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Is canopy interception increased in semiarid tree plantations? Evidence from a field investigation in Tehran, Iran

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Abstract: From 30 January 2011 to 30 January 2012, we measured the rainfall interception (*I*) and canopy storage capacity (*S*) of individual trees of *Pinus eldarica* and *Cupressus arizonica* planted in the Chitgar Forest Park near Tehran, Iran. Gross rainfall (*GR*) in this semiarid region was measured using the mean of 6 plastic rain gauges placed in an open area adjacent to the trees. To measure throughfall (*TF*), 20 plastic rain gauges were installed beneath the crowns of 5 individual trees of each species. *I* was calculated as *GR* minus *TF*. *S* was estimated using indirect methods: the minimum, Gash and Morton, mean, and Pereira methods. The cumulative mean values of relative percentage of *I* (*I*:*GR*) for *P. eldarica* and *C. arizonica* trees averaged 44.2% and 34.4%, respectively. Significant negative relationships were observed between the percent of *I*:*GR* and *GR* for *P. eldarica* (R^2 = 0.63) and *C. arizonica* (R^2 = 0.67) trees. For *P. eldarica*, *S* was estimated to be 1.10 mm, 1.00 mm, 1.09 mm, and 1.05 mm using the minimum, Gash and Morton, mean, and Pereira methods, respectively. For *C. arizonica*, the corresponding values are 0.58 mm, 0.52 mm, 0.56 mm, and 0.55 mm. This study proposes that in this climate dominated by small storms, planting *C. arizonica* is preferable to planting *P. eldarica*. However, the differences in the transpiration of these species should be quantified. Our results also indicated that the *I* value in this semiarid climate was higher than that of a humid climate.

Key words: Canopy storage capacity, *Cupressus arizonica*, *Pinus eldarica*, plantation, rainfall interception, semiarid climate

1. Introduction

Forest plantations cause major changes in the abiotic and biotic components of an ecosystem and provide a wide range of economic, ecological, and social benefits. Plantations have been reported to positively alter soil properties, soil protection, vegetation composition, carbon sequestration, and the hydrological cycle, as well as combat desertification and support recreation (George et al., 1999; Xiao and McPherson, 2002; Bellot et al., 2004; Chang, 2006; Oxbrough et al., 2006; Nosetto et al., 2007; Shachnovich et al., 2008; Jobbágy et al., 2012). The negative impacts of forest plantations on the function of an ecosystem, however, must also be taken into consideration (Zhang et al., 2001; Iroumé and Huber, 2002). Establishing a forest plantation can have important hydrological consequences. For example, establishing a plantation may reduce groundwater recharging (e.g., Holmes and Colville, 1970; Allison and Hughes, 1972) and result in an increase in canopy interception and transpiration (Vose et al., 2011; Buttle and Farnsworth, 2012). Forest canopy hydrology strongly influences ecosystem processes. Hence, changes in the forest canopy structure can alter the hydrology of the forest (Geiger et al., 2003; Renaud and Rebetez, 2009).

On an event basis, rainfall interception loss (*I*), or wet canopy evaporation, is the proportion of gross rainfall (*GR*) that is intercepted and stored on the branches, leaves/needles, and trunks and then evaporated into the atmosphere after or during a rainfall event or longer period (Dunkerley, 2000; Muzylo et al., 2009). Much of the remaining water reaches the forest floor either by dripping from the forest canopy (canopy drip), or falling directly to the forest floor through canopy gaps as direct throughfall (*p*) (direct throughfall + canopy drip = *TF*) (Crockford and Richardson, 2000; Chappell et al., 2001). Rainwater that reaches the forest floor by running down the trunks/stems of the trees is defined as stemflow (*SF*) (Shachnovich et al., 2008). *I* can be simply described as the difference between *GR* and net rainfall (*NR*), where *NR* is the sum of *TF* and *SF* (Xiao et al., 2000).

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It is necessary to consider the heterogeneity of *I* since it controls the water input to a forest plantation and, therefore, impacts ecological, hydrological, and biogeochemical processes. *I* is a rather complicated process; interception models, for instance, need information from up to 39 variables (Muzylo et al., 2009). Past research has demonstrated that needle-leaved trees produced less *TF* in comparison to broad-leaved trees (e.g., Aussenac, 1968; Aussenac and Boulangeat, 1980; Bryant et al., 2005; Cao et al., 2008). In needle-leaved forests the relative percentage of *I* (*I*:*GR*)% can range from 14% to 60% (Forgeard et al., 1980; Huber and Iroumé, 2001), whereas in broad-leaved forests it can range from 18% to 36% (Rutter et al., 1975).

Canopy storage capacity (*S*) is the amount of water the canopy can hold while saturated. *S* is a key parameter of rainfall interception and other ecohydrological processes (Rutter et al., 1971; Gash, 1979; Bruijnzeel et al., 1987; Liu 1997; Crockford and Richardson, 2000; Dunkerley, 2000, 2008; Link et al., 2004, Pypker et al., 2005). In needle-leaved forest ecosystems, *S* can be considerable, ranging between 0.3 mm (Lankreijer et al., 1993) and 3.8 mm (Aussenac, 1968). In broad-leaved forests, *S* can range from 0.26 mm (David et al., 2006) to 1.7 mm (Gash et al., 1980).

To accurately study the processes controlling *I*, an accurate estimate of *S* is necessary. Several direct and indirect methods have been used to estimate *S*. Direct methods include the cantilever deflection method (Hancock and Crowther, 1979; Huang et al., 2005), the ray-attenuation methods (Calder and Wright, 1986; Bouten et al., 1991), remote sensing (Liu, 1998; Vegas Galdos et al., 2012), and the artificial wetting of vegetative surfaces (Aston, 1979; Herwitz, 1985; Hutchings et al., 1988; Liu, 1998; Keim et al., 2006). These methods need specific, advanced, and expensive instrumentation, and difficulties may arise in scaling *S* from the specific storage capacities determined for the different plant parts. Indirect methods include graphical estimation of *S* (Leyton et al., 1967) and model optimizations (Rutter and Morton, 1977; Gash 1979; Gash et al., 1995; Whelan and Anderson, 1996; Pereira et al., 2009). Indirect methods are relatively inexpensive and require no complex instruments; however, a long measurement period is needed. Several common indirect methods include the minimum (Leyton) method (Leyton et al., 1967, Llorens and Gallart, 2000), the Gash and Morton method (Gash and Morton, 1978), and the mean method (e.g., Jackson, 1975; Klaassen et al., 1998). A relatively new indirect method for estimation of *S* by individual trees was proposed by Pereira et al. (2009). Compared to the minimum, Gash and Morton, and mean methods, the Pereira method is less sensitive to spatial variability in *TF*.

Most previous attempts to measure *I* and *S* in natural and plantation forests have occurred at the stand level (e.g., Rutter et al., 1975; Carlyle-Moses and Price, 1999; Bryant et al., 2005; Andrè et al., 2008; Ahmadi et al., 2009; Brauman et al., 2010; Shi et al., 2010; Buttle and Farnsworth, 2012) and few reports are available concerning the *I* and *S* of individual trees in forest plantation ecosystems (Gómez et al., 2001; Pereira et al., 2009). Moreover, a direct comparison of the *I* and *S* of 2 different tree species under similar meteorological conditions is rare. *Pinus eldarica* and *Cupressus arizonica* are popular species for plantations in arid and semiarid zones of Iran as well as in other countries with identical climatic conditions since both tolerate drought and high temperatures (Fink and Ehrler, 1986; Fisher et al., 1986; Sardabi, 1998; Harrington et al., 2005). Furthermore, *C. arizonica* is vital for controlling erosion (Vines, 1960) and is able to grow in calcareous, clayish, dry, and poor soils (Gallis et al., 2006). The aim of this study was to estimate the *I* and *S* of individual trees of *P. eldarica* and *C. arizonica* in a semiarid climate zone of Iran.

2. Materials and methods

2.1. Experimental site

The study area is located in the Chitgar Forest Park (35°42′N, 51°08′E, mean elevation 1250 m above sea level), on a southern-facing slope of the Alborz mountain chains, near Tehran, Iran (Figure 1). The park was established in 1968 after a combination of deciduous and coniferous tree species were planted. The park area is 1450 ha and was established to mitigate air pollution and provide green space for the Tehran megacity. When this study occurred, 48% of the park was covered by 42-year-old even-aged, homogeneous stands of either *P. eldarica* or *C. arizonica* trees.

2.2. Meteorological parameters

Climatic data from 1997 to 2012 were obtained from a meteorological station located within 4 km of the study site at 1215 m above sea level (Chitgar Meteorological Station, 35°42′N, 51°08′E). The mean annual rainfall in the region is 271 mm (standard error: ±15.3 mm), with March (46.6 mm; SE: ±5.5 mm) and August (1.4 mm; SE: ±0.3 mm) representing the wettest and driest months, respectively. The wet period extends from November to May, and historically accounts for 92% of the total annual precipitation (249.3 mm). Measureable rainfall occurs on approximately 71 days (SE: ±4 days) and snow in this region accounts for only a small fraction of the annual precipitation. The mean annual air temperature is 17 °C (SE: ±0.1 °C). August is the warmest month, with

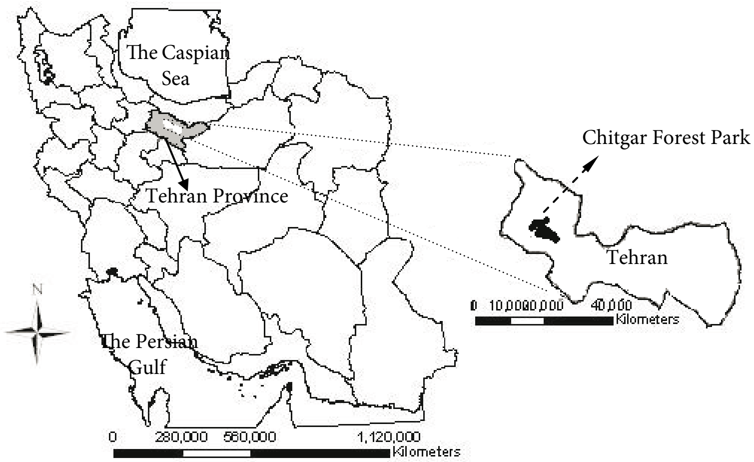

Figure 1. Map showing the location of the study area in the Tehran Province of Iran.

an average temperature of 29.9 °C (SE: ±0.3 °C), and January is the coldest month (3.9 °C; SE: ±0.3 °C). The "de Martonne" climate classification categorizes the study site as a semiarid climate type (de Martonne Aridity Index = 10.0). The prevailing wind direction is from the west to the northwest.

2.3. Tree selection

Measurements were conducted in separated flat plantations of *P. eldarica* and *C. arizonica* inside the Chitgar Forest Park. The elevation difference between the *P. eldarica* and *C. arizonica* plantations was only 16 m. Five individual, even-aged, healthy trees of each species with similar morphologies, i.e. tree height, diameter at breast height (DBH), height under branch, crown area, and crown closure were selected (Table 1). The crowns of the trees did not overlap with the neighboring trees (Owens et al., 2006).

2.4. Field measurements

The measurement period was between 30 January 2011 and 30 January 2012. Individual rain events were defined as having at least a 3-h-long dry period between rainfalls, which was long enough to allow the canopy to dry out completely (Carlyle-Moses et al., 2004). A total of 53 rainfall events occurred during this period and there was

Table 1. Characteristics of 5 individual *Pinus eldarica* (P) and *Cupressus arizonica* (C) trees.

Species	Diameter at breast height (cm)	Diameter of crown (m)	Height (m)	Height under branch (m)	Crown area (m^2)
P_1	25	4.8	7	2.7	7.5
P_2	29	5.1	7.4	3.2	8
P_3	21	4.6	6.8	3	7.2
P_4	22	4.7	6.5	2.9	7.4
P_5	23	4.5	6.6	3.1	7.1
Mean	**24**	**4.7**	**6.9**	**3**	**7.4**
C_1	24	4.9	5.8	3.8	7.7
C_2	19	4.6	5.3	3.4	7.2
C_3	17	4.6	5.4	3.3	7.2
C_4	20	4.7	5.1	3.4	7.4
C_5	22	4.4	5.2	3.6	6.9
Mean	**20**	**4.6**	**5.4**	**3.5**	**7.3**

no measureable snowfall during the measurement period. Previous studies demonstrated that an above-canopy *GR* volume is similar to the *GR* measured in an adjacent clearing (Loustau et al., 1992; Brauman et al., 2010). Hence, *GR* was measured using 6 plastic rain gauges 9 cm in diameter placed in a clearing about 100 m away from the *P. eldarica* and *C. arizonica* plantations (Shachnovich et al., 2008). The quantity of water collected was manually measured using a graduated cylinder with an accuracy of 1 mL. The average of the 6 rain gauges was used to measure *GR*.

TF was measured under each tree using 20 rain gauges of the same design as the rain gauges used to quantify *GR* (Shachnovich et al., 2008). The rain gauges were randomly located in a radial layout centered at the tree trunk. Past research has shown that separated trees have high spatial variability of *TF* (Lloyd et al., 1988). Therefore, we minimized the impact of the spatial variability on *TF* estimates by randomly locating *TF* collectors beneath each tree species. *TF* for each tree was obtained from the mean of the 20 rain gauges. All the *TF* and *GR* rain gauges were emptied and dried after each rainfall event. There was no understory vegetation in the vicinity of any of the rainfall collectors.

Equivalent *TF* was assumed to be equal to $TF = GR - I - SF$. No attempt was made to measure *SF*, since it was likely to be a very small fraction of *GR* for both *P. eldarica* and *C. arizonica*. Both of these species have very rough bark that likely limits *SF* (e.g., Helvey and Patric 1965; Geiger et al., 2003). In addition, other coniferous species that have similar canopy architecture as *P. eldarica* and *C. arizonica* experience little *SF* (Helvey and Patric, 1965; Crockford and Richardson, 1990; Lankreijer et al., 1993; Llorens, 1997; Llorens and Galart, 2000; Geiger et al., 2003; Link et al., 2004, Llorens and Domingo 2007; Asadian and Weiler, 2009; Bagheri et al., 2011; Motahari et al., 2013). The Duncan test was also employed to compare the *I*:*GR* for individual trees.

2.5. Canopy storage capacity (*S*)

The canopy saturation point (mm) is the amount of *GR* required to saturate the canopy. The canopy saturation point is always higher than *S* (or equal to *S* if direct throughfall (*p*) is zero). *S* was estimated through the following indirect methods that compare *GR* and *TF*:

1. The minimum method, or Leyton method (Leyton et al., 1967; Llorens and Gallart, 2000): *S* is determined by extrapolating the linear relationship between *GR* and *TF* for individual continuous rainfall events that are sufficient to saturate the canopy and have low evaporation rates during the storm. *TF* begins at the beginning of the storm if *p* is greater than zero, i.e. *GR* at $TF = 0$ is equal to *S*.

2. The Gash and Morton method: Gash and Morton (1978) demonstrated that the minimum (Leyton) method tends to underestimate *S* as a result of random measurement error. The Gash and Morton method, like the minimum method, determines *S* by plotting *GR* versus *TF* for individual continuous rainfall events that saturate the canopy and have minimum evaporation. However, instead of using the x-intercept, *S* is estimated as the absolute value of *TF* when $GR = 0$.

3. The mean method (e.g., Jackson, 1975; Klaassen et al., 1998): The mean method estimates *S* by generating 2 linear regressions (R_1 and R_2) that relate *TF* to *GR* (Klaassen et al., 1998). The first regression line (R_1) is fit to all the storm events where *GR* is insufficient to saturate the canopy. The second regression line (R_2) is fit to all rainfall events where *GR* is sufficient to saturate the canopy. To determine which rainfall events were applied to R_1 or R_2, the regression lines were visually fit. When using the mean method, the slope of R_1 provides an estimate of the direct throughfall coefficient (*p*), 1 – the slope of R_2 provides an estimate of the ratio of the mean evaporation rate from the wet canopy (mm h^{-1}) to the mean rainfall intensity (mm h^{-1}) ($\overline{E}/\overline{R}$), the value of *GR* at the intersection point of R_1 and R_2 provides an estimate of the canopy saturation point (inflection point), and the difference between *GR* and *TF* at the intersection point provides the estimate of *S*.

4. The Pereira et al. method (2009): This method estimates *S* using a tree-based equation that is an adaptation of the mean method (Klaassen et al., 1998). Based on this method, a linear relationship between *TF* and *GR* for rainfall events that are large enough to saturate the canopy is generated:

$$TF = aGR + b, \tag{1}$$

where *a* is the slope of *TF* vs. *GR* and *b* is an intercept of the regression line. *S* is determined with the following equation (Eq. (2)):

$$S = -\frac{b}{\left[\left(\frac{\overline{E}}{\overline{R}}\right)-1\right]}\frac{\overline{E}}{\overline{R}}\frac{1}{\ln\left[1-\left(\frac{\overline{E}}{\overline{R}}\right)\right]}, \tag{2}$$

where $\overline{E}/\overline{R}$ was estimated as 1 – the slope of the above-mentioned regression line (Leyton et al., 1967; Klaassen et al., 1998; Pypker et al., 2005).

2.6. Direct throughfall coefficient (*p*)

As *p* cannot be directly determined, several indirect methods have been used to estimate *p*, such as a graphical method, a regression method, and an optical method (Leyton et al., 1967; Llorens and Gallart, 2000). In this study, *p* was estimated using the mean method. The slope of the regression line that relates *TF* to *GR* for rainfall events that are insufficient to saturate the canopy provides an estimate of *p* (Leyton et al., 1967; Shi et al., 2010). In general, storms that are insufficient to saturate the canopy are determined by subjectively identifying the inflection point on a graph that relates *TF* against *GR* for all measured rainfall events (Motahari et al., 2013). All points below the inflection point are used to quantify *p*.

3. Results

3.1. Long-term mean and observed meteorological parameters

The cumulative rainfall for the study period was 307.3 mm, slightly more than the long-term average (271 mm). During the study period, the highest and lowest monthly rainfall occurred in February (56.1 mm) and June (1.6 mm), respectively (Figure 2). Mean air temperature was 17.0 °C during the study period, which matched the historic record. August was the warmest month both historically (29.9 °C) and during the study period (29.4 °C).

3.2. Gross rainfall (*GR*)

From 30 January 2011 to 30 January 2012, 232.5 mm of rain fell in 59 individual rainfall events. *GR* ranged from 0.4 mm to 15.2 mm and had a mean of 3.9 mm (SE: ±0.72 mm).

3.3. Interception (*I*)

During the measurement period, *I* under the *P. eldarica* and *C. arizonica* trees was 30.3% (cumulative: 70.51 mm), and 22.0% (cumulative: 51.16 mm) of *GR*, respectively (Figure 3). *I* depended on storm size, with the percentage varying from 12.2% for large storms (*GR* = 13.3 mm) to 71.8% for small storms (*GR* = 0.4 mm) under *P. eldarica* trees. In contrast, *I* under the *C. arizonica* trees ranged from 7.1% mm to 71.8% for the largest (*GR* = 10 mm) and smallest (*GR* = 0.7 mm) *GR* values.

The mean *I* (±SE) for an individual rainfall event was 1.19 mm (±0.10 mm) and 0.87 mm (±0.07 mm) under the *P. eldarica* and *C. arizonica* trees, respectively (Table 2).

The mathematical relationships between *I*:*GR* and *GR* for all the trees are shown in Table 3 and were obtained from scatter plots of *GR* against the corresponding *I* (not shown).

Duncan tests suggest that there was no significant difference between *I*:*GR* ratios for the *P. eldarica* trees; however, the *I*:*GR* ratios were significantly different among some of the *C. arizonica* trees (Table 4).

The mean percentage of *I*:*GR* was 44.6% under the *P. eldarica* trees and 34.2 under the *C. arizonica* trees. *I*:*GR* decreased as *GR* increased for *P. eldarica* and *C. arizonica*, as reported by previous studies (e.g., Xiao et al., 2000; David et al., 2006) (Figure 4). Significant negative logarithmic relationships were observed between the mean values of (*I*:*GR*)% and *GR* for the 5 *P. eldarica* and the 5 *C. arizonica* individual trees (*P. eldarica* ($I{:}GR = -14.39\ln(GR) + 57.44$, $R^2 = 0.63$), *C. arizonica* ($I{:}GR = -14.07\ln(GR) + 46.64$, $R^2 = 0.67$)). The mean values of *I*:*GR* for the *P. eldarica* and *C. arizonica* trees were significantly different ($t = 2.93$, $P < 0.001$).

3.4. Direct throughfall coefficient (*p*) and canopy storage capacity (*S*)

In this study, the canopy saturation points for the *P. eldarica* and *C. arizonica* trees were *GR* = 1.4 mm and *GR* = 1.2 mm, respectively. Based on the canopy saturation point, *p* was calculated as 0.17 for *P. eldarica* and as 0.24 for *C. arizonica* (Figure 5).

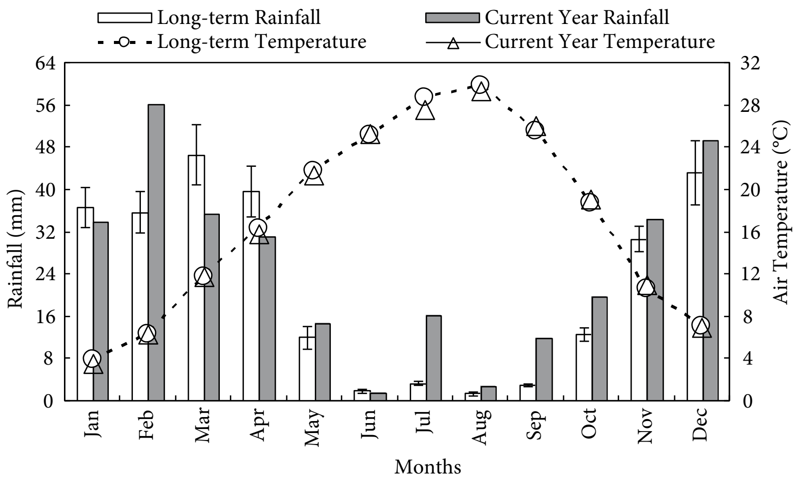

Figure 2. Monthly mean rainfall and air temperature for the study period (Jan 2011 to Jan 2012) and the previous 15 years (1997–2011), as recorded by a nearby meteorological station. Error bars show the standard error (SE) of the monthly rainfall for the long-term period.

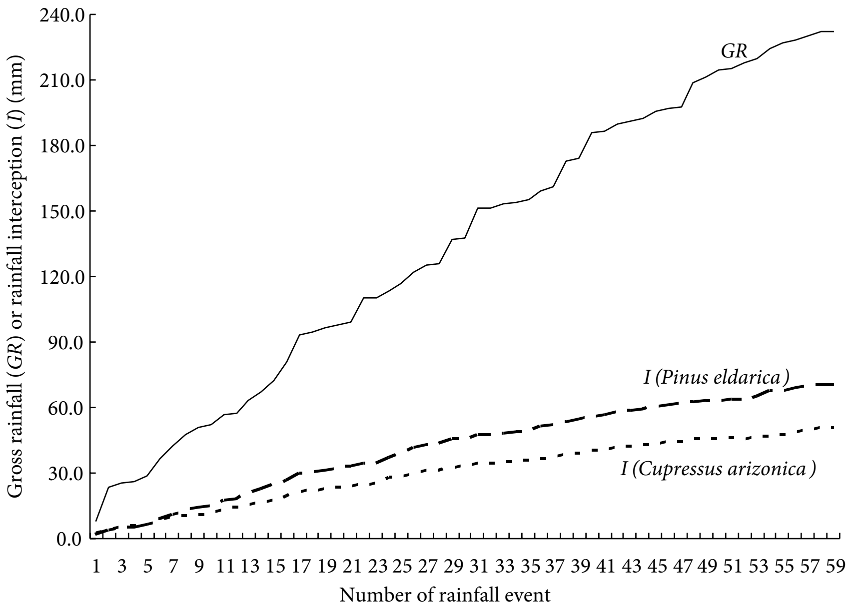

Figure 3. Accumulated gross rainfall (*GR*) and interception (*I*) by *Pinus eldarica* and *Cupressus arizonica* trees.

Table 2. The mean, maximum, minimum, standard error, and cumulative interception (*I*) of 5 individual trees of *Pinus eldarica* (P) and *Cupressus arizonica* (C) for 59 rainfall events. The subscripts 1 to 5 refer to each of the individual trees.

Species	*I*				
	Mean	Maximum	Minimum	Standard error	Cumulative
	mm	mm	mm	mm	mm
P_1	1.07	2.95	0.20	0.09	63.25
P_2	1.23	3.50	0.15	0.11	72.35
P_3	1.34	3.35	0.15	0.12	79.20
P_4	1.16	3.15	0.15	0.09	68.60
P_5	1.17	3.20	0.20	0.10	69.15
Mean	**1.19**	**2.99**	**0.19**	**0.10**	**70.51**
C_1	0.70	1.75	0.10	0.05	41.55
C_2	0.97	3.05	0.15	0.08	57.40
C_3	0.81	3.10	0.15	0.07	47.55
C_4	0.99	3.15	0.15	0.09	58.10
C_5	0.87	3.00	0.15	0.08	51.20
Mean	**0.87**	**2.31**	**0.16**	**0.07**	**51.16**

*Gross rainfall (*GR*) value is 232.5 mm.

Table 3. The logarithmic relationships between relative interception (*I*:*GR*) and gross rainfall (*GR*) for 5 individual trees of *Pinus eldarica* (P) and *Cupressus arizonica* (C). The subscripts 1 to 5 refer to each of the individual trees. The R^2 represents the correlation coefficient.

Species	Equation	R^2	P value
P_1	$I{:}GR = -14.36\ln(GR) + 53.79$	0.55	0.012
P_2	$I{:}GR = -14.82\ln(GR) + 58.60$	0.53	0.046
P_3	$I{:}GR = -11.89\ln(GR) + 57.49$	0.44	0.095
P_4	$I{:}GR = -14.21\ln(GR) + 56.93$	0.55	0.060
P_5	$I{:}GR = -16.67\ln(GR) + 60.41$	0.62	0.009
C_1	$I{:}GR = -11.11\ln(GR) + 37.59$	0.52	0.071
C_2	$I{:}GR = -17.06\ln(GR) + 53.89$	0.61	0.023
C_3	$I{:}GR = -14.47\ln(GR) + 45.91$	0.61	0.042
C_4	$I{:}GR = -15.18\ln(GR) + 52.09$	0.54	0.019
C_5	$I{:}GR = -12.57\ln(GR) + 44.27$	0.58	0.048

Table 4. Summary of the Duncan tests comparing *I*:*GR* for individual *Pinus eldarica* (P) and *Cupressus arizonica* (C) trees. The subscripts 1 to 5 refer to each of the individual trees. There was no significant difference ($\alpha < 0.05$) between trees denoted by the same letters.

Species	*I*:*GR* (%)	Standard error (%)	Significant
P_1	40.99	±2.57	a
P_2	45.39	±2.70	a
P_3	46.88	±2.37	a
P_4	44.27	±2.53	a
P_5	45.55	±2.81	a
C_1	27.69	±2.04	c
C_2	38.69	±2.88	b
C_3	33.01	±2.45	bc
C_4	38.55	±2.75	b
C_5	33.06	±2.19	bc

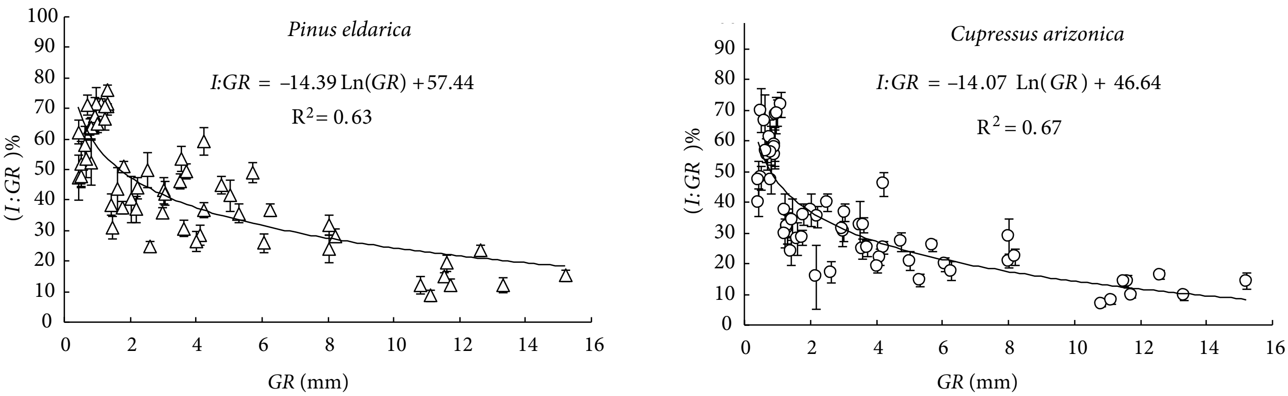

Figure 4. Scatter plots of percent of relative interception (*I*:*GR*)% versus gross rainfall (*GR*) for the mean of 5 individual *Pinus eldarica* and *Cupressus arizonica* trees during the study period. Error bars represent the standard error (SE).

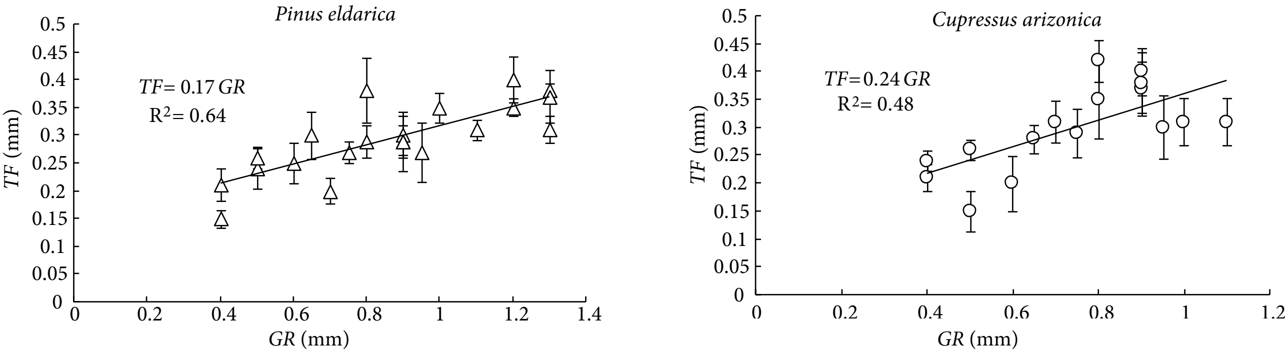

Figure 5. The relationship between gross rainfall (*GR*) and throughfall (*TF*) for rainfall where *GR* was less than the canopy saturation point. The slope of the regression line represents the direct throughfall coefficient (*p*). Error bars represent the standard error (SE).

S was estimated using 4 indirect methods that relate *GR* to *TF* for each tree (Table 5; Figures 6 and 7). For *P. eldarica*, *S* was estimated to be 1.10 mm, 1.00 mm, 1.09 mm, and 1.05 mm using the minimum, Gash and Morton, mean, and Pereira methods, respectively. For *C. arizonica*, *S* was estimated to be 0.58 mm, 0.52 mm, 0.56 mm, and 0.55 mm, by the same methods, respectively.

4. Discussion

Llorens (1997) reported that the average value of *I*:*GR* in a *Pinus sylvestris* forest in the Eastern Pyrenees, Spain was 24% and Mahendrappa (1990) reported *I*:*GR* for a *Pinus strobus* plantation in Canada to be 31%. However, in semiarid climate regions, research on *I* has been mostly limited to shrub vegetation (Guevara-Escobar et al., 2007) and there are few reports available for individual trees. Návar and Bryan (1994) studied *I* in a *Prosopis levigata* and *Acacia farnesiana* forest within a semiarid climate zone in Mexico, where they measured *I* to be 28% of *GR*. *I* also fluctuates among plantations grown in the same climate (Calder, 1990; Valente et al., 1997; Chang, 2006). The differences in *I* in the same climate may result from differences in tree characteristics such as leaf size, leaf area and shape, branch angle, phenological stage, crown roughness, crown density, and crown architecture, which can modify *TF* drop sizes (Lloyd et al., 1988, Marin et al.,

Table 5. Canopy storage capacity (*S*, in mm) calculated using 4 indirect methods and free throughfall coefficient (*p*) calculated using the mean method for 5 *Pinus eldarica* (P) and *Cupressus arizonica* (C) trees. The subscripts 1 to 5 refer to each of the individual trees.

Species	*S* (mm)				*p*
	Minimum method	Gash and Morton method	Mean method	Pereira method	
P_1	0.95	0.86	0.94	0.90	0.19
P_2	0.98	0.85	0.96	0.91	0.15
P_3	1.21	1.05	1.20	1.13	0.11
P_4	1.22	1.15	1.22	1.19	0.18
P_5	1.15	1.07	1.13	1.11	0.23
Mean	**1.10**	**1.00**	**1.09**	**1.05**	**0.17**
C_1	0.48	0.44	0.47	0.46	0.24
C_2	0.57	0.50	0.54	0.53	0.23
C_3	0.57	0.51	0.55	0.54	0.26
C_4	0.71	0.64	0.72	0.68	0.08
C_5	0.57	0.51	0.53	0.54	0.38
Mean	**0.58**	**0.52**	**0.56**	**0.55**	**0.24**

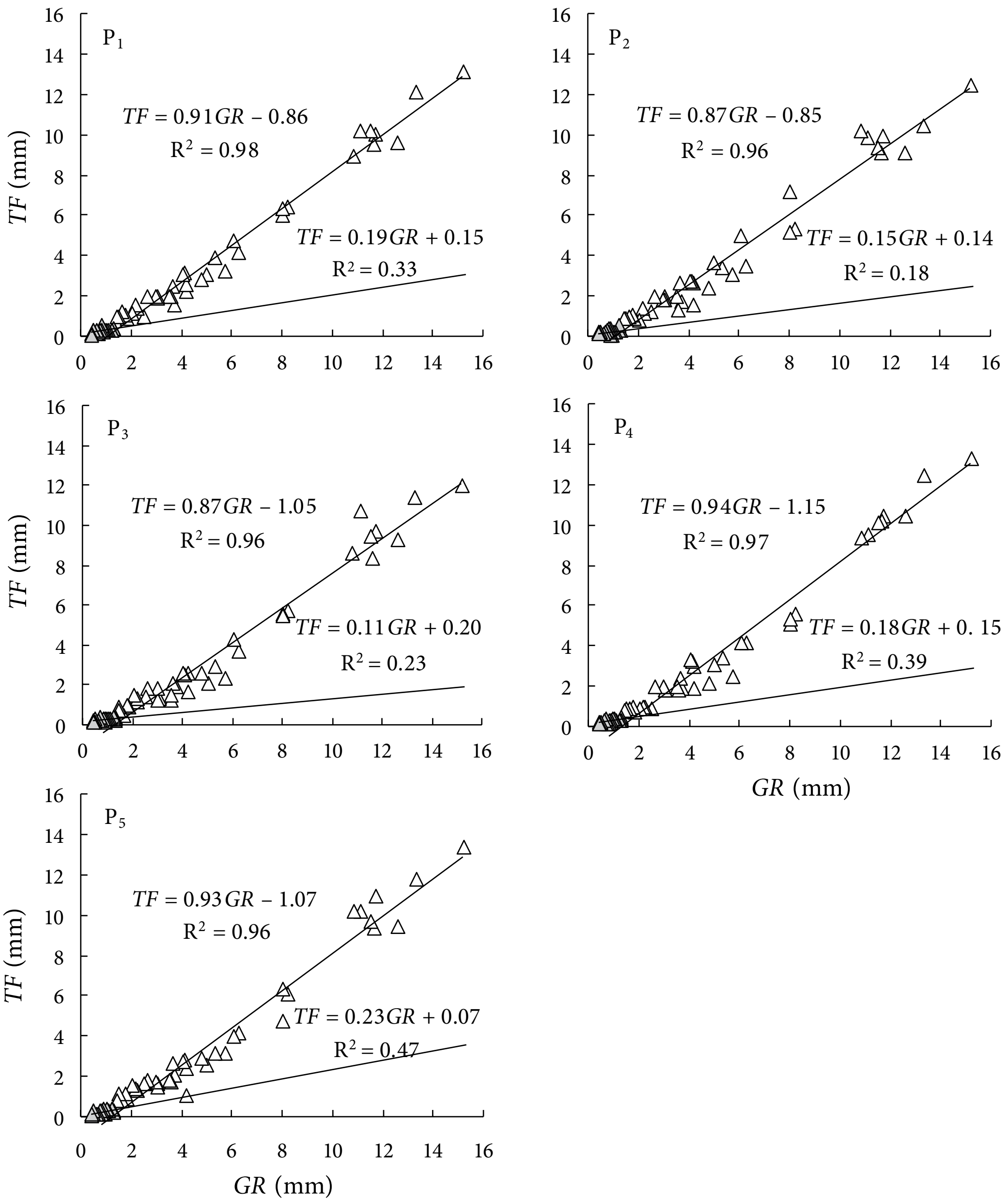

Figure 6. The relationship between gross rainfall (*GR*) and throughfall (*TF*) for all rainfall events with $GR \geq 1.4$ mm (open triangle) and $GR < 1.4$ mm (filled triangle) during the study period for the 5 individual *Pinus eldarica* (P) trees. Subscripts 1 to 5 refer to each of the individual trees. Each triangle (Δ) refers to a rainfall event.

2000; Dunkerely, 2000, 2008; Carlyle-Moses et al., 2004; Fleischbein et al., 2005; Toba and Ohta, 2005; Chang, 2006; Deguchi et al., 2006; De Schrijver et al., 2007; Llorens and Domingo, 2007; Muzylo et al., 2009). The results indicate that the *I* value in this semiarid location was higher than that of trees located in other humid climates (e.g., Rowe, 1983; Ahmadi et al., 2009).

In the present study, the different indirect methods for estimating *S* provided estimates that varied from 1.00 mm to 1.10 mm for *P. eldarica* trees and ranged from 0.52 mm to 0.58 mm for *C. arizonica* trees (Table 5). The difference in *S* likely results from differences in leaf area index (LAI) because *S* typically increases with greater LAI (Marin et al., 2000, Fleischbein et al., 2005; Staelens et al., 2006). The size of *S* under the *P. eldarica* trees was similar to that found for other pine forests (Table 6). The method of estimating *S* was based on the proposed method by Pereira et al. (2009) adapted for tree-based measurements (Pereira et

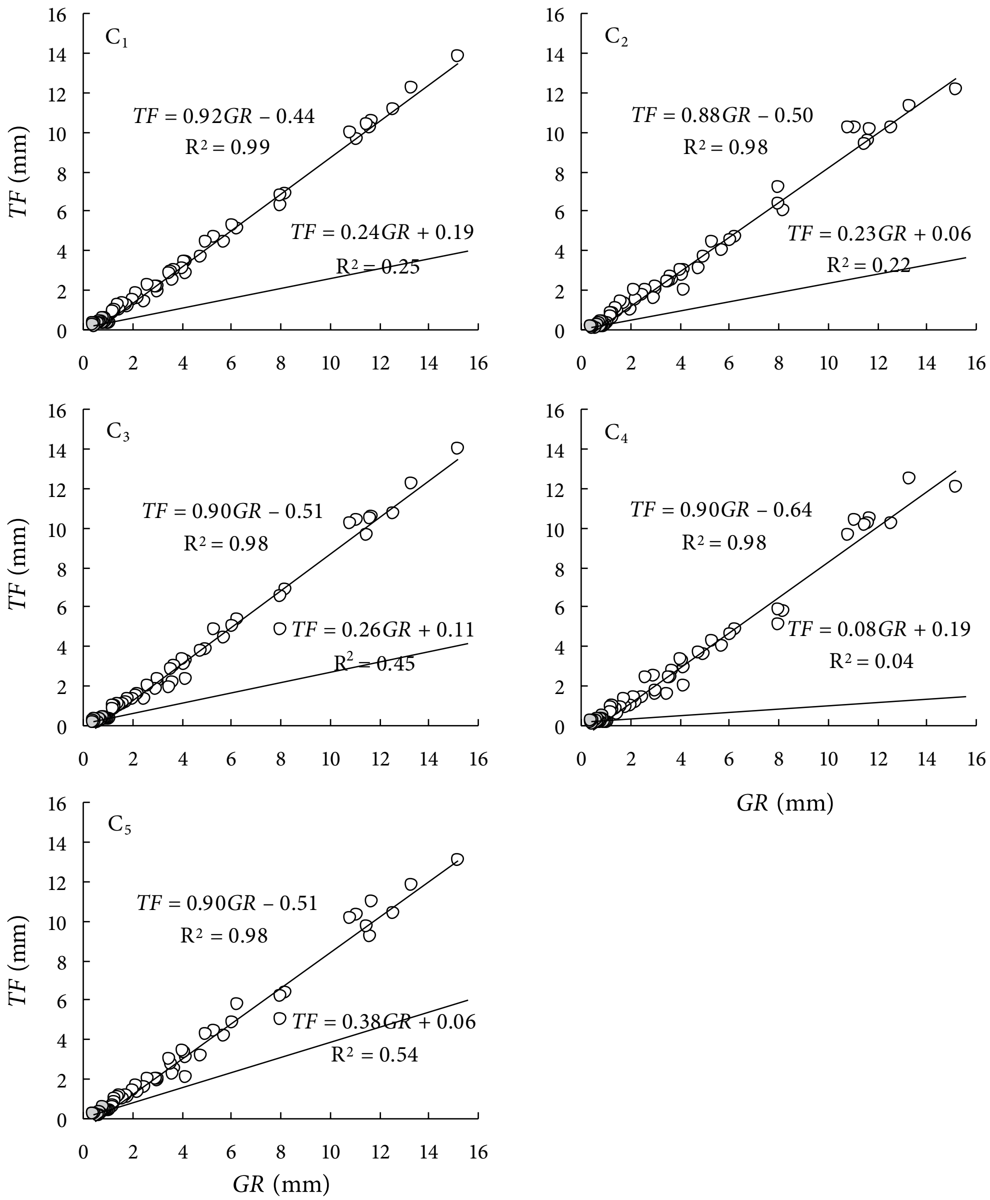

Figure 7. The relationship between gross rainfall (*GR*) and throughfall (*TF*) for all rainfall events with $GR \geq 1.2$ mm (open circle) and $GR < 1.2$ mm (filled circle) during the study period for the 5 individual *Cupressus arizonica* (C) trees. Subscripts 1 to 5 refer to each of the individual trees. Each triangle (Δ) refers to a rainfall event.

al., 2009; Fathizadeh et al., 2013). The calculated *S* values for individual trees of *P. eldarica* and *C. arizonica* using the minimum, mean, Gash and Morton, and Pereira methods were similar. This suggests that all 4 methods could be used for these tree types, as the Pereira method was designed to calculate *S* at the tree level in semiarid environments.

Interception loss differed considerably between the 2 tree types, with the *P. eldarica* trees losing 10% more rainfall to *I* than the *C. arizonica* trees during the study period. The 2 main evaporative losses attributed to *I* result from rainfall lost during the storm and after the storm. During the storm, $\overline{E}/\overline{R}$ largely controls the rainfall interception loss, whereas evaporation after the storm is controlled largely by *S*. $\overline{E}/\overline{R}$ in both tree species was strikingly similar, with both forest types averaging 0.10. Therefore, the differences in *I* between the 2 forests can be attributed to changes in *S*.

In the current research, *p* was estimated to be 0.17 and 0.24 for the *P. eldarica* and *C. arizonica* trees, respectively. To our knowledge, there is no information on the values

Table 6. Canopy storage capacity (*S*) and direct throughfall coefficient (*p*) measured in various research studies for needle-leaved species using indirect methods.

Tree species	*p*	*S* (mm)	Method	Reference
Pinus eldarica	0.17	1.05	Pereira	This study
		1.10	Minimum	
		1.09	Mean	
		1.00	Gash and Morton	
Cupressus arizonica	0.24	0.55	Pereira	This study
		0.58	Minimum	
		0.56	Mean	
		0.52	Gash and Morton	
Pinus eldarica	0.1	1.7	Minimum	Motahari et al. 2013
	0.1	1.77	Mean	Motahari et al. 2013
	0.1	1.4	Gash and Morton	Motahari et al. 2013
Pinus sylvestris	0.1	1.3	Minimum	Llorens 1997
Pinus pinaster	0.4	0.41	Minimum	Valente el al. 1997
Pinus pinaster	0.4	0.3	Minimum	Lankreijer et al. 1993
Pinus radiata	-	0.4	Gash and Morton	Kelliher et al. 1992
Pinus pinaster	0.6	0.5	Gash and Morton	Loustau et al. 1992
Pinus sylvestris	0.1	1	Gash and Morton	Gash et al. 1980
Pinus sylvesrtis	0.3	0.8	Gash and Morton	Gash and Morton 1978
Pinus nigra	0.3	1.1	Minimum	Rutter et al. 1971
Pinus sylvestris	-	1.6	Minimum	Rutter 1963

of *S* or *p* for individual trees in semiarid environments. Hence, we compared the results with those of other forests. Jackson (1975) reported the *p* of montane tropical forests to be 0.23. Llorens (1997) and Llorens and Gallart (2000) reported *p* in a *Pinus sylvestris* forest to be 0.1 and 0.2, respectively. Motahari et al. (2013) estimated *p* to be 0.14 for a *Pinus eldarica* afforestation in a semiarid climate zone of Iran. The low values for *p* suggest that the canopy gap fraction of *P. eldarica* and *C. arizonica* trees is fairly small. On the other hand, the thickness of the tree canopies of *P. eldarica,* which is greater than that of *C. arizonica*, can result in higher values of *I* and *S* in *P. eldarica*.

As reported by many authors, *I*:*GR* values increased as the size of *GR* events increased; however, as expected, higher *I*:*GR* values were observed for smaller *GR* events in both sites during the study period (Rowe, 1983; Lankreijer et al., 1993; Xiao et al., 2000; Marin et al., 2000; Llorens and Domingo, 2007; Ahmadi et al., 2009). The higher *I*:*GR* values for the small *GR* events are a result of a large portion of incident rainfall retained on the canopy, which evaporates during/after the rainfall. However, because of the greater *S* for *P. eldarica* trees, the smaller storms lose considerably more water to *I* under those trees than under the *C. arizonica* trees.

The greater interception losses by the *P. eldarica* trees suggest that in climates that are dominated by small storms, the planting of *P. eldarica* trees relative to *C. arizonica* trees will have a significant impact on the hydrology of the watershed. Background meteorological data recorded from 1997 to 2013 by the Chitgar Meteorological Station show that average annual rainfall in this semiarid climate is 271 mm and averages 3.82 mm per event. The historical climate of the region also indicates that 25 rainfall events (i.e. 34% of the total number of yearly storms) provide less rainfall than the canopy saturation point of *P. eldarica* trees, 1.4 mm. Furthermore, during the previous decade, the number of rainfall events lower than 1.4 mm increased from 20 days to 26 days. This implies that over the 10 years the number of small storms is increasing. Therefore, if the future climate in the region results in more frequent and smaller storms, then areas with *P. eldarica* will experience more evaporative loss relative to areas with *C. arizonica*. If *P. eldarica* is planted instead of *C. arizonica* within a semiarid region with frequent small rainfall events, it is plausible that these areas will experience reduction in the available water because of increased evaporative loss. However, to fully quantify the effect of the 2 species on the loss of water to the atmosphere, the differences in transpiration must be quantified (Motahari et al., 2013), as in some cases the differences in interception loss are offset by differences in transpiration losses (e.g., Licata et al., 2010).

Vegetation cover has an important influence on hydrological and biogeochemical cycles. The importance of plantations on hydrology is recognized worldwide. Thus, understanding the interaction between canopy characteristics and *I* is essential for quantitative modeling of the effects of forest plantations on water budgets. The rainfall partitioning occurring in plantation forest ecosystems of the semiarid climate zone is suffering from insufficient information, especially information from individual tree measurements. The present study demonstrates that *I* represents a significant portion of *GR* in *P. eldarica* (44.2%) and *C. arizonica* (34.4%) plantations in the semiarid climate zone of Iran. Based on *I* measurements alone, planting with *C. arizonica* would be better for water yield.

The current study is the first to record *I* and *S* in a semiarid climate zone at the individual tree level. The *S* of the trees was averaged as 1.06 mm and 0.56 mm for *P. eldarica* and *C. arizonica* via 4 indirect methods, respectively. Our research confirmed that *I* should be considered in future water budget plans and in the selection of tree species for plantations in the semiarid arid climate zones.

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