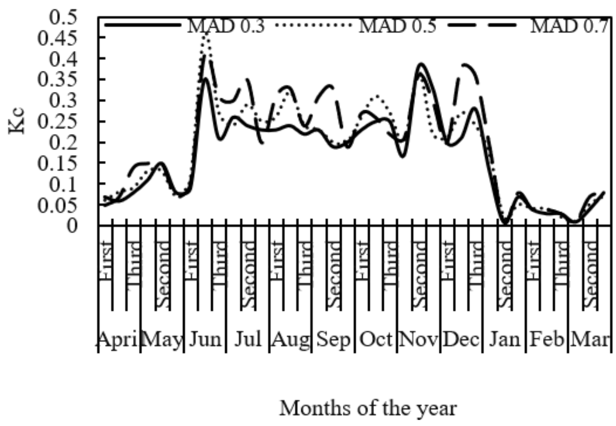

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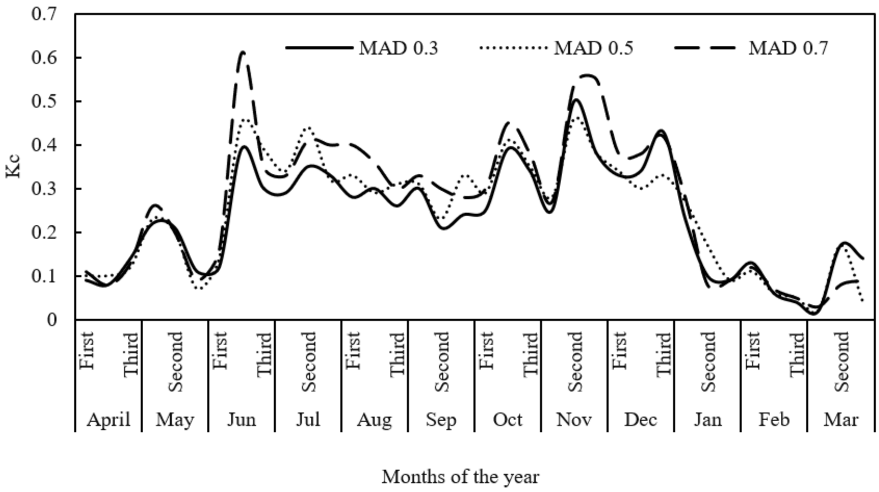

(c)

Figure 7. Plant coefficient for chinaberry at different MAD and ages. **(a)** 1-year-old chinaberry; **(b)** 1-year-old chinaberry; **(c)** 5-year-old chinaberry.

The plant coefficient of a 3-year-old Chinaberry under drought stress exhibits seasonal variation. Specifically, from June to December, the plant coefficients are 0.3 MAD, 0.5 MAD, and 0.7 MAD. However, from January to May, the coefficients are generally lower, with the exception of the stress level of 0.3 MAD, which demonstrates a relatively high plant factor. Importantly, the peak frequency of the plant coefficient for the 3-year-old Chinaberry under drought stress with MAD = 0.3 occurs during the second decade of November, with a value of 0.38. Conversely, the lowest value of 0.01 is recorded during the second decade of January (**Figure 7b**).

The vegetation coefficient for 5-year-old Chinaberry trees experiencing drought stress exhibits a range of values, namely 0.3 MAD, 0.5 MAD, and 0.7 MAD from May to December, with the lowest value observed during January to April. In the context of drought stress, the maximum plant coefficient for 5-year-old Chinaberry trees is MAD = 0.3, occurring in the second decade of November, equating to 0.50. Conversely, the minimum value, equivalent to 0.02, is evident in the first decade of March (**Figure 7c**).

The cumulative water use of both species at different MAD levels and seedling ages was calculated (**Figure 8**). The abundance graph depicting cumulative water content for both species demonstrates an overall increase throughout the study period. Specifically, for one-year-old seedlings under drought stress at 0.3 MAD, Chinaberry exhibited higher plant ET than Turkish pine. Conversely, under 0.5 MAD drought stress, one-year-old Turkish pine seedlings consumed more water than Chinaberry. At 0.7 MAD, the cumulative water use indicated that Turkish pine required a greater amount of water than Chinaberry (**Figure 8a**).

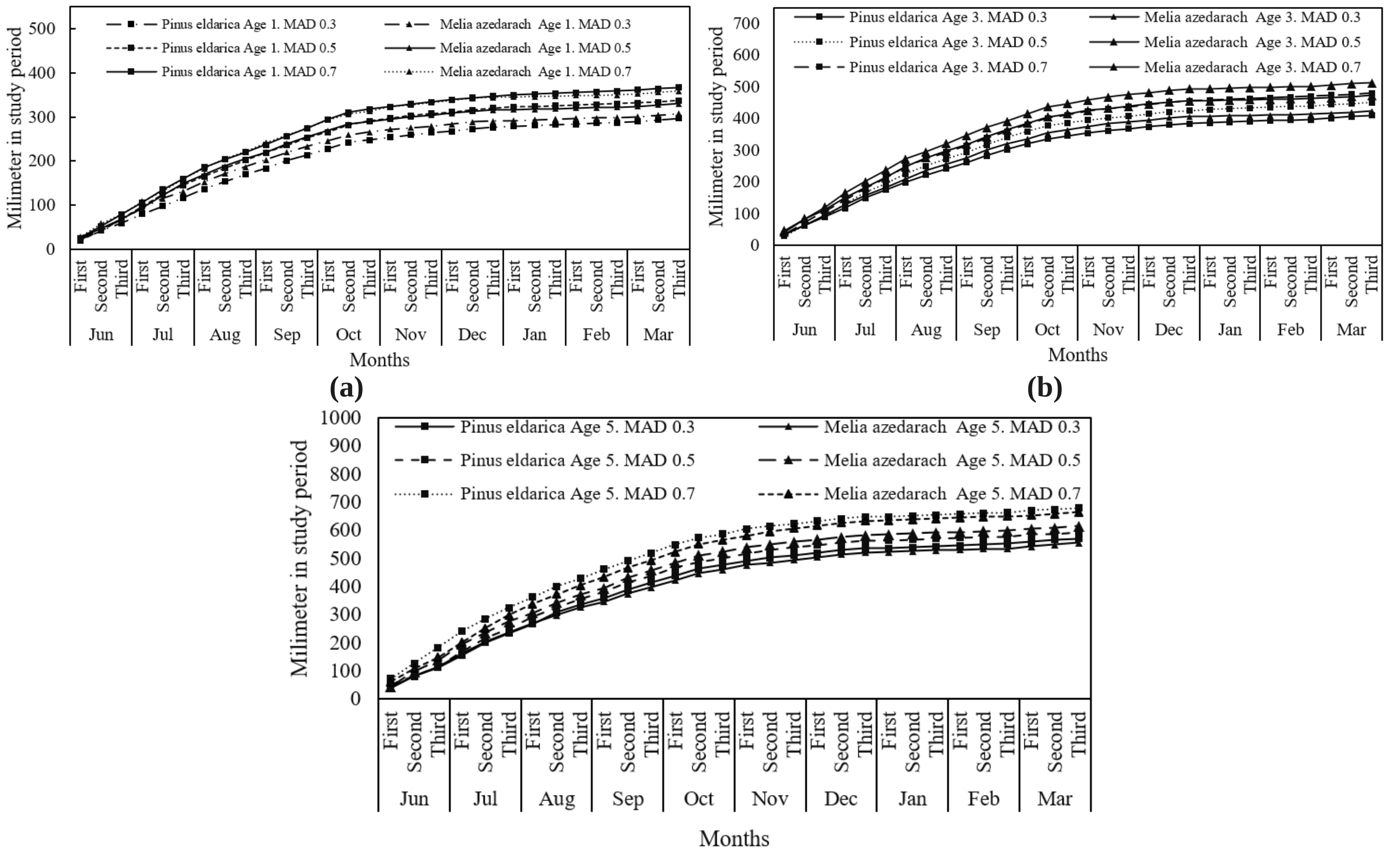

Figure 8. Cumulative water use of Turkish pine and chinaberry at different MAD and age 1, 2 and 3. **(a)** age 1 and different MAD; **(b)** age 3 and different MAD; **(c)** age 5 and different MAD.

A consistent upward trend in cumulative water use was observed in both Turkish pine and Chinaberry throughout the study period. For three-year-old seedlings under 0.3 MAD drought stress, plant ET was higher in Chinaberry compared to Turkish pine. Similarly, under 0.5 MAD drought stress, three-year-old Chinaberry seedlings exhibited greater water use than Turkish pine. However, at 0.7 MAD, Turkish pine showed higher cumulative plant ET than Chinaberry (**Figure 8b**).

A similar pattern was observed in five-year-old seedlings, with cumulative water use increasing steadily throughout the study. Under 0.3 MAD drought stress, Turkish pine exhibited higher plant ET than Chinaberry. In contrast, under 0.5 MAD, water usage was greater in Chinaberry. Finally, under 0.7 MAD drought stress, Turkish pine seedlings again demonstrated higher plant ET than Chinaberry (**Figure 8c**).

The results of the analysis of variance for treatments, plant species, drought stress, and the interaction effects of treatment on plant species under drought stress on the vegetative coefficient are shown in **Table 3** (Turkish pine) and **Table 4** (Chinaberry). For both the Turkish pine and the Chinaberry, the effect of species and age was significant, but the effect of drought stress and the interaction effect of species age under drought stress were significant at the 1% probability level.

Table 3. Analysis of variance for the effect of drought stress and age on the vegetative coefficient of the Turkish pine species.

	sum of squares	df	average of squares	*F*	Sig.
Corrected model	0.740	8	0.093	8.39	0.000**
age	0.705	2	0.353	31.96	0.000**
drought	0.033	2	0.017	1.517	0.221 ns
age* drought	0.002	4	0.000	0.041	0.997 ns
error	3.475	315	0.011		
total	16.11	324			
modified total	4.215	323			

**, *, ns: significance at the level of 1%, 5% and non-significance, respectively.

Table 4. Variance analysis of the effect of drought stress and age on plant factor of chinaberry.

	sum of squares	df	average of squares	*F*	Sig.
Corrected model	0.87	8	0.109	8.92	0.000**
age	0.822	2	0.411	33.7	0.000**
drought	0.045	2	0.022	1.84	0.161 ns
age* drought	0.003	4	0.001	0.056	0.994 ns
error	3.84	315	0.012		
total	16.4	324			
modified total	4.7	323			

**, *, ns: significance at the level of 1%, 5% and non-significance, respectively.

The results of the analysis of variance for treatments, plant species, drought stress, and the interaction effects of treatment on plant species under drought stress on the vegetative coefficient of the Chinaberry are shown in **Table 4**. The effect of species and age was significant, but the effect of drought stress and the interaction effect of species age under drought stress on the vegetative coefficient were not significant at the 1% level.

4. Discussion

4.1. The role of green spaces in urban sustainability

One of the crucial and key factors in the sustainability of natural and human life in today's urbanization is green spaces and the environment. Green spaces are effective in producing oxygen, reducing air dust, especially in windy areas, preventing soil erosion, and decreasing severe soil evaporation. However, one of the limiting factors in expanding green spaces is the shortage of accessible water resources. Expanding the current green spaces to meet global urban green space standards leads to increased vegetation coverage, which in turn means an increased consumption of water resources. Therefore, considering the dry and semi-arid climate of the country and the limitations in water supply, it is necessary to change urban green space management strategies to be compatible with long-term urban management goals in designing, creating, and maintaining green spaces. Various solutions exist to address these conditions, including water resource management and green space irrigation, selecting and planting drought-resistant species suitable for the regional climate, soil improvement operations, pruning and weed control, and managing green space development.

4.2. Climate and plant ET patterns in Robat Karim

Many studies worldwide have been conducted on determining the plant ET, most of which focus on agricultural species. However, the plant ET of species used in afforestation, green belts, urban green spaces, and nurseries in arid and semi-arid regions have been less studied, and there is also limited information on the irrigation interval for seedlings based on their plant ET. According to the meteorological data from Imam Khomeini Airport over a 15-year period from 2004 to 2019, the average annual rainfall is 147.6 mm, and the region's thermal regime shows that July and August are the warmest months while January and February are the coldest. Robat Karim, according to the De Martonne climate classification, is in a dry area. The calculated ET_0 maximums show that the highest ET_0 occurs in June and July due to high temperatures and increased heat. In accordance, the measured actual evapotranspiration in all treatments applied to both species showed that due to the warmer weather in June and July, actual evapotranspiration is higher than in other months.

The results of Shokrollahzadeh et al. [24] in determining the plant ET of elm and oleander species do not align with the current research findings. In this study, the highest ET_0 was in August at 8.2 mm/day, and the lowest was in February at 2.2 mm/day. The average minimum plant ET for oleander was 1.54 mm/day and for elm was 1.76 mm/day in February, while the highest plant ET for oleander was 6.314 mm/day and for elm was 6.56 mm/day in August. The difference in the highest and lowest indices during the study period likely relates to the species type, climate types being compared, geographical latitude of the area, and even the experimental environment.

The results of Delfan Azari et al. [35] on the effects of different irrigation levels on some morphophysiological traits of Turkish pine seedlings in the green spaces of Tehran in 2016 and 2017 partially align with the present study's results. The highest water uses in both years were in June (204.6 and 246.45 liters per month), and the lowest in the first and second years (139.5 and 117 liters per month) were in May and October, respectively.

The findings of Ewaid et al. [36] on determining the plant ET and irrigation programs for major crops in southern Iraq align with this study's findings. Their results showed that ET_0 during the day varied from 2.18 to 10.5 mm/day, and effective rainfall varied from 0 to 1.23 mm. There was a high water demand for crops in the warm season and a low water demand in the cold seasons.

It is important to acknowledge that these findings are specific to the climatic and edaphic conditions of Robat Karim, where Turkish pine has been studied under localized environmental gradients. Soil properties, including texture, water-holding capacity, and organic matter content, vary across the region and influence water availability. However, the lack of temporal soil moisture data limits a more precise understanding of how soil variability affects Kc values over time. Future studies incorporating long-term soil moisture monitoring could provide a more comprehensive assessment of the interactions between tree age, drought stress, and site-specific soil characteristics, enhancing the applicability of these results to broader forestry and water management practices.

4.3. Turkish pine vs. chinaberry: Evapotranspiration and plant ET

This research showed that with increasing soil moisture, the evapotranspiration of both species increases, meaning that as we approach field capacity, evapotranspiration increases. Conversely, applying drought stress treatments reduces evapotranspiration. Among the one-year-old seedlings, the plant coefficient for Turkish pine was higher than for Chinaberry, indicating higher plant ET for Turkish pine seedlings compared to Chinaberry. However, in three- and five-year-old seedlings, the plant coefficient was equal for both species. Among the drought stresses, the 0.3 MAD stress in Turkish pine had a higher plant coefficient compared to other drought stresses in both species, consistent with the study by Rad et al. [37], who examined evapotranspiration, plant coefficient, performance, and water use efficiency of two eucalyptus species using lysimeter experiments at different moisture treatments. The results showed that in both species, with increasing soil moisture, evapotranspiration increased, and there was a significant difference between different levels.

Rahimi et al. [38] also found that with increasing soil moisture, evapotranspiration increases, consistent with this study’s results. They found that in all treatments applied, the plant coefficient for Judas tree seedlings was higher than for Chinaberry seedlings, indicating higher plant ET for Judas tree seedlings. However, in general, reducing moisture decreased evapotranspiration, and increasing moisture increased evapotranspiration.

4.4. Plant ET patterns across different drought stress treatments

Overall, the evapotranspiration of Turkish pine and Chinaberry seedlings under drought stresses of 0.3 MAD, 0.5 MAD, and 0.7 MAD is generally highest in June and July and lowest in January and February. In addition, the plant ET of the studied species under drought stresses at MADs of 0.3, 0.5, and 0.7 show a decreasing trend. The results of Ahmadaali et al. [7] align with the current study’s results. Their findings on the plant ET and plant coefficients of Chinaberry in soil and different irrigation levels showed that the average 10-day ETc in MADs of 0.3, 0.5, and 0.7 in sandy loam soil were 15.35, 13.81, and 12.63 mm, respectively, and in clay loam soil were 19.35, 16.9, and 16.58 mm, respectively. The total net plant ET of Chinaberry in clay loam soil for MADs of 0.3, 0.5, and 0.7 were 445.15, 388.59, and 381.4 mm, respectively, and in sandy loam soil were 353.02, 317.59, and 290.54 mm, respectively. Furthermore, the average Kc of Chinaberry during the growth period in clay loam soil for MADs of 0.3, 0.5, and 0.7 were 0.34, 0.3, and 0.28, respectively, and in sandy loam soil were 0.27, 0.24, and 0.22, respectively.

Alaei et al. [8] found the highest evapotranspiration in July, consistent with this study's results. In their study, the highest evapotranspiration of oleaster in July was 41.57 mm, and the lowest in January was 6.65 mm. The total evapotranspiration of oleaster was estimated at 266.31 mm. Irrigation started on June 1st with 12.28 mm and ended on October 15th with 10.23 mm. The highest net irrigation requirement was 20.23 mm from July 16th to 31st, and the lowest was 10.23 mm from October 15th to 30th.

Asgari et al. [10] studied the plant ET and plant coefficients of tree species suitable for afforestation and green spaces in the dry region of Robat Karim, aligning with this study's findings. They reported that among the six species studied, the highest evapotranspiration was in early July for white mulberry (146 mm), ash (142 mm), and black maple (128.2 mm), and the lowest was in late November for Turkish pine (10.1 mm), mountain elm (11.24 mm), and black locust (16 mm). Tadros et al. [39] also reported that the plant ET for irrigating Prosopis in similar vegetative areas and different months vary.

4.5. Evapotranspiration trends in different growth stages

Evapotranspiration during different growth stages during the study period started from the beginning of the growing season, increased during the peak growth or development stage, reached its peak during the reproductive stage, and decreased again at the end of the season. The findings of Mostafazadeh-Fard et al. [40] on species factor and evapotranspiration of ash and Shiraz cypress are consistent with the current research. The species factor values for ash during four growth stages (initial stage, crop development, reproductive stage, and late season) were 0.24, 0.56, 0.73, and 0.37, respectively, and for Shiraz cypress were 0.32, 0.44, 0.58, and 0.34, respectively, showing a similar trend to the current study's findings.

The findings of Lozano et al. [20] on plant ET and plant coefficient are also consistent with the current research. They found that the plant's vegetative stages in the early, mid, and late growth periods were lower compared to FAO data. The determined crop coefficients were 0.87, 1.15, and 0.64 for the initial, mid, and late stages, respectively.

These findings provide critical insights into how Turkish pine's water use evolves with age and how such patterns may extend to mature trees or other arid ecosystems. In mature Turkish pine stands, water-use efficiency is likely to be more stable due to well-developed root systems that enable access to deeper soil moisture reserves. Unlike younger trees, which exhibit more pronounced fluctuations in Kc due to limited root development, mature trees may mitigate drought effects more effectively, maintaining higher transpiration rates even during dry periods.

Furthermore, the patterns observed in Turkish pine can inform water-use strategies for other tree species in arid and semi-arid environments. Many drought-adapted species exhibit similar age-related shifts in water uptake, with younger plants being more sensitive to short-term water deficits and mature individuals displaying greater resilience. This knowledge is essential for forest management and conservation planning, particularly in regions facing prolonged droughts due to climate change.

5. Conclusion

This research demonstrates that species' plant ET varies significantly based on climatic conditions and drought stress. Evapotranspiration rates peak during the hot months of June and July, aligning with the findings of similar studies conducted in arid environments. The study highlights that Turkish pine generally consumes more water than Chinaberry, especially under stress conditions, which has implications for species selection in water-scarce regions.

In conclusion, urban green space management strategies must adapt to local climatic realities by selecting drought-resistant species, improving soil management practices, and using efficient irrigation systems. These steps will allow urban planners to maintain sustainable green spaces while minimizing water usage.

For further research on the role of green spaces in urban sustainability, several areas could be explored to enhance our understanding and improve management strategies such as Drought-Resistant Plant Species, Innovative Irrigation Techniques, Soil Improvement and Water Retention, Climate Change Adaptation, Green Space Design for Urban Cooling, Socioeconomic and Ecological Trade-offs and Remote Sensing and GIS in Water Management.

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