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Transpiration of Woody Plants in the Desert Zone of Mangistau

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Abstract

Objective: The present research on the transpiration flow conducted in the arid conditions of Mangistau allowed three groups of introduced species to be distinguished: low transpiration (3 types of trees); average transpiration (7 types of trees and shrubs) and high transpiration (3 types of trees).

Methods: The research subjects included 22 introduced species of trees and shrubs of the different geographical origin, degree of biological resistance and growth forms, among them 4 conifers, 15 deciduous trees, and 3 fruit trees. The following methods were applied in the physiological research: the total water content and the transpiration rate. The selection of leaves was made in the middle part of the crown in the 5-10-fold repetition.

Results: According to the correlation analysis, a close relationship has been set between the transpiration rate and the water content of leaves. Soil moisture determines from 11.6% to 43.6% of the transpiration rate variation. Reliable at the 5% significance level is the ratio of correlation with the relative moisture and the air temperature. The conjugation with the value of illumination is statistically unreliable. Seasonal dynamics in the majority of introduced species is seen as a unimodal curve with a peak value in June. Three types have been determined for the daily transpiration rhythm: "rising", "falling" and "variable".

Conclusion: The intensity of the transpiration process, due to its considerable variability and multifactor nature, cannot be referred to the resistance criteria of woody plants, but at the same time, there is a noticeable connection between the biological stability of introduced species and the coefficient of transpiration variation. With the increase of its values, the resistance of introduced species to the arid habitat conditions is generally enhanced due to their increased ability to the self-regulation of water exchange.

Keywords

Woody plants; Transpiration rate; Correlation; Water content; Regression

Introduction

Transpiration is one of the main environmentally improving indicators of tree plantations for the desert conditions of Mangistau. Physiological water return is also relevant because in the conditions of the soil moisture limit, the process of maximizing the productivity of plants comes down to a simultaneous optimization of solar radiation absorption and water flow through transpiration. The amount of water evaporated by the plant is very often many times greater than the volume of water contained in it. At the same time, the economical water consumption is one of the most important phyto introduction problems in the arid regions. Transpiration in regular sizes is indeed not necessary. Thus, if plants are grown in the conditions of the low and high soil moisture, naturally, in the first case transpiration will be much less intensive. However, the growth of plants in a certain moisture range will be about the same (within statistical accuracy bounds). Therefore, it is necessary to find a balance by selecting a specific spectrum and regulating the irrigated soil regime. Moreover, transpiration is an indispensable physiological process of the plant body and is essential to its life activity as a defense mechanism against overheating in direct contact with the sunlight and as a creator of the continuous flow of water and mineral nutrients from the root system to other anatomical organs. Due to the special importance of this physiological parameter for the desert habitat, Mangyshlak Experimental Botanical Garden (MEBS) conducted a detailed study of the transpiration moisture rate for the prevailing types of trees and shrubs in the garden and parkland of the region in 2012-2014. Its purposes were to identify the regularities of its daily and seasonal dynamics, to establish the correlation and regression relationship with the soil moisture supply and the main meteorological factors, and to determine the possibility of using woody introduced species as an indicator of biological resistance.

Materials and Methods

The research subjects included 22 introduced species of trees and shrubs of the different geographical origin, degree of biological resistance and growth forms, among them 4 conifers, 15 deciduous trees, and 3 fruit trees. The following methods were applied in the physiological research: the total water content - by drying leaves to a constant weight at a temperature of 100ºC -105ºC; the transpiration rate - by the method of rapid weighing proposed by A.A. Ivanov [1,2]. The selection of leaves was made in the middle part of the crown in the 5-10-fold repetition. The statistical processing of the findings was performed by the method of G.F. Lakin with the use of statistical software package - Statgraphics Centurion XVI.I. [3].

Results and Discussion

According to the average three-year data, all the introduced species were divided into three groups by the values of the transpiration rate (Table 1): 1) low transpiration (less than 250 mg/g of the weight of moist leaves per hour) - all conifers (*Platycladus orientalis* (L.) Franco, *Juniperus virginiana* L. and *Pinus pallasiana* Lamb.); 2) average transpiration (250-500 mg/g of the weight of moist leaves per hour) - *Gleditsia triacanthos* L., *Maclura aurantiaca* Nutt., *Elaeagnus oxycarpa* Schlecht., *Populus bolleana* Lauche, *Populus diversifolia* Schrenk., *Amygdalus nana* L., *Betula verrucosa* Ehrh., *Berberis vernae* Schneid., *Fraxinus sogdiana* Bunge, *Armeniaca vulgaris* Lam.; and 3) high transpiration (more than 500 mg/g of the weight of moist leaves per hour) - *Crataegus ambigua* C. A. Mey, *Quercus robur* L., *Malus sieversii* (Ldb.) M.Roem. The absolute maximum of the transpiration rate (TR) was observed in the water-loving tree - *Populus bolleana* (1,578 mg/g per hour), and other woody plants of the mesophytic and mesohydrophytic species: *Betula verrucosa* (1,115). *Crataegus ambigua* (1,546), *Berberis vernae*

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Table 1: Correlation of the transpiration rate with the number of month of the vegetation season and the main meteorological factors in the study of seasonal dynamics.

Plant name	Number of month of the vegetation season	Meteorological factors		
		Air temperature, °C	Relative moisture, %	Illumination, klx
Platycladus orientalis	-0,69	0,37	0,97	0,70
Juniperus virginiana	-0,62	0,51	0,87	0,80
Pinus pallasi-ana	-0,62	0,41	0,99	0,72
Betula verrucosa	-0,47	0,71	0,84	0,92
Crataegus ambigua	-0,49	0,31	0,22	0,47
Gleditsia triacanthos	-0,80	-0,72	0,19	-0,41
Quercus robur	0,00	0,64	0,01	0,57
Maclura aurantiaca	-0,87	-0,28	0,48	0,03
Amygdalus nana	-0,88	-0,50	0,06	-0,20
Elaeagnus oxycarpa	-0,77	-0,64	-0,14	-0,42
Populus bolleana	-0,10	0,74	0,83	0,82
Populus diversifolia	-0,60	0,44	0,47	0,65
Fraxinus sogdiana	-0,91	-0,32	0,32	0,03
Note. The critical value of the correlation coefficient at the 5% significance level - 0.88				

(1,011), *Gleditsia triacanthos* (1,428) and *Quercus robur* (1,313 mg/g per hour).

Transpiration has daily and seasonal dynamics. There are several approaches to the interpretation of the seasonal dynamics of transpiration. Most researchers, associating the course of physiological water return with a set of meteorological factors, indicate a close correlation only if there is a sufficient moisture supply of woody plants [4-6]. According to the authors' observations, the transpiration rate increases from spring to mid-summer and then drops to autumn. Another approach is based on the gradual aging of biocolloids of the leaves' protoplasm, resulting in a natural reduction in the transpiration flow during the vegetation season [7,8]. Sudnitsyn also observed such dynamics of transpiration but explained it with a steady depletion of soil moisture reserves [9]. In the present research, in each vegetation month soil moisture varied in a strictly defined range - from the antecedent irrigation level (70-75%) to the value of the full field moisture capacity (100%). That was because all the introduced species of woody plants are grown only in the conditions of systemic irrigation, and sampling was carried out in the middle of the inter-irrigation period. There was a change only in meteorological factors and the physiological state of woody plants. The resulting picture of the TR seasonal dynamics in the vast majority of introduced species is given as a unimodal curve with a peak value in June, which is conditioned by the depression of physiological water return in July-August due to a high temperature and insolation, in September – due to leaf apparatus aging, temperature deterioration and moisture increase (Table 2).

The TR seasonal dynamics is very unusual in one of the most biologically resistant types - *Elaeagnus oxycarpa* (Table 2). Its value strictly corresponds to the course of temperature variation, therefore, a maximum is observed in July, and a minimum - in May and September. This is also confirmed by the correlation analysis, according to which this species has the highest negative correlation (r=-0.64) with the air temperature (Table 3).

According to the average data, the correlation ratio of the transpiration rate is statistically reliable in the study of seasonal dynamics only with the number of month from the beginning of the vegetation season (r=-0.91). With the air temperature (r=0.13) and moisture (r=0.49), as well as illumination (r=-0.37), the correlation is unimportant at the 5% significance level (Table 3).

In the seasonal and timing aspect, the TR correlation between the selected taxa is estimated to be high only between the representatives of one morphological and taxonomic group or when the stability and confinement of the natural habitat is similar. For example, the types of conifers – r=0.91-0.92, *Elaeagnus oxycarpa* and *Populus diversifolia* - 0.70.

According to the TR variability, during the vegetation season woody plants were divided as follows (Table 4): 1) Low variability (C_v<10%): *Betula verrucosa*; 2) Average variability (C_v=10-20%): *Amygdalus nana*, *Quercus robur*, *Populus diversifolia*, *Fraxinus sogdiana*; and 3) High variability ($C_{v>}$20%): *Platycladus orientalis*, *Juniperus virginiana*, *Pinus pallasi-ana*, *Crataegus ambigua*, *Gleditsia triacanthos*, *Maclura aurantiaca*, *Elaeagnus oxycarpa*, *Populus bolleana*. The most common taxa in the green areas of Mangistau fall into the groups with a higher variability due to a better adaptation to the desert growing conditions. Unlike the seasonal development of transpiration, daily dynamics is influenced by a smaller number of endogenous and exogenous factors. However, its character is very heterogeneous and depends both on the change in weather conditions, and on the biology of species (Table 5). According to the averaged data, the following types of the TR daily rhythm were identified: 1) "rising" (from the morning to the evening) - *Platycladus orientalis*, *Juniperus virginiana*, *Betula verrucosa*; 2) "falling" (from the morning to the evening) - *Gleditsia triacanthos*; 3) "variable" (with a maximum at noon) - *Pinus pallasi-ana*, *Crataegus ambigua*, *Quercus robur*, *Maclura aurantiaca*, *Amygdalus nana*, *Elaeagnus oxycarpa*, *Populus bolleana*, *Populus diversifolia*, *Fraxinus sogdiana*.

However, in July, the hottest and driest month, most of the plants should be attributed to the "variable" type with a minimum at noon. Transpiration curves seem to be flattened. The variation of the transpiration rate stops to comply with the daily course of meteorological factors. There is an asymmetry of transpiration curves towards the antemeridian or afternoon hours. Alekseyenko and Khashes also pointed out this feature. The latter explains the shift of the maximum transpiration rate with endogenous causes [10,11]. Without the regulatory activity of plants themselves, the transpiration flow should gradually increase by 1400, and then just as slowly decrease. However, at some period of the day the plant starts not to be able to provide the leaves with the quantity of water necessary for evaporation in accordance with the supply of energy.

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Table 2: Transpiration rate and water content in the leaves of woody plants (average three-year data for 2012-2014).

Plant name	Transpiration rate, mg/g of the weight of moist leaves per hour			Water content in leaves, %		
	min.	max.	avg.	min.	max.	avg.
CONIFEROUS TREES						
Platycladus orientalis	62	559	215	38	80	57,0
Juniperus virginiana	54	591	204	35	85	59,5
Pinus pallasi-ana	69	590	199	37	85	60,5
DECIDUOUS TREES						
Betula verrucosa	151	1115	478	40	85	64,0
Crataegus ambigua	78	1546	520	48	78	67,5
Berberis vernae	180	1011	480	46	93	67,0
Gleditsia triacanthos	72	1428	353	45	87	61,5
Quercus robur	34	1313	533	61	85	70,0
Maclura aurantiaca	14	980	404	44	80	60,0
Elaeagnus oxycarpa	91	838	367	44	85	64,0
Populus bolleana	20	1578	459	34	80	60,0
Populus diversifolia	165	1023	417	45	92	64,5
Fraxinus sogdiana	122	822	441	40	84	64,5
FRUIT TREES						
Armeniaca vulgaris	162	1292	465	43	96	69,5
Amygdalus nana	153	1134	401	43	94	71,5
Malus sieversii	115	969	571	47	96	72,5

Table 3: Seasonal dynamics of the transpiration rate of woody plants (three-year average data for 2012-2014, in mg/g of the weight of moist leaves per hour).

Meteorological factors,plant names	Month of the vegetation season					Average
	May	June	July	August	September	
Number of month from the beginning of the vegetation season	2	3	4	5	6	4
Meteorological factors						
Air temperature, °C	24,9	27,1	28,5	27,3	25,8	26,7
Relative air moisture, %	57,5	53,4	68,0	60,2	34,1	54,6
Illumination, klx	39,0	56,5	65,4	54,4	36,7	50,4
Woody plants						
Platycladus orientalis	266	251	288	251	152	241
Juniperus virginiana	230	288	277	254	96	229
Pinus pallasi-ana	225	209	254	219	123	206
Betula verrucosa	429	484	511	441	369	447
Crataegus ambigua	352	517	365	359	308	380
Gleditsia triacanthos	510	282	266	253	239	310
Quercus robur	279	439	374	318	340	351
Maclura aurantiaca	483	372	420	299	306	376
Amygdalus nana	396	390	311	313	310	344
Elaeagnus oxycarpa	466	413	334	273	355	368
Populus bolleana	429	424	629	474	374	466
Populus diversifolia	361	435	386	353	321	371
Fraxinus sogdiana	398	398	329	344	304	355

At this time, there is a maximum of transpiration, after which it is weakened, no longer corresponds to the course of meteorological conditions, and is defined by the physiological state [10]. Thus, even in the conditions of the high relative water supply, the desert climate makes the plant to actively adjust its water exchange. On average, all of the test plants (Figure 1) in May, June, August and September have a fixed maximum of the transpiration rate at 14^{30} with a reduction and increase towards the morning and evening hours. In July, the transpiration rate gradually falls during the day, but only slightly - by 5-12%.

As far as transpiration is the final stage of the cycle of irrigation

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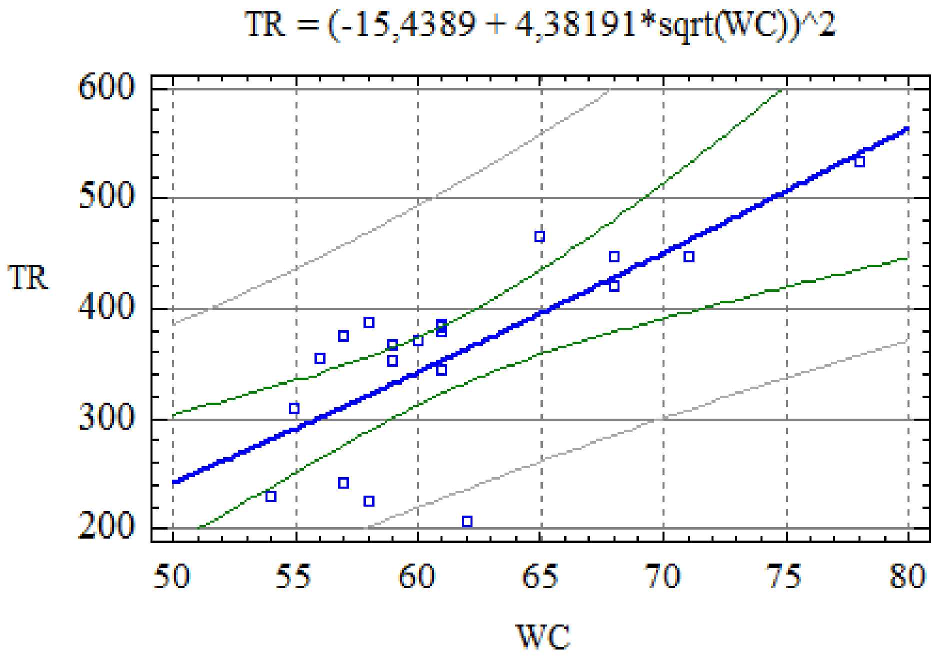

Figure 1: Dependence diagram of the TR and the water content of leaves (WC), η = 0,79; $η_{cr05}$ = 0,42.

Table 4: Basic statistics of the transpiration rate based on the study of seasonal dynamics (in mg/g of the weight of moist leaves per hour).

Plant name	X	S_x	C_v	Plant name	X	S_x	C_v
Platycladus orientalis	242	23,4	21,7	Maclura aurantiaca	376	34,8	20,7
Juniperus virginiana	229	34,7	33,9	Amygdalus nana	344	20,0	13,0
Pinus pallasi-ana	206	22,1	23,9	Elaeagnus oxycarpa	368	33,2	20,1
Betula verrucosa	447	12,1	9,8	Populus bolleana	466	43,7	21,0
Crataegus ambigua	380	35,6	21,0	Populus diversifolia	371	19,0	11,5
Gleditsia triacanthos	310	50,5	36,4	Fraxinus sogdiana	355	18,8	11,9
Quercus robur	350	27,1	17,3				
Note. X – the average value of the variable; S_x – the error of the mean, and C_v – the coefficient of variation, %							

Table 5: Daily dynamics of the transpiration rate (average data for 2013, in mg/g of the weight of moist leaves per hour).

Meteorological factors, plant names	Time				Average
	09^{30}	11^{30}	14^{30}	16^{30}	
Meteorological factors					
Air temperature, °C	21,2	24,8	28,6	27,2	25,45
Relative air moisture, %	55	49	36	40	45
Illumination, klx	49,6	53,1	52,8	45,0	50,1
Woody plants					
Platycladus orientalis	254	300	251	249	264
Juniperus virginiana	270	289	261	260	270
Pinus pallasi-ana	281	277	235	274	267
Betula verrucosa	583	509	535	445	518
Crataegus ambigua	344	392	413	448	399
Gleditsia triacanthos	347	332	277	346	325
Quercus robur	375	370	369	480	399
Maclura aurantiaca	383	407	464	345	400
Amygdalus nana	312	359	396	355	355
Elaeagnus oxycarpa	330	365	514	442	413
Populus bolleana	445	502	529	460	484
Populus diversifolia	337	422	422	549	432
Fraxinus sogdiana	424	347	378	395	386

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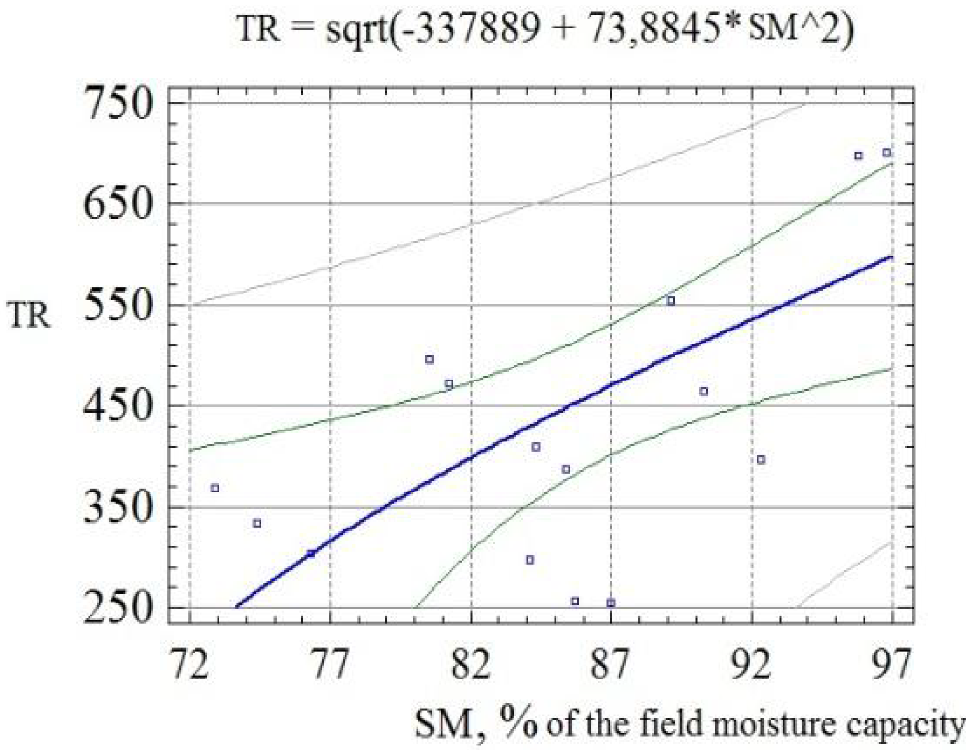

Figure 2: Dependence diagram of the TR and soil moisture (SM), η = 0,66; η_{cr05} = 0,42.

water in the soil and the plant, its correlation with soil moisture and the water content of leaves is unquestionable even from a logical point of view Gunn and Kolov [12]. Experimentally, it is confirmed by a number of authors [13-17]. With the decrease in soil moisture, the transpiration level decreases [18]. The less water is in the soil, the less water is in the plant. The reduction of the water content in the plant body automatically decreases the transpiration process due to a stomatal and non-stomatal adjustment [19]. In our studies, even with the use of the composite power connection (Figure 2), the correlation of the transpiration rate and the water content of leaves is statistically reliable at the 5% significance level (η=0.79). Soil moisture determines 11.6% of the TR variation (r=0.34), primarily due to its dependence on other factors, particularly, meteorological (Table 6). Moreover, for a variety of taxa, the correlation coefficient varies in a very wide range - from 0.17 to 0.56. On average, for all of the test plants, the most reliable equation of regression between the TR and soil moisture in order of importance has a square-power form (Figure 3), and the correlation ratio (η) is 0.66. In addition to soil moisture reserves, the main environmental factors influencing transpiration include the illumination intensity, the relative air moisture and temperature, and the wind speed. The internal factors are as follows: area, location, and structure of leaves, behavior of stomata and effectiveness of the root absorption surface. There are also complex interactions between different factors Garnier, Berger and Martin [20]. The higher the air moisture stress is, the lower (more negative) its water potential is, and the faster the evaporation is. This is also true for transpiration, but it should be noted that when there is a shortage of water in the leaf, there is a stomatal and non-stomatal adjustment, by virtue of which the effect of external conditions is made in a moderate form. Analysis of study materials showed the presence of a significant close correlation between the TR and the relative air moisture ($\eta>\eta_{cr05}$) for almost all the woody plants selected for the experiment (Table 7). The diagram of the multiplicative correlation between the TR and the relative air moisture demonstrates an explicit tendency of the transpiration flow reduction with the increase of the water content in the air (Figure 1). Another investigated factor influencing the process of transpiration is the air temperature. As known, when the temperature increases, there is a significant increase in the amount of water vapor which fills this space. The growth of the water vapor pressure leads to the moisture stress, which in turn increases the amount of transpiration moisture. Both by the value of the correlation coefficient - r=0.46 (Table 7), and by the correlation ratio (0.40) of the complex multiplicative power equation (Figure 4), there is a statistically reliable correlation between the TR and the AT. During the research, the equation of the correlation between the TR and illumination was derived for the first time for the conditions of Mangistau. As seen from the diagram in Figure 5, in the studied range from 29.1 to 75.6 klx, an increase in illumination does not lead to the depression of the transpiration process due to the protection of stomata against strong solar radiation and overheating. The transpiration rate also depends on the development phase. With the increase of the plant's age, transpiration tends to fall. High evaporation rates in young leaves can occur by increasing the level of cuticular transpiration, as far as the cuticle is still poorly developed during this period. Thus, according to Henkel [21], cuticular transpiration in young birch leaves is about 50%, and in old leaves - only 20% of the total evaporation. It should also be taken into account that young leaves have higher water content. It is interesting that the evaporation rate is affected not only by the leaf's own age, but also by the overall age of the plant body. P.L. Henkel believes that a gradual decrease in the transpiration rate

Table 6: Dependence of the transpiration rate on soil moisture (2012), in mg/g of the weight of moist leaves per hour).

Soil moisture, meteorological factors, plant names	Number of days after irrigation				Average	Correlation coefficient
	1	3	5	8		
Moisture content in the soil layer of 1 m						
- in the whole, m³/ha	1433	1356	1227	1116	1283	-
- in % of the field moisture capacity	95,8	90,6	81,9	74,5	85,7	-
Platycladus orientalis	185	224	155	161	181	0,23
Juniperus virginiana	180	157	160	170	167	0,21
Pinus pallasi-ana	162	214	184	208	192	0,31
Betula verrucosa	484	545	476	484	497	0,56
Crataegus ambigua	659	799	601	577	659	0,46
Gleditsia triacanthos	392	308	371	347	354	0,29
Quercus robur	838	784	876	705	801	0,32
Maclura aurantiaca	607	650	582	502	585	0,17
Amygdalus nana	598	553	518	457	531	0,35
Elaeagnus oxycarpa	461	276	442	410	397	0,31
Populus bolleana	405	600	528	514	512	0,25
Populus diversifolia	446	392	367	356	390	0,31
Fraxinus sogdiana	712	700	536	473	605	0,50

Note. The critical value of the correlation coefficient at the 5% significance level - 0.47

Table 7: Correlation of the transpiration rate with the time of the day and the main meteorological factors in the study of daily dynamics for 2013.

Plant name	Time of day	Meteorological factors		
		Air temperature, °C	Relative moisture, %	Illumination, klx
Platycladus orientalis	-0,07	0,21	-0,51	0,44
Juniperus virginiana	-0,06	0,08	-0,42	0,62
Pinus pallasi-ana	-0,06	0,11	-0,51	0,62
Betula verrucosa	-0,26	0,05	-0,37	0,59
Crataegus ambigua	0,23	0,18	-0,57	0,19
Gleditsia triacanthos	-0,06	0,61	-0,21	-0,23
Quercus robur	0,18	0,20	-0,69	0,14
Maclura aurantiaca	-0,02	0,43	0,05	-0,31
Amygdalus nana	0,21	0,30	-0,50	0,05
Elaeagnus oxycarpa	0,32	0,36	0,09	-0,29
Populus bolleana	0,06	0,31	-0,06	-0,02
Populus diversifolia	0,30	0,32	-0,70	0,02
Fraxinus sogdiana	-0,05	0,52	-0,33	0,07

Note. The critical value of the correlation coefficient at the 5% significance level - 0.39

in the process of ontogeny of both the body and the plant in total may serve as a confirmation of the biogenetic law (ontogeny recapitulates phylogeny) [21]. Indeed, there is a correspondence between the way of adaptation of the plant to terrestrial life in phylogeny and the better retention of moisture in ontogeny. In our experiments, even in the age range of 2 - 20 years a pattern of the reduction of the transpiration rate with age is observed for the majority of woody plants, but in a mild form. On average, for all the introduced species, even with the use of the S dependence curve (Figure 6), the correlation ratio is 0.38 at the critical value of 0.47.

The variability and multifactor nature of the transpiration process does not allow it to be referred to the number of biological markers of plant resistance. The one thing, noted in the analysis of the collected materials, is a certain conjugate resistance to dry environmental conditions with a coefficient of variation of the TR. The more it is, the more stable the introduced species are due to the autoregulation of the water regime. For example, a number of plants with the greatest variation of physiological evaporation (38.2-47.2%) included such resistant species in local conditions as *Platycladus orientalis*, *Elaeagnus oxycarpa*, *Populus bolleana* and *Populus diversifolia*. To the contrary, the less resistant species are *Betula verrucosa*, *Crataegus ambigua*, *Gleditsia triacanthos* and *Fraxinus sogdiana*, which have a coefficient of variation by 5-15% less.

Conclusion

Thus, based on the results of the three-year study on the values of the transpiration flow of moisture, three groups of introduced species were distinguished: low transpiration (3 types of trees), average transpiration (7 types of trees and shrubs) and high transpiration (3 types of trees). According to the correlation analysis, a close correlation between the TR and the water content in the leaves of woody plants was set (r=0.79). Soil determines from 11.6% to 43.6% of the transpiration rate variation (r=0.34; η=0.66). Reliable at the 5% significance level is the ratio of correlation of the TR with the relative moisture (r=-0.59) and the air temperature (r=0.46). Its conjugation with the value of illumination is statistically unreliable (r=0.19).

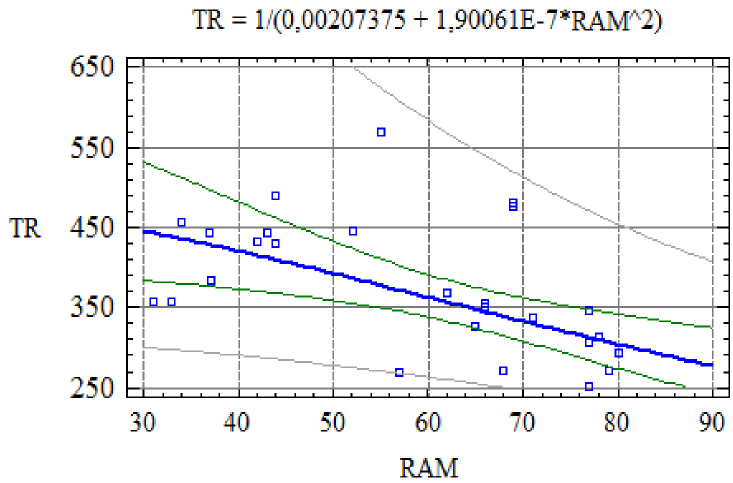

Figure 3: Dependence diagram of the TR and the relative air moisture (RAM), η = 0.59; $η_{cr05}$ = 0.39

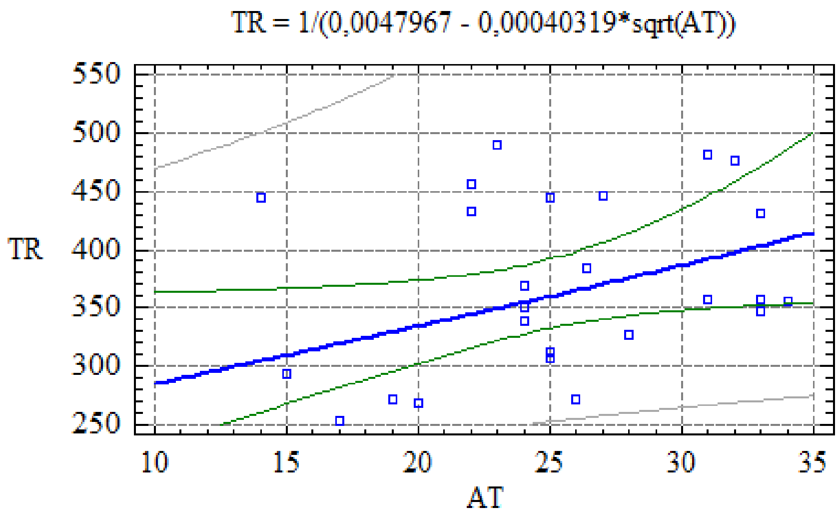

Figure 4: Dependence diagram of the TR and the air temperature (AT), η = 0.40; $η_{cr05}$ = 0.39

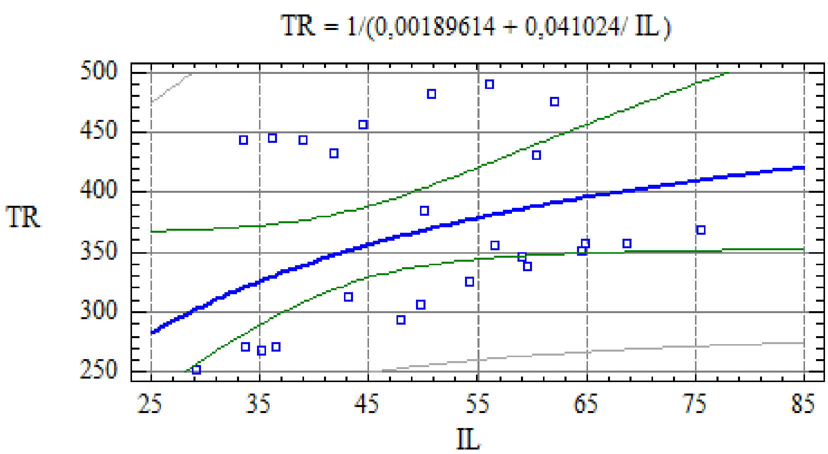

Figure 5: Dependence diagram of the TR and illumination (IL), η = 0.38; $η_{cr05}$ = 0.39.

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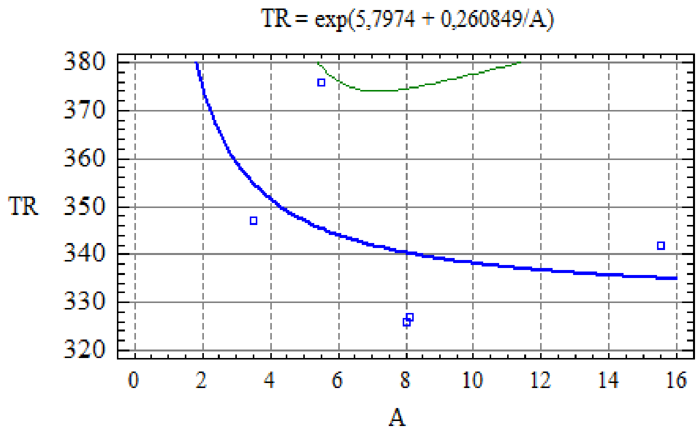

Figure 6: Dependence diagram of the TR and the plant age (A), η = 0.48; η_{cr05} = 0.88.

Seasonal dynamics in the majority of introduced species is seen as a unimodal curve with a peak value in June. Three types were determined for the daily transpiration rhythm: "rising" (from the morning to the evening - 3 types of trees), "falling" (from the morning to the evening - one type of trees) and "variable" (with a maximum at noon - 9 types of trees and shrubs). According to the research material, the intensity of the transpiration process, due to its considerable variability and multifactor nature, cannot be referred to the resistance criteria of woody plants. However, at the same time, there is a noticeable connection between the biological stability of introduced species and the coefficient of variation of the TR. With the increase of its values, the resistance of plants to the arid habitat conditions is generally enhanced due to their increased ability to the self-regulation of water exchange.

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