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Applying the Hargreaves model to *Catalpa bignonioides* water requirements under drip irrigation on light soil

Ariel Łangowski*, Roman Rolbiecki

Bydgoszcz University of Science and Technology, Faculty of Agriculture and Biotechnology, Bernardyńska 6, 85-029 Bydgoszcz, Poland

* Corresponding author

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Abstract: This study evaluated the Droogers and Allen modification of the Hargreaves model for estimating potential evapotranspiration (ET_p), determining crop coefficients (k_c), and assessing the water requirements of *Catalpa bignonioides* grown in row plantings on light soils. A field experiment ran from 2019 to 2022 at the Białe Błota forest nursery on sandy soil with limited water retention. Subsurface drip irrigation was applied in two variants based on soil water potential: W1 (−40 kPa) and W2 (−20 kPa). Meteorological data came from the Mochełek weather station. Reference evapotranspiration (ET_o) was computed with the Hargreaves approach and converted to ET_p using k_c and shading-dependent correction factors (k_r). Seasonal ET_p under W1 ranged from 240.30 to 422.83 mm, whereas W2 produced higher totals of 251.83–455.46 mm. The kc coefficients differed between irrigation variants, most clearly during the first three years after planting, and were consistently higher under W2; this pattern continued in subsequent years. Correlation analysis between field water consumption and Hargreaves-based ET_p showed very strong, highly significant relationships ($r > 0.94$ for July and $r > 0.93$ for June and August), confirming the robustness of the methodology. The derived kc values provide the first climate-criterion-based estimate of *C. bignonioides* water needs in central Poland and support irrigation scheduling for row-planted nursery species on light soils. Field water consumption (S) was determined using a soil water-balance method for the 0–60 cm soil layer. These parameters offer a straightforward framework for planning irrigation dates and doses in nurseries.

Keywords: *Catalpa bignonioides*, crop coefficients, Hargreaves model, light soils, subsurface drip irrigation

INTRODUCTION

Due to increasingly limited water resources (both surface and groundwater), horticultural, agricultural, and nursery production systems require the implementation of detailed methods for the determination of plant water requirements, along with the adoption of modern automatic irrigation systems. A key prerequisite for effective irrigation management is the determination of natural precipitation (as water input) and evapotranspiration (as water output). According to the recommendations of the Food and Agriculture Organization, the Penman–Monteith equation is the preferred method for calculating reference evapotranspiration (ET_o) (Allen, 1986; Allen *et al.*, 1998; Walter *et al.*, 2001; Allen *et al.*, 2005). In practice, however, applying the Penman–Monteith equation under Polish conditions requires extensive meteorological input data. Therefore, there is a need to adapt simpler computational models based on readily available meteorological parameters, primarily air temperature and humidity. The Hargreaves model, modified by Droogers and Allen, meets these criteria (Treder, Wójcik and Żarski, 2010; Rolbiecki, 2013; Sositko, 2019).

In Poland, light soils constitute nearly 50% of land designated for cultivation (Pierzgalski and Jeznach, 2006; Rolbiecki, 2021). As noted by Dzieżyc and Trybała (1989), their major disadvantages include unfavourable hydrological properties, such as excessive permeability, weak capillary rise, low water retention, short-lived reserves of readily available soil water, rapid drying, and more frequent and severe drought periods compared with medium and heavy soils (Rzekanowski, Żarski and Rolbiecki, 2011; Rolbiecki, 2021). Enhancing crop productivity on such soils requires compensating for recurrent water deficits; therefore, irrigation becomes an essential agronomic practice (Grabarczyk *et al.*, 1994; Żarski *et al.*, 2004; Rolbiecki, 2013; Rolbiecki, 2021).

Stachowski *et al.* (2021) compared several methods of estimating the water requirements of fruit trees in central Poland. The study showed that regardless of the method used to estimate water requirements in central Poland, they usually do not cover the full water requirements, which justifies the need for rational irrigation planning. Rolbiecki *et al.* (2025) described a detailed assessment of the water requirements of grapevines in southern Poland, which is an example of the application of modern water balance analyses in the context of climate change and irrigation system design. In addition, research by Rolbiecki *et al.* (2023) on the water requirements of cherry trees highlights the impact of climate change on seasonal water demand, which has direct implications for irrigation practices in nurseries and horticulture.

Due to the limited availability of complete meteorological data from many stations, a modified version of the Hargreaves formula was used. The need for local calibration of this type of simplified ET_o models for Central European conditions was also demonstrated by Rattayová *et al.* (2024).

The aim of the present study was to evaluate the suitability of the Hargreaves model, modified by Droogers and Allen, for calculating potential evapotranspiration (ET_p) and to determine crop coefficients (k_c) and the water requirements of *Catalpa bignonioides* grown in row plantings based on a climatic criterion (ET_p).

To date, k_c values for *C. bignonioides* under Polish climatic conditions and subsurface drip irrigation on light soils have not been reported, which constitutes the main research gap addressed in this study.

STUDY MATERIALS AND METHODS

FIELD STUDY

The study was conducted as a single factor field experiment from 2019 to 2022 at the Białe Błota forest nursery (53.104218, 17.926802) in the Kuyavian-Pomeranian Voivodeship, Poland. The experiment involved row plantings of *Catalpa bignonioides* supplied with a subsurface drip irrigation system operating under two irrigation variants: W1, where irrigation was initiated when soil moisture decreased to –40 kPa, and W2, where irrigation was applied when soil moisture decreased to –20 kPa. Irrigation was delivered through Eurodrip drip lines equipped with emitters discharging 2 $dm^3 \cdot h^{-1}$, spaced 30 cm apart and installed at a depth of 15 cm. Irrigation doses were precisely adjusted according to the occurrence of rainfall. Irrigation doses were adjusted according to daily rainfall recorded at the Mochełek meteorological station. Effective precipitation was subtracted from the planned irrigation dose, and irrigation was postponed or cancelled when rainfall fully compensated for the estimated soil water deficit within the controlled soil layer.

The experiment consisted of seven replications, each represented by a single tree. The spacing between trees within the row was 1.5 m. Each tree constituted an independent experimental unit. Spatial variability was minimised by conducting the experiment within a single row characterised by uniform soil texture, topography, and irrigation conditions.

Irrigation timing and volumes were determined on the basis of soil moisture monitored using Watermark sensors. The irrigation period covered the full growing season, beginning in the first ten-day period of April and ending in the third ten-day period of September.

Based on the cumulative water use measured within the controlled soil layer, the seasonal water demand of *C. bignonioides* during the study period ranged from 241.3 to 428.7 mm for irrigation variant W1 and from 266.1 to 458.8 mm for irrigation variant W2 (Łangowski, 2025). Seasonal variability of water demand was mainly related to the summer period. The highest ET_p values occurred in June–August, whereas April and September showed the lowest water demand. Differences between study years were primarily driven by variability in summer evapotranspiration.

SOIL CHARACTERISTICS OF THE EXPERIMENTAL FIELD

In the prepared soil samples (dried and sieved through a 2.0 mm mesh), the particle-size distribution was determined using laser diffraction with a MALVERN MS 2000 analyzer. Based on the percentage share of granulometric fractions for both irrigation variants, the soil was classified into the textural group of sand and the subgroup of loamy sand (PTG, 2009). The soil contained, on average, 78.8% sand, 19.7% silt, and 1.5% clay. Considering the proportion of particles <0.02 mm, the soil in the 0–30 cm layer was classified as light soil, whereas the 30–60 cm layer was classified as very light soil.

METEOROLOGICAL CONDITIONS

The study period was characterised by substantial variability in both rainfall and thermal conditions. The highest mean daily air temperatures during the growing season were recorded in 2019, reaching 15.9°C. The lowest seasonal mean temperatures, corresponding to the long-term average for the 1991–2020 reference period (14.8°C), occurred in 2020 and 2021. During the four-year period, the first two months of the growing season (excluding April 2019) exhibited temperatures below the long-term average. From June to September, the opposite pattern was observed, with mean monthly temperatures exceeding long-term values.

With respect to rainfall, the years 2019–2022 were generally characterised by a deficit relative to the long-term average, except for 2020. The mean rainfall total for the growing season across the four-year period was 307.8 mm, which was 16.6 mm lower than the long-term average for the 1991–2020 reference period. The driest year was 2021, with a seasonal total of only 260.7 mm, whereas the highest rainfall during the growing season was recorded in 2020 (435.5 mm). The maximum monthly precipitation occurred in June 2020 (153.9 mm). In 2022, the mean growing-season temperature reached 15.2°C, similar to 2019, while the seasonal rainfall total (267.7 mm) remained markedly below the long-term average, contributing to increased plant water demand.

EVAPOTRANSPIRATION INDEX

Field water consumption (S) was determined using the water balance method in a layer with controlled moisture content of 0–60 cm. The value of S was calculated using the Equation (1):

$$S = M_I + R - M_F \tag{1}$$

where: S = field water consumption (mm); M_I = initial moisture (mm); R = water revenue (effective rainfall + irrigation; mm); M_F = final moisture (mm);

Initial moisture (M_I) and final moisture (M_F) were determined based on soil suction pressure readings from Watermark soil sensors. Soil retention curves in the range of readily available water were used to determine moisture content in volume percent ($cm^3 \cdot cm^{-3}$). The soil retention curve was plotted based on the granulometric composition of the soil using the Varallyay indirect method (Varallyay and Mironienko, 1979). Based on the pF curves for the experimental soil, soil moisture was determined as a percentage of volume and the water content for the layer with controlled moisture was calculated.

The result of the formula was used to calculate the field water consumption for the growing season. This made it possible to determine the water demand during the growing season of the *Catalpa*. Water consumption was balanced in pentadic periods, and then decadal, monthly, and seasonal consumption was calculated for the water variants tested in the experiment.

The Hargreaves model in the Droogers and Allen modification provides an alternative for estimating ET_o compared to the Penman–Monteith method, which generally requires a larger set of input data (Allen *et al.*, 1998). The calculations using the Equation (2):

$$ET_o \ = \ 0.0025(T_{\text{mean}} + 16.8) \cdot (T_{\max} - T_{\min})0.5R_a \tag{2}$$

where: ET_o = reference evapotranspiration (mm), 0.0025 = empirical coefficient proposed by the authors, T_{mean} = average daily air temperature (°C); 16.8 = empirical coefficient proposed by the authors; $T_{\max}$ = maximum air temperature (°C); $T_{\min}$ = minimum air temperature (°C); 0.5 = empirical coefficient proposed by the authors; R_a = extraterrestrial radiation ($mm \cdot day^{-1}$).

Reference evapotranspiration was calculated using the Hargreaves model for individual days. The obtained ET_o values were then aggregated for ten-day periods, months, and years. Meteorological data were obtained from the meteorological station of the Bydgoszcz University of Science and Technology in Mochełek. The data derived from S and ET_o were used to calculate the crop coefficient (k_c) in order to determine the potential evapotranspiration during the irrigation period. Values of k_c were determined for *C. bignonioides* for each month of the growing season (April–September), starting from the second year of vegetation, i.e., during the period of formation and development of generative shoots. The k_c values were calculated using the Equation (3):

$$k_c = \frac{S}{ET_o} \tag{3}$$

where: S = field water consumption (mm), ET_o = reference evapotranspiration (mm).

To calculate potential evapotranspiration on a surface with limited wetting (ET_pK), the equation by Vermeiren and Jobling (1984) was used:

$$ET_pK \ = \ ET_o \cdot k_c \cdot k_r \tag{4}$$

where: ET_o = reference evapotranspiration (mm), k_c = crop coefficient, k_r = reduction (correction) coefficient.

Based on the percentage of ground surface shading by the plants, the values of the correction coefficient k_r were adopted according to Treder (2021). According to Treder, the value of the correction coefficient k_r depends on the degree of ground surface shading. For 10% shading, k_r = 0.28; for 20%, k_r = 0.48; for 30%, k_r = 0.65; for 40%, k_r = 0.80; for 50%, k_r = 0.90; and for 60%, k_r = 1.00.

RESULTS AND DISCUSSION

The potential evapotranspiration of *Catalpa bignonioides* was calculated using a climatic criterion, i.e., by incorporating the crop coefficient (k_c) (Tab. 1), which reflects the species-specific characteristics and its developmental stage. The reference evapotranspiration (ET_o), calculated using the Hargreaves model modified by Droogers and Allen, was multiplied by the corresponding k_c values. The coefficients were determined for each month of the growing season and for the two irrigation variants (W1 and W2). Following the approach of Żakowicz (2010), the k_c values were classified into two categories: up to three years after planting and more than three years after planting. In this study, the correction coefficient (k_r) according to Treder (2021) was applied based on the percentage of ground surface shading by plants to calculate water requirements under drip irrigation (restricted soil wetted area).

Table 1. Crop coefficients (k_c) for the months of the growing season used to calculate the potential evapotranspiration of *Catalpa bignonioides* using the Hargreaves formula

Period	Variant	Value of k_c for month					
		Apr	May	Jun	Jul	Aug	Sep
First 3 years after planting	W1	0.40	0.50	0.50	0.60	0.60	0.60
	W2	0.50	0.50	0.60	0.70	0.70	0.60
More than 3 years after planting	W1	0.50	0.50	0.60	0.60	0.70	0.70
	W2	0.60	0.60	0.60	0.70	0.70	0.70

Explanations: W1 = irrigation performed when soil moisture decreases to −40 kPa, W2 = irrigation performed when soil moisture decreases to −20 kPa.
Source: own study.

Analysis of the Hargreaves-derived k_c values for the first three years after planting showed only slight differences between irrigation variants (approximately 0.1) in April, June, July, and August, while in May and September both variants exhibited identical values. Beyond three years after planting, an increase in k_c by 0.1 was observed for variant W2 in April, May, and July, whereas in June, August, and September the values were identical for both irrigation variants. The low variability of k_c between the two age classes results from the gradual development of the tree crown and the use of the k_r, which reduces the impact of plant size differences on estimated evapotranspiration.

The values of the k_r were determined for each month and year of the study and showed a tendency to increase as *C. bignonioides* grew during the subsequent years of the experiment (Tab. 2). The lowest coefficient was recorded in the first year of growth, which resulted from the limited canopy coverage, whereas the highest values were observed from the third year of cultivation (mid-2021) onward, remaining at a similar level until the end of the study.

Table 2. The correction coefficient (k_r) according to Treder for the months of the growing season, used to calculate potential evapotranspiration under conditions of a restricted soil wetted area (subsurface drip irrigation)

Year	Value of k_r for month					
	Apr	May	Jun	Jul	Aug	Sept
Variant W1						
2019	0.55	0.55	0.55	0.55	0.60	0.70
2020	0.65	0.80	0.80	0.90	0.90	0.90
2021	0.90	0.95	0.95	1.00	1.00	1.00
2022	0.95	0.95	0.95	1.00	1.00	1.00
Variant W2						
2019	0.55	0.55	0.55	0.55	0.60	0.75
2020	0.75	0.85	0.85	0.95	0.95	0.95
2021	0.95	0.95	0.95	1.00	1.00	1.00
2022	0.95	0.95	0.95	1.00	1.00	1.00

Explanations as in Tab. 1.
Source: own study.

The k_c determined for *C. bignonioides* based on field water consumption interpreted under conditions of optimal soil moisture as the plant's potential evapotranspiration (ET_p) represent the first attempt for central Poland to estimate the water requirements of this species using a climatic criterion and the Hargreaves model.

In this study, k_c values are presented for individual months of the growing season, which is consistent with the literature for other plant groups, including fruit trees (Rolbiecki, 2018), deciduous trees (Sositko, 2019), shrubs (Koniarski, Matysiak and Treder, 2016), and vegetable crops such as asparagus (Rolbiecki, 2013). The k_c values obtained here were comparable to those reported by Montague *et al.* (2004) for small-leaved lime based on lysimetric measurements. According to these authors, monthly k_c values for woody species may range from 0.3 to 1.2 depending on the month of the growing season. Pardossi, Incrocci and Marzialetti (2004) reported k_c values for deciduous trees, including lime, ranging from 0.5 to 0.8. Żakowicz and Hewelke (2012) presented similar k_c values using the Blaney–Criddle formula for deciduous species in reclamation plantings. In contrast, Lechnio (2005) reported substantially lower coefficients, although these were calculated for much taller trees. Values of k_c clearly below those obtained in the present study, generally not exceeding 0.4 for tall deciduous stands, depending on hydrological conditions.

According to Doorenbos and Pruitt (1977), k_c values for orchard trees reach their maximum in July and August (0.75–1.25), depending on species, soil type, and developmental stage. Pittenger and Shaw (2013) emphasised that determining accurate crop coefficients is essential for effective irrigation management in landscape plantings. Meiresonne *et al.* (2003) reported k_c values for Scots pine ranging from 0.71 to 0.97, while Schaap, Bouten and Verstraten (1997) provided values from 0.75 to 1.0 for deciduous species. In the present study, k_c values were derived from field water consumption (S) measured in a soil layer with controlled moisture under subsurface drip irrigation. Crop coefficients may also be determined through lysimetric measurements (Montague *et al.*, 2004; Łabędzki *et al.*, 2011). Łykowski (1989) noted that both approaches are appropriate. The correctness of k_c calculations in this study was further supported by the low groundwater table (preventing capillary rise) and by the use of a precise micro-irrigation system that maintained soil moisture within the range of readily available water.

According to Table 3, the average potential evapotranspiration calculated with the Hargreaves model during the study period was 331.55 mm for irrigation variant W1 and 370.37 mm for variant W2. Over the four-year period, ET_p in W1 ranged from 240.30 mm in the first year to 422.83 mm in the final year. Variant W2 exhibited an analogous trend, with ET_p values ranging from 251.83 to 455.46 mm. When comparing irrigation variants across 2019–2022, ET_p values were consistently higher under W2, on average by 11.6%. In both irrigation variants, the highest monthly ET_p occurred in June and August (48.44–102.20 mm).

Table 3. Potential evapotranspiration (ET_p) of *Catalpa bignonioides* during the growing season (April–September) in the study years 2019–2022, calculated using the Hargreaves model

Year	Variant	Value of ET_p for month						Σ
		Apr	May	Jun	Jul	Aug	Sep	
2019	W1	14.34	28.62	50.21	49.33	48.44	28.91	240.30
	W2	17.92	28.63	60.23	57.56	56.51	30.98	251.83
2020	W1	16.54	42.40	56.08	78.89	73.51	43.16	310.58
	W2	23.86	45.05	71.50	97.15	90.52	45.56	373.64
2021	W1	18.07	50.64	76.26	91.50	70.80	45.20	352.47
	W2	23.84	50.65	91.51	106.75	82.60	45.20	400.55
2022	W1	26.11	58.94	92.28	93.88	102.21	49.41	422.83
	W2	31.33	70.72	92.28	109.52	102.20	49.41	455.46

Explanations as in Tab. 1.
Source: own study.

The calculated ET_p values for *C. bignonioides* are consistent with or show a similar tendency to those reported by Żakowicz and Hewelke (2012) using the Blaney–Criddle method for deciduous species in reclamation plantings (e.g., *Acer negundo*). *Acer negundo* is classified as moderately drought-tolerant, similar to small-leaved lime (Cerny *et al.*, 2002). The use of crop-coefficient-based approaches (k_c and k_r) for estimating plant water requirements is also recommended by Howell *et al.* (1998), Allen *et al.* (1998), Kjelgren *et al.* (2016), and Rashall (2016). Klimek *et al.* (2009) reported that the seasonal water requirement of silver birch, calculated using the Drupka method, was 497 mm, and similar to the present study the highest evapotranspiration occurred in July. Hall and Roberts (1990) reported annual evapotranspiration of ash amounting to 372 mm.

Based on the field water consumption data for *C. bignonioides* (Łangowski, 2025), correlation coefficients describing the relationship between *S* and ET_p calculated using the Hargreaves method were determined and are presented in Table 4.

Table 4. Correlation coefficient (*r*) between field water consumption (*S*) and potential evapotranspiration (ET_p) calculated using the Hargreaves method for selected periods of the growing season

Variant	Value of *r* in period			
	Apr-Sep	Jun	Jul	Aug
W1	0.961*	0.944*	0.998*	0.819*
W2	0.994*	0.963*	0.998*	0.934*

Explanations: * = significance at α = 0.05; other symbols as in Tab. 1.
Source: own study.

The analysis of the correlation coefficients shows that July exhibited the highest values for both irrigation variants (0.998). Lower values were recorded for June, amounting to 0.944 and 0.936 for W1 and W2, respectively. The lowest correlation values were observed in August; however, they remained high (0.819 for W1 and 0.934 for W2).

Overall, despite the observed differences among individual coefficients, the relationships between field water consumption and ET_p were characterised by very high statistical significance, confirming the robustness of the applied methodology.

Correlation analysis was based on monthly values of *S* and ET_p. For the entire growing season (April–September), correlations were calculated using 24 observations (6 months × 4 years). For individual summer months (June, July, and August), correlations were based on four observations, corresponding to one value per year. Data from individual years were not averaged prior to analysis; each month–year combination was treated as an independent observation and then jointly included in the correlation calculations.

In addition, a simple quantitative comparison between irrigation variants showed that seasonal ET_p was consistently higher under the W2 regime. On average, ET_p in W2 exceeded W1 by approximately 11.6% over the study period, with the lowest difference observed in 2019 (about 4.8%) and the highest in 2020 (about 20.3%). This indicates that maintaining higher soil moisture levels (−20 kPa) resulted in increased evapotranspiration and overall water consumption compared with the −40 kPa threshold.

The results obtained are of practical importance for irrigation planning in forest nurseries, especially on light soils with low water retention capacity. The determined seasonal water demand of *C. bignonioides* indicates that maintaining soil moisture at −20 kPa leads to higher water consumption by *Catalpa* and higher potential evapotranspiration. This confirms the validity of using soil water potential thresholds as a criterion for irrigation control.

High correlation coefficients between field water consumption and evapotranspiration calculated using the Hargreaves method (in the summer months) indicate that simplified climate models can be effectively used for irrigation planning in nurseries, especially in conditions of limited availability of meteorological data. The determined plant coefficients k_c enable direct conversion of reference evapotranspiration into the water requirements of the species.

The limitation of the study is its local nature and the fact that it concerns only one species and a selected irrigation system.

CONCLUSIONS

The potential evapotranspiration (ET_p) of *Catalpa bignonioides* calculated using the Hargreaves model in the Droogers and Allen modification ranged from 240.30 mm to 422.83 mm for irrigation variant W1 during the growing season. Irrigation variant W2 consistently exhibited higher values in each study year, ranging from 251.83 mm to 455.46 mm.

The crop coefficients (k_c) derived using the Hargreaves model were higher for irrigation variant W2 in most months of the growing season during the first three years after planting. This tendency persisted into the fourth year, indicating the important role of this irrigation variant in determining ET_p using the selected climatic model.

The correlation coefficients calculated for representative growth periods of *C. bignonioides* despite differences in their absolute values demonstrated very high statistical significance. This confirms the validity of the adopted methodology for estimating the water consumption (ET_p) of *C. bignonioides*. Under conditions of limited water availability, typical for light soils in Poland, the most effective approach involves implementing irrigation systems based on the precise determination of plant water requirements using climatic indicators (ET_p).

The study demonstrated that the Hargreaves model in the Droogers and Allen modification is a reliable alternative to the Penman–Monteith method. It allows reference evapotranspiration to be estimated using only basic temperature data, which significantly simplifies the calculation of plant water requirements in row plantings.

Seasonal variability of water demand was mainly driven by summer climatic conditions, with the highest ET_p consistently observed in June–August. Differences between irrigation variants indicated that maintaining higher soil moisture −20 kPa increased seasonal evapotranspiration by approximately 10–15% compared with the −40 kPa threshold. These results confirm that irrigation control based on soil water potential significantly affects water consumption dynamics and should be considered a key operational parameter in irrigation scheduling for forest nurseries on light soils.

The obtained k_c values apply to young *Catalpa* plantings under subsurface drip irrigation (SDI) conditions on light soils in central Poland and should be interpreted with caution outside these conditions.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interest.

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