ESTIMATION OF EVAPOTRANSPIRATION EMPIRICAL COEFFICIENTS OF SCOTS PINE (*PINUS SYLVESTRIS*) UNDER CLIMATE CHANGE CONDITIONS

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Abstract. The aim of this study was to assess the feasibility of estimating the evapotranspiration of Scots pine (Pinus silvestris) using an indirect method. The field experiment was conducted at the Agro and Hydrometeorology Observatory of the Faculty of Environmental Engineering and Geodesy of the Wrocław University of Life Sciences in Poland from 1 May to 31 October from 2016 to 2019. The experiment covered the period from the 6th to the 9th year of cultivation of Scots pine (Pinus silvestris) on arable land. Evapotranspiration of Scots pine (ETR) was measured in soil evaporometers of 0.3 m^2 and 0.7 m soil monolith thickness, with a daily time step, in triplicate. In order to avoid the oasis effect, the soil evaporometers were installed so that the measured trees grew in a compact enclave, as they do under natural conditions. In parallel, the actual evaporation values from the free water surface were measured directly with the EWP 992 evaporometer, and the daily indicator evaporation values were calculated using the FAO Penman-Monteith formula. In the next step, using evaporation measurements from the EWP 992 evaporometer and determined with the FAO Penman-Monteith formula, decadal and monthly empirical coefficients were determined to estimate the evapotranspiration of Scots pine. Evaluation of the weather conditions in the individual years of the experiment was also carried out, relating it to the normative multi-year period 1981–2010.

Keywords: Scots pine, afforestation, evapotranspiration, empirical coefficients, FAO Penman-Monteith.

Introduction

Evapotranspiration is a significant component of the water balance of annual and perennial plants on which most climate models are based. In both agricultural and forestry crops, the amount of evapotranspiration significantly determines the productivity of the resulting plant biomass. Methods for studying the process of evapotranspiration of crops with an annual cycle are largely recognized, as precise measuring devices in the form of soil lysimeters [1; 2] or ground evaporometers [3; 4] have been used both in the past and currently. The use of lysimeters allows modeling of soil texture [5; 6]. Independently of these methods, measurements of various environmental factors [7; 8], measurements of pine ecosystem evapotranspiration in conjunction with potential evapotranspiration determined by various methods [8; 9], catchment water balance, eddy covariance, and sapwood density [10; 11], or water balances and stand age are described [12; 13].

These methods differ in their spatial and temporal scale, the number of measured components of the evapotranspiration process, also in their assumptions, technical difficulties, or the magnitude of measurement errors. As conifer stands form the basis of planted forest enclaves, the process of evapotranspiration in such an environment is equally important not only on the water cycle but also on oxygen production and carbon dioxide sorption [14; 15]. Measuring evapotranspiration in the case of cultivated plants is less complicated due to the nature and dimensions of the plants. In contrast, for trees, the process is extremely complex bearing in mind also the soil water balance and spatial structure [16], the specific water use, and the age of the trees [13; 17].

Forest crops have a significant impact on the environment and contribute, among other things, to enriching the water retention of the areas in which they are located, modifying the microclimate in a human-friendly way, and intercepting significant amounts of pollutants from the air. This is the reason for studies aimed at estimating tree evapotranspiration by direct and indirect methods [4], which is also important for assessing the magnitude of tree mass potential [18]. To increase the forest cover of areas with poor soils, afforestation is used. The main species in these areas is Scots pine. In addition to the soil, an important factor for the high productivity of Scots pine biomass is the climate, most often characterized by two meteorological elements, namely the air temperature and precipitation totals occurring in the afforested area.

The study of the evapotranspiration of trees is a complex process because in order to capture it, it is necessary to create conditions that mirror the environment in which they grow. To do this, individual trees must be isolated so that their root system is in soil monoliths separated from the ability of capillary rise to replenish soil water.

An equally important element is to set up the field experiment in such a way that the oasis effect is avoided, i.e. to create such growth conditions for the trees that they grow in a compact enclave, as occurs under natural conditions. Such conditions can only be achieved in lysimeters or soil evaporometers with an adequate surface area and thickness of soil monoliths.

The aim of this study was to assess the feasibility of estimating the evapotranspiration of Scots pine (*Pinus silvestris*) using an indirect method.

Materials and methods

The field experiment was conducted on the grounds of the Agro and Hydrometeorology Observatory of the Faculty of Environmental Engineering and Geodesy of the Wrocław University of Life Sciences in Poland from 1. May to 31. October in 2016-2019. The experiment covered the period from the 6th to the 9th year of cultivation of Scots pine (*Pinus silvestris*) on the arable land. Evapotranspiration of Scots pine (*Es*) was measured with soil evaporometers of 0.3 m^2 and 0.7 m soil monolith thickness, with a daily time step, in triplicate. In order to avoid the oasis effect, the soil evaporometers were installed so that the measured trees grew in a compact enclave, as they do under natural conditions, as shown in Fig. 1.

Fig. 1. **Scot pine planting in the experimental plot and in the evaporometers:**
A – 2016; B – 2019 source: A. Żyromski

In parallel, direct measurements of actual evaporation values from the free water surface (*EW*) were carried out with the EWP 992 evaporometer, placed under the louver canopy. Daily index evaporation values were also calculated using the FAO Penman-Monteith (*EP*) formula. In the next step, due to the stability of the values obtained, decadal empirical coefficients were determined for estimating the evapotranspiration of Scots pine in two variants.

In the first variant, the quotient of the measured evapotranspiration *Es* and evaporation from the free water surface *Ew* (coefficient *kw*) was determined. In the second variant, the quotient components *Es* and indicator evaporation were calculated using the *EP* formula (coefficient *kp*). In order to assess the variability of the empirical *kw* and *kp* coefficients, the same relationships were also determined for monthly periods. The site is located in the northeastern part of the city, separated from the centre by a complex of parks, stadiums, meadows and fields, and the Oder-Vidawa canal.

In the area of the observatory, the superficial soil layers consist of fine-grained clayey sands, changing at a deeper level into weakly clayey sands and loose sands with thinner interbedding of clayey sands and sandy loams, less frequently gravelly sands. They are underlain by glacial till with a grain size of fine sandy clay, less frequently by glacial till. Typologically, the site is dominated by silts, which are typical river valley soils. The full water-holding capacity of the soils in the established fields ranges from 306.1 mm to 339.5 mm for a soil layer with a thickness of 100 cm. The average value for the whole site is 322.8 mm. The soils are characterized by a high water-holding capacity. The field capacity is 217.0 mm in the 100 cm soil layer. They are also distinguished by a high capillary rise of water. With groundwater at a depth of 1.0 m, the surface layers contain approximately 18% water by volume. The wilting coefficient for plants is on average around 5%. The average depth of the groundwater in the observatory area is around 1.0 m. The characterization of meteorological conditions of the summer half-year in 2014 was carried out for decadal periods with reference to the normative multiannual period; 1981-2010.

The average values of the air temperature and the whole half-year were classified based on the Institute of Meteorology and Water Management normative. In order to find out the weather conditions during the experiment, measurements of basic meteorological elements were carried out. Their evaluation was based on decadal and monthly average values of the air temperature and decadal and monthly precipitation totals.

The 30-year period 1981-2010, currently recommended as the climatological norm, was used as the background. The analysis of the precipitation observational material for the decade interval, presented in Fig. 2.a, for the multi-year period indicated the 1st decade of July with the highest precipitation sum of 31.4 mm.

During the experimental period, the values were much higher, as they ranged from 46.0 to 77.9 mm, and with the exception of 2019, concerning the July decades. As for the monthly precipitation totals (Fig. 2.c), the maximum values fell in July, and only in 2018 was the sum lower than the multiannual 83.2 mm and amounted to 72.9 mm. In the other years included in the experiment, the totals were higher than the multi-year value and ranged from 92.8 mm in May 2019 to 142.6 mm in July 2018.

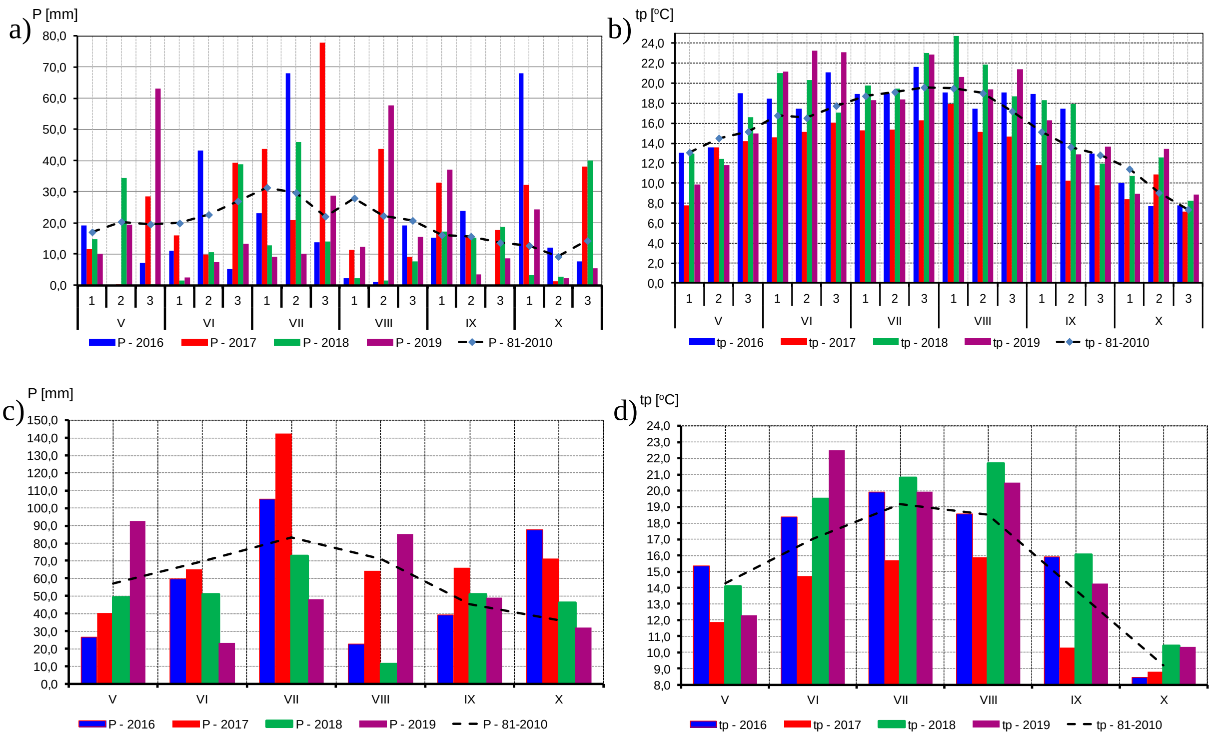

Fig. 2. **Variability of precipitation totals and mean air temperature values over the study period:** a and b – decadal and multi-year values respectively; c and d – monthly and multi-year values respectively

The maximum decadal air temperatures (Fig. 2.b) for the multi-year period fell during the third decade of July and the first decade of August at 19.6 ºC and 19.5 ºC, respectively. In contrast, during the experimental period in 2017 and 2018, they fell in the 1st decade of August at 17.9 ºC and 24.8 ºC, respectively. In 2019, the maximum decadal mean air temperature was recorded in the 2nd decade of

June 23.3 ºC. In terms of monthly mean values (Fig. 2.d), the highest was recorded in June 2019 at 22.5 ºC, respectively, while the lowest was recorded in August 2017 at 15.9 ºC, respectively.

Results and discussion

The measurements carried out show a variation in the magnitude of evapotranspiration totals in individual years for decadal periods (Fig. 3.a). On the other hand, the averaged values from successive years of the experiment show a stabilization of the evapotranspiration values (Fig. 3.b). This is particularly evident from the 3rd decade of September onwards. The observations made during the field experiment clearly indicate that the Scots pine, relying only on rainwater, adapts its evapotranspiration to the rhythm of the water supply. The maximum values of this indicator in each year occurred in the periods from the second decade of July to the second of August, respectively 50.4 mm in 2016 and 57.1 mm in 2017. An outlier was observed in 2019 where the maximum value of this indicator was measured in the third decade of May with 48.6 mm respectively. The same trend can be observed when the analysis period is extended to a month (Fig. 3.c and d).

During the course of the field experiment, it was observed that under conditions where the root system of Scots pine does not have access to groundwater, and such conditions are created by the soil evaporometers, the evapotranspiration process is significantly reduced, which also translates into limited growth capacity. In the next stage of the study, empirical coefficients *kw* (1st variant) and *kp* (2nd variant) were determined for estimating pine evapotranspiration. Their variability is shown in Fig. 3. The decadal values of the *kw* coefficients, ranged from 0.105 for the 2nd decade of August 2018 to 2.392 for the 3rd decade of May 2019. In the second variant, in which the calculated potential evaporation values using the FAO Penman-Monteith method were used, the range of variability of the *kp* coefficient took on values from 0.126 for the 2nd decade of August 2018 and up to 1.783 for the 2nd decade of August 2017.

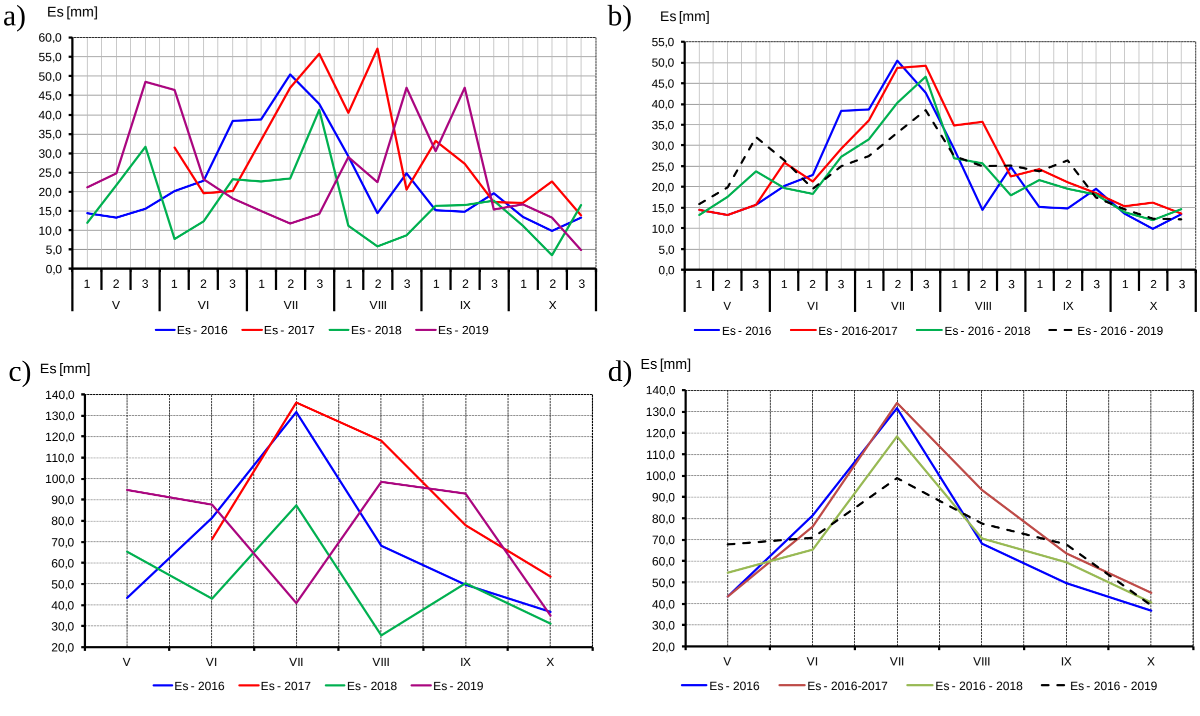

Fig. 3. **Variability in evapotranspiration of Scots pine measured in evaporometers:**
a – decadal values in consecutive years; b – decadal cumulative values;
c – monthly values in successive years; d – monthly cumulative values

As it can be seen from Figure 4 a and c, similar values of *kw* and *kp* coefficients were obtained in the vast majority of decades for both variants. This is especially true for the periods from the 1st decade of May to 1st July inclusive and from the 2nd decade of August to 3rd October inclusive.

The comparative analysis of the obtained coefficients calculated by both methods indicates the fact of obtaining higher extreme values for the variant referring to the measurements of evaporation from the free water surface from the Wild's evaporometer allowing calculation of *kw* coefficients (Fig. 4. a and c). The calculated values of the empirical kw coefficients for the monthly periods in each year ranged from 0.151 in August 2018 to 1.866 in September 2017, while the empirically obtained *kp* values based on potential evaporation values calculated using the FAO method took on extreme values ranging from 0.184 in August 2018 to 1.456 in September 2017. In both variants, extending the period by averaging the values of the coefficients cumulatively from successive years, resulted in their decreasing trend and a clear levelling out of the differences in the values obtained for both variants of *kw* and *kp*.

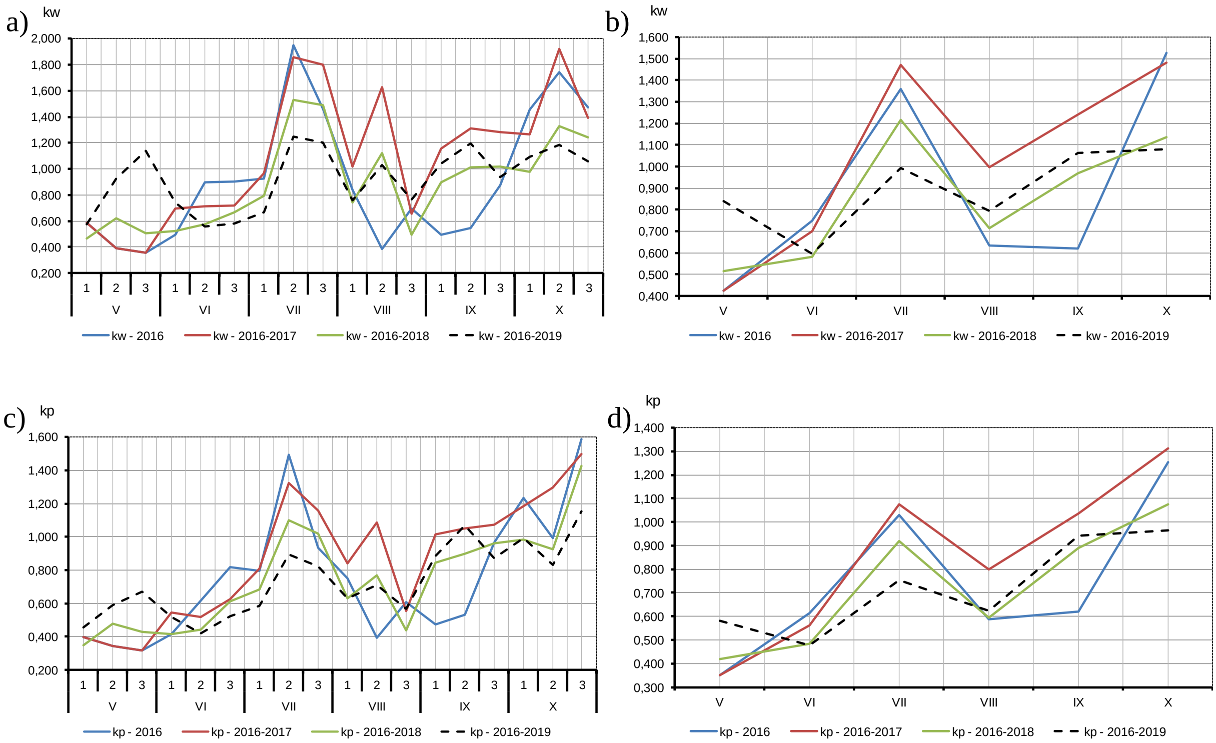

Fig. 4. **Variability of empirical coefficients for Scots pine:**
a – decadal values in consecutive years; b – decadal cumulative values;
c – monthly values in successive years; d – monthly cumulative values

Conclusions

1. The analysis of the four-year study period showed that the maximum decadal sums of *Es* pine evapotranspiration measured in individual years fall into different periods. Only the values averaged over successive years indicate a stabilized period with the maximum evapotranspiration sum falling between the second and third decades of July and with a noticeable downward trend until the end of the study period in October.
2. On the basis of a four-year study, it was concluded that Scots pine, relying only on rainwater, adapts its evapotranspiration to the rhythm of water supply, as indicated, among other things, by the extreme values of this indicator from precipitation totals.
3. The analyses of the calculated empirical coefficients based on evaporation measurements from the free water surface performed with the EWP 992 evaporometer and on the calculated index evaporation values using the FAO-Penman-Monteith formula confirm the hypothesis that they can be used to interpret the spatial evapotranspiration of Scots pine. The maximum relative difference between coefficient extremes were respectively 21.9% (min) and 20.9% (max).
4. Comparative analyses of the courses of variation of the empirical coefficients calculated by the two methods show a high similarity in their values and allow their interchangeable determination,

depending on the available apparatus or calculation possibilities taking into account the FAO-Penman-Monteith formula. The correlation coefficient was statistically significant and the R^2 reached 90% both for monthly and decadal values.

Author contributions

Conceptualization, A.Z.; methodology, A.Z. and M.W.; software, A.Z. and B.K.; validation, A.Z., M.W. and B.K; formal analysis, A.Z and M.W.; investigation, A.Z., M.W. and B.K; data curation, A.Z., M.W. and B.K; writing – original draft preparation, A.Z., M.W. and B.K.; writing – review and editing, A.Z., M.W. and B.K; visualization, A.Z., and B.K; project administration, A.Z.; funding acquisition, B.K. All authors have read and agreed to the published version of the manuscript.

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