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MATHEMATICAL MODEL OF EXTENSIVE GREEN ROOF WITH A STEEP TYPE OF PHYTOCENOSIS

Abstract. *A mathematical model of the influence of weather conditions on the development of plants of a green roof with steppe type of phytocenosis for the eastern region of Ukraine with a sharply continental type of climate was developed. The main factors are the average annual relative humidity, temperature, percentage of sunny days and wind speed. By the method of least squares three equations are obtained for three groups of plants having the same phenotype. The analysis of the equations shows that the coefficients under various factors are comparable, which shows the same importance of taking into account all the factors. The smallest coefficients for all factors correspond to the group of plants II. These plants are the most resistant to weather influences. Plants of group III are characterized by insignificantly higher values of coefficients – within 0 ... 18.2%. Thus, plants of group III have approximately the same resistance to weather conditions. Plants of group I are characterized by values of coefficients that are 1.8 ... 2.1 times greater than group II, and the value of the free member is 4% less than group II. Thus, the first group is most prone to weather conditions and, with an average value of ambient air properties, has a lower score. These plants are more likely to lose their decorative qualities and require more frequent replacement or planting. The sensitivity of the plants to the action of the wind is established. This factor can have a negative impact on the decorative properties of plants. The action of wind is proposed to be adjusted using a parapet. When perforated parapet in the summer, the effect of the wind increases, which reduces decorative, but increases the «cooling effect». With a blind parapet, the effect of the wind decreases, the decorative nature of the plants increases, but the "cooling effect" decreases. This fact must be taken into account when using the green roof.*

Key words: *extensive green roof, steppe type of phytocenosis, mathematical model, least squares method, plant resistance, weather conditions.*

Formulation of the problem

In many European countries, green constructions have moved from the category of exclusive elements to the required attribute of green building a long time ago. In countries such as Germany, Great Britain, France, Denmark, Switzerland, Canada, USA, Japan, the creation of green structures has been supported at the state level. These countries have proven superiority green designs for modern urbocenosis in the concept of sustainable development. The technologies of green construction are well-developed. Market leaders in green construction are determined. There are ZinCo, Bauder GmbH & Co, Hydrotech, Euroroof, Technocol. The main problems that the green constructions solve in the Europe are: minimizing rainwater to storm sewers, recycling rain water accumulated in the reservoirs of green structures for domestic use, reducing the effect of «heat islands» in the city, reducing CO_2 emissions, create additional recreational areas of open type. Roof greening is typical for construction projects of all types of industrial and civil, residential and commercial, high-rise and low-rise [1].

Relevance of research

Unfortunately, the using of green constructions in building is a new direction in Ukraine. Existing green roofs are private objects that perform decorative and recreational functions. There are no technical experimental studies on green roofs, no norms and standards of their design, no concept of the needs and the possibility of introduction in modern cities to reduce the people-caused environment. The above emphasizes the scientific novelty and relevance of our research. An exception is the textbook of the Pridniprovsk State Academy of Civil Engineering and Architecture [2], which deals with the using of elements of vertical, container and roofing landscaping. By appointment, green roofs are divided into several types: medical (in hospitals), recreational (at homes), training (on buildings of schools, colleges and libraries), household (for the purpose of harvesting, grazing of cattle, etc.) etc. The main criterion for the ability to perform these functions is an assortment of plants for roofing landscaping. Due to the fact that green roofs are a complex mixed system that depends on climatic factors, the research findings in different climatic zones can vary significantly. On the other words, they are new and original and can be applied to a particular climatic zone.

The object and methods of research

The object of our research was a flat roof of a private house at a height of 12 m above the surface of the earth greened by the author. The total area of the roof is 1443.75 m^2. The area of the green part is 200 m^2. An intensive greening of the roof (it is assumed that people can go to the roof) with a steppe type of landscaping was made. This type of landscaping is most suitable for the arid climatic conditions of the region. In our case, the creation of a green roof was carried out in conjunction with architects and builders, using nine preparatory layers [3]. The layer of soil substrate was made on the basis of soil, sand, claydite, perlite, peat, clay and crushed bark. The thickness of the layer – 0.80 m (including sealing). For additional wetting of the soil on the roof was installed autosprinkling. In order to comply with safety, the entire roof surface was enclosed with parapet height of about 1 m. Within the composition of the roof to facilitate walking and watering special paths of ceramics were laid, resembling a wood saw cut.

We evaluated the general condition of plants after wintering visually on a five-point scale of Tumanov [4]: 5 – the absence of traces of plant death; 4 – slight damage of the tops of the shoots; 3 – 50% of damage, about half of plants die; 2 – 70…80% of damage, death of more than half of plants; 1 – complete destruction, or preservation of individual plants only. In addition, the ability of plants to tolerate unfavorable summer conditions, namely a strong increase in temperature, was determined. The condition of plants in this period was also determined visually on the same scale.

Plants are conveniently divided into three groups having the same mark on the phenotype: group I – *Armeria*, *Aster alpinus*, *Dianthus deltoids*, *Iris Sabina*, *Centaurea*; group II – *Stipa, Aster, Alyssum, Gypsophila*, *Saponaria*, *Tanacetum*, *Lisimachia*, *Deschampsia cespitosa*, *Elymus*, *Helictotrichon*, *Filipendula*, *Euphorbia*; group III – *Festuca, Salvia, Phlomis, Polygonum, Hypericum, Iberis, Iris sibirica, Artemisia, Thymus serpyllum, Melica, Carex, Scutellaria.* As influential factors we take the average annual temperature: θ,° C, relative humidity φ,%, percentage of sunshine days n_{sun},% and wind speed *V*, m / s (Table 1).

Table 1 – Observation data from 2006 to 2013

Year	Month	Weather data							Phenotype of a group of plants, point		
		Temperature, °C,			Relative humidity φ, %	Percentage of sunny days	Wind speed *V*, m/s	I	II	III
		day	night	average						
1	2	3	4	5	6	7	8	9	10	11
2006	8	29	22	25.5	50	45	4	4	4	4
	9	22	15	18.5	44	53	5	4	4	4
	10	15	10	12.5	60	58	4	4	4	4
	11	6	3	4.5	74	23	4	4	4	4
	12	1	0	0.5	78	39	5			
	Average	**14.6**	**10.0**	**12.3**	**61.2**	**43.8**	**4.4**	**4.0**	**4.0**	**4.0**
2007	1	2	0	1	83	10	6			
	2	0	-4	-2	70	36	6			
	3	7	1	4	57	52	6			
	4	11	4	7.5	38	40	5	1	2	3
	5	23	14	18.5	34	65	5	4	4	4
	6	25	16	20.5	33	53	5	4	4	4
	7	29	18	23.5	25	87	4	4	5	5
	8	30	19	24.5	27	68	5	5	5	5
	9	21	13	17	42	53	5	5	5	5
	10	14	8	11	52	39	5	5	5	5
	11	2	0	1	68	37	5	5	5	5
	12	-1	-2	-1.5	88	23	5			
	Average	**13.7**	**7.3**	**10.5**	**51.3**	**46.8**	**5.2**	**4.1**	**4.4**	**4.5**
2008	1	-3	-7	-5	79	48	6			
	2	0	-3	-1.5	74	45	6			
	3	9	3	6	61	23	6	3	4	4
	4	14	8	11	61	23	5	3	4	4
	5	18	10	14	51	45	5	4	5	5
	6	23	14	18.5	39	57	4	5	5	5
	7	27	17	22	39	58	5	4	4	4
	8	29	18	23.5	27	90	4	4	4	4
	9	19	11	15	46	53	5	5	5	5
	10	14	8	11	56	48	5	5	5	5

Continuation of the table 1

1	2	3	4	5	6	7	8	9	10	11
	11	6	2	4	61	47	5	4	4	4
	12	-1	-4	-2.5	71	48	5			
	Average	**13.0**	**6.4**	**9.7**	**55.4**	**48.9**	**5.1**	**4.1**	**4.4**	**4.4**
2009	1	-3	-5	-4	93	26	5			
	2	0	-1	-0.5	86	14	5			
	3	5	1	3	79	23	5	3	4	4
	4	13	3	8	36	60	5	4	4	5
	5	18	11	14.5	49	32	4	5	5	5
	6	27	17	22	33	77	5	5	5	5
	7	28	17	22.5	48	33	4	4	4	4
	8	25	14	19.5	48	45	5	4	4	4
	9	21	12	16.5	56	47	5	5	5	5
	10	15	8	11.5	77	19	5	5	5	5
	11	6	3	4.5	92	0	5	4	4	4
	12	7	3	5	88	17	7			
	Average	**13.1**	**6.6**	**9.9**	**65.1**	**33.6**	**4.9**	**4.4**	**4.5**	**4.6**
2010	1	-7	-9	-8	90	9	8			
	2	-2	-4	-3	89	4	8			
	3	4	0	2	65	26	5	3	4	4
	4	13	6	9.5	45	13	4	4	5	5
	5	21	13	17	50	26	4	5	5	5
	6	27	17	22	31	53	5	5	5	5
	7	30	20	25	28	61	4	4	4	4
	8	32	19	25.5	10	81	5	4	4	4
	9	23	13	18	40	75	4	4	5	5
	10	10	3	6.5	61	52	4	5	5	5
	11	11	6	8.5	67	57	4	4	4	4
	12	1	-1	0	80	29	4			
	Average	**13.8**	**7.1**	**10.5**	**54.2**	**39.2**	**4.9**	**4.2**	**4.5**	**4.5**
2011	1	-4	-7	-5.5	85	35	3			
	2	-6	-10	-8	81	36	7			
	3	2	-3	-0.5	73	45	5	2	2	2
	4	12	4	8	42	13	5	3	4	4
	5	22	11	16.5	54	34	4	4	5	5
	6*	24	20	22	64	10	5	5	5	5
	7*	29	24	26.5	57	29	4	4	4	4
	8*	26	20	23	57	32	5	4	4	4
	9	21	12	16.5	44	71	4	4	5	5
	10	11	4	7.5	65	32	4	5	5	5

Continuation of the table 1

1	2	3	4	5	6	7	8	9	10	11
	11	1	-2	-0.5	73	20	4	4	4	4
	12	2	0	1	88	16	4			
	Average	**11.4**	**5.9**	**8.7**	**66.1**	**29.7**	**4.5**	**3.9**	**4.2**	**4.2**
2012	1	-3	-7	-5	82	32	4			
	2	-7	-11	-9	78	28	4			
	3	3	0	1.5	67	32	5	4	4	4
	4	18	8	13	40	33	4	5	5	5
	5	23	14	18.5	29	58	4	5	5	5
	6	26	16	21	26	71	4	5	5	5
	7	29	19	24	18	58	4	4	4	4
	8	28	17	22.5	22	45	5	4	4	4
	9	21	11	16	35	70	3	5	5	5
	10	16	9	12.5	53	55	4	4	5	5
	11	7	3	5	67	30	4			
	12	-2	-4	-3	85	23	6			
	Average	**12.8**	**6.0**	**9.4**	**51.0**	**43.6**	**4.3**	**4.5**	**4.6**	**4.6**
2013	1	0	-2	-1	88	13	4			
	2	1	-2	-0.5	77	21	5			
	3	4	-1	1.5	65	29	5	4	4	4
	4	16	6	11	30	50	5	5	5	5
	5	25	15	20	18	65	4	5	5	5
	6	26	16	21	23	37	4	4	5	5
	7	27	16	21.5	19	45	4	4	4	4
	8	27	17	22	40	42	3	4	4	4
	9	15	10	12.5	65	20	4	5	5	5
	10	10	6	8	74	19	4	4	4	4
	11	7	3	5	74	27	4			
	12	0	-3	-1.5	85	26	4			
	Average	**13.2**	**6.8**	**10.0**	**54.7**	**32.9**	**4.2**	**4.4**	**4.5**	**4.5**

Notes: 1. Weather data were taken from the NETHOLDING Weather Archive: https://net.dn.ua/weather/archieve.php?year=2006, except for June, July and August 2011, for which the data is https: // www. gismeteo.ru/diary/5080/2011/6/ and http://www.pogodaiklimat.ru/weather.php?id=34519&bday=1&fday=30&amonth=6&ayear=2011 (relative humidity).
2. The average for the year is based on the number of days in each month. At the same time for some months, the available data are not every day, namely: July 2009 – 12 days, January 2010 – 23 days, September 2010 – 12 days, October 2010 – 21 days, May 2011 – 29 days, September 2011 – 17 days, June 2012 – 17 days. Loss of data in weather archives may be related to military actions in eastern Ukraine.

During observations (2007–2013), each of these parameters varied within (variation intervals) given in Table 2. For each of these intervals we find the center point as the simple average and the step of variation as half the difference between intervals (Table 2). This allows reducing of all the intervals of variation to the standard limits [-1, 1]. We accept a linear regression equation containing only a free member and members with the first degree of each factor [5].

Table 2 – Bringing factors to standard variation intervals

Factor X	Average relative humidity φ, %	The average percentage of sunny days n_{sun}, %	Average tempera-ture θ, °C	Average wind speed *V*, v/c
Maximum value X_{max}	66.1	48.9	10.5	5.2
Minimum value X_{min}	51.0	29.7	8.7	4.2
Center $\bar{X}=(X_{max}+X_{min})/2$	58.55	39.3	9.6	4.7
The step of variation $\Delta X = (X_{max} - X_{min})/2$	7.55	9.6	0.9	0.5
Factor in standard interval [-1,1]: $\tilde{X}=(X-\bar{X})/\Delta X$	$\tilde{\varphi}=\frac{\varphi-58,55}{7,55}$	$\tilde{n}_{sun}=\frac{n_{sun}-39,3}{9,6}$	$\tilde{\theta}=\frac{\theta-9,6}{0,9}$	$\tilde{V}=\frac{V-4,7}{0,5}$

Using the least squares we find the following equations:

$$\Phi T_1 = 4,28+0,69\tilde{\varphi}+0,75\tilde{n}_{sun}+0,63\tilde{\theta}-0,78\tilde{V}\pm 0,090; \quad (1)$$

$$\Phi T_2 = 4,46+0,33\tilde{\varphi}+0,40\tilde{n}_{sun}+0,34\tilde{\theta}-0,39\tilde{V}\pm 0,067; \quad (2)$$

$$\Phi T_3 = 4,49+0,39\tilde{\varphi}+0,43\tilde{n}_{sun}+0,39\tilde{\theta}-0,39\tilde{V}\pm 0,089. \quad (3)$$

In such a sample, the estimation of the dispersion of each parameter is complicated. In this case, the significance of each member of the equation can be estimated in the following way. Points are evaluated with an accuracy of one. On averaging, the accuracy is about 0.1 point. Deviation to 0.1 point of the value obtained by the regression equation (1–3) is considered as insignificant. Let us assume that each parameter is insignificant one after another. We remove it from the equation and repeat the solution by the method of least squares. If the deviation of the results for the new regression equation significantly exceeds 0.1, then the assumption is considered wrong and the parameter is significant. As a result, deleting each parameter from each equation gives a deviation of each result over 0.15…0.2. Thus, all the members are meaningful. The deviation of equations 1–3 does not exceed 0.09. Thus, the choice of parameters can be considered expedient.

The analysis of the equations shows that the coefficients in factors are comparable, that means equal importance of taking into account all factors. The smallest coefficients for all factors correspond to the second group of plants. These plants are the most resistant to weather conditions. Plants of group III are characterized by insignificantly higher values of coefficients. The difference between the corresponding coefficients of equations (2) and (3) is within the range of 0…18.2%. Thus, plants of group III have approximately the same resistance to weather conditions. Plants of group I are characterized by the values of the coefficients of equation (1), which is 1.8 ... 2.1 times greater than the corresponding coefficients of equation (2) for group II. In addition, the value of the free term of the equation (1) is 4% less than the value of the absolute term of the equation (2). Thus, the first group of plants is most sensitive for weather conditions and has a lower score at the average value of ambient air parameters. Thus, these plants are more likely to lose their decorative qualities and require more frequent replacement or planting.

The increase in relative humidity, the number of sunny days and the average annual temperature favorably affects plants, as evidenced by the plus sign in the corresponding terms of the equations (1–3). The wind suppresses the development of plants, showing the sign "minus" with the corresponding term of equations (1–3). On the other hand, in the warm period of the year, the increase in wind speed increases the "cooling effect" of plants and reduces energy consumption for air conditioning.

The rate of air flow above the plants can be guided by a parapet. Blind parapet reduces air velocity and increases the relative humidity of air by reducing airflow. It improves the decorative qualities of plants and reduces the energy efficiency of the building in hot season. On the contrary, perforation of the parapet intensifies air exchange, worsens the decorative qualities of plants, but increases energy efficiency. Formulas (1–3) and equation describing the reduction of surface temperature under the plant layer due to the "cooling effect" [6].

$$\Delta T_{c.e} = \left(0{,}508\,atan(V) + 0{,}543\right) atan^2(V) + 0{,}752 \text{ , K,} \qquad (4)$$

allow reaching the most expedient operation conditions of a roof depending on requirements of the customer. In the future, it is recommended to develop mathematical models for green roofs of the other regions of Ukraine with the appropriate assortment of plants.

Conclusions

The developed mathematical model of the influence of weather factors on plant development makes it possible to assume that the steppe phenotype is well suited for the sharply continental climate of the eastern region of Ukraine. The second and the third groups are the most resistant to climatic conditions. They are recommended for green roofs of similar type of climate. The sensitivity of the plants to the wind influence is established. This factor can have a negative impact on plant decoration, but it improves the energy efficiency of buildings during the warm period of the year. It is proposed to regulate air velocity over plants using a parapet. With perforated parapet in the summer, the effect of wind increases, which reduces decorative properties, but increases the "cooling effect". With a blind parapet, the effect of the wind decreases, the decorative properties of the plants increase, but the "cooling effect" decreases. This fact must be taken into account when using the green roof.

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МАТЕМАТИЧНА МОДЕЛЬ ЕКСТЕНСИВНОЇ ЗЕЛЕНОЇ ПОКРІВЛІ ЗІ СТЕПОВИМ ТИПОМ ФІТОЦЕНОЗУ

Анотація. Розроблена математична модель екстенсивної зеленої покрівлі зі степовим типом фітоценозу для східного регіону України з різко континентальним типом клімату. Головними факторами є середньорічна відносна вологість повітря, температура, відсоток сонячних днів та швидкість вітру. Методом найменших квадратів отримано три рівняння. Аналіз рівнянь показує, що коефіцієнти при

факторах є сумірними, що свідчить про однакову важливість врахування всіх факторів. Найменші коефіцієнти при всіх факторах відповідають групі рослин II. Ці рослини найбільш стійкі до зовнішніх впливів. Рослини групи III характеризуються несуттєво більшими значеннями коефіцієнтів – у межах 0…18,2%. Таким чином, рослини групи III мають приблизно таку саму стійкість до впливу погодних умов. Рослини групи I характеризуються значенням коефіцієнтів, що в 1,8…2,1 раза більші за групу II. Крім того, значення вільного члена на 4% менше за групу II. Таким чином, перша група найбільш вибаглива до погодних умов і при середньому значенні параметрів навколишнього повітря має нижчий бал. Тобто, ці рослини з більшою ймовірністю втрачають свої декоративні якості і вимагають більш частої заміни або досадження. Встановлена чутливість рослин до дії вітру. Даний фактор може мати негативний вплив на декоративність рослин. Дію вітру пропонується регулювати за допомогою парапету. При перфорованому парапеті в літній період дія вітру посилюється, що знижує декоративність, але збільшує "охолоджуючий ефект". При глухому парапеті дія вітру знижується, декоративність рослин підвищується, але зменшується "охолоджуючий ефект". Цей факт необхідно враховувати при цільовому використанні зеленої покрівлі.

Ключові слова: екстенсивна зелена покрівля, степовий тип фітоценозу, математична модель, метод найменших квадратів, стійкість рослин, погодні умови.

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A mathematical model of the influence of weather conditions on the development of plants of a green roof with steppe type of phytocenosis for the eastern region of Ukraine with a sharply continental type of climate was developed.

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