Phenological phenomena in the life of plants in Zhiguli Nature Reserve in the changing climate (using the example of *Laser trilobum* and *Euphorbia zhiguliensis*)

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Phenological processes of two rare species, *Laser trilobum* and *Euphorbia zhiguliensis*, in Zhiguli Reserve, and their changes associated with climate change during more than 38 years of observations are discussed. Long-term weather condition phenorhythms in the reserve were summarized, and the behavior of the plants in the changing environment was studied.

Keywords: phenology, rare species, Zhiguli Nature Reserve, climate change, *Laser trilobum*, *Euphorbia zhiguliensis*, mean air temperature, amount of precipitation.

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Introduction

Changes in the natural greenhouse and climate, contributed to by human activities, have recently been the subject of increasing number of scientific studies (Snakin, 2019). Considerable data have been obtained on the change in the phenological reactions of plants to climatic factors, although in Zhiguli Reserve, research in this direction began relatively recently. These studies are conducted within the framework of the “Letopis’ prirody” (Nature Record) program and are considered as a basis for monitoring the state of ecosystems.

Two ecologically different plant species belonging to different families were selected as the study objects: *Laser trilobum* (L.) Borkh. and *Euphorbia zhiguliensis* (Prokh.) Prokh. Both species are rare, listed in the Red Data Book of the Samara Region (2017), and have been observed for over 30 years. They were selected as study objects to trace their ‘responsiveness’ to changes in climatic environmental

factors; in addition, they are objects of the “Letopis’ prirody” (Nature Record) program (section “Rare plant species”). The “Letopis’ prirody” (Nature Record) is the main annual scientific report on the fulfillment of the State Assignment, which includes primary data on observations of natural assemblages, the results of scientific research, information on the economic activities of the reserve, as well as reports from third-party organizations. All sections of the “Letopis’ prirody” (Nature Record), and in particular “Rare Plant Species”, are conducted in accordance with the methodological recommendations of K.P. Filonov and Yu.D. Nukhimovskaya (1990). The “Letopis’ prirody” (Nature Record) of Zhiguli Reserve has been published annually since 1966, and since 1979 there has been a permanent network of phenological research trips (Letopis’ prirody, 1979).

The purpose of this work is to trace changes in plant development against the background of long-term climate dynamics.

Material and methods

Phenological and meteorological observations of the two plant species were conducted in Zhiguli State Reserve. We used data from the “Letopis’ prirody” documentation of the reserve from 1979 to 2017. Our own research on plant phenology was conducted in 2014–2017.

Study objects

Laser trilobum (gladich) is a perennial herb of the family Apiaceae (Umbelliferae). This Pliocene relic of deciduous forests is included in the Red Data Book of the Samara Region as a rare species with a wide range, within which it occurs sporadically. It grows in shady forests and along their edges, in steppe mountain forests, broad-leaved pine forests and steppe low-mountain oak forests, preferring calcareous and clayey soils (Krasnaya kniga..., 2017).

Euphorbia zhiguliensis is a perennial herb of the family Euphorbiaceae. This is a narrow-local mountain-steppe endemic of the Zhiguli Upland, included in the Red List of the Russian Federation (2008) and in the Red Data Book of Samara Region, with the status of an extremely rare species, gradually declining. It grows on stony steppes, in sparse pine forests, on rocky slopes and rocks (Krasnaya kniga..., 2017).

The selected species have been shown to be excellent bioindicators of the state of the environment; when compiling the “Nature Record” reports, the duration of their vegetation was shown to be changing, which determined the choice of study objects. Observations of these species were conducted on two permanent phenological routes: no. 2 and no. 7 for *L. trilobum*, no. 2 and no. 6 for *E. zhiguliensis*.

Phenological route no. 2 (Shkolny Ravine) (PR no. 2) refers to the system of ravines of the Bakhilovo Valley, covered with forests. The left side of the ravine (angle 15–20°), the middle part of the slope of the southeastern aspect is covered by mountain forest growths. In the forest community, two tiers are clearly distinguished: the first tier is represented mainly by *Pinus sylvestris*; the second tier is represented by the main forest species of the reserve: *Acer platanoides* and *Tilia cordata*. The undergrowth includes *Corylus avellana*, *Sorbus aucuparia*, *Carex fruticosa*, and *Cerasus fruticosa*. The grass cover is also two-tiered: *L. trilobum*, *Centaurea ruthenica*, *Libanotis sibirica*, *Solidago virgaurea*, and *Echinops ruthenicus* were recorded in the first tier, while *Polygonum odoratum*, *Geranium sanguineum*, *Pulsatilla patens*, and *E. zhiguliensis* were in the second.

Phenological routes (PR) no. 6 and no. 7 pass along the slope of Mount Zmeinaya in the southwestern part of the village of Bakhilova Polyana. PR no. 6 (Mount Zmeinaya) runs along a rocky steppe, which stretches in a narrow strip (from 0.5 to 15 m) along the

edge of a deciduous forest, running along the crest. The rocky steppe is characterized by a time-division tiering of vegetation, which gives several clearly pronounced color aspects (Letopis’ prirody, 1980).

PR no. 7 (mountain forest on Mount Zmeinaya) includes forest phytocenoses and stony steppe communities. Here, the steep southern slope is occupied by thickets of *P. sylvestris* and *C. frutex*, and the observed area with *L. trilobum* is located on the ridge of the mountain and is adjacent to the stony steppe and low-mountain oak forest. The grass cover is heterogeneous and is represented by patches of *P. odoratum*, *C. ruthenica*, *E. ruthenicus*, *Hieracium virosum*, and *Convallaria majalis*.

Phenological observations

In our observations we followed the method proposed by M.E. Terenteva in 1973 (Terenteva, 1990). This technique was shown to be a simple and effective way to determine phenological phases on stationary routes. For all species we used 14 phenological indicators proposed by Beideman (1974): germination, leafing, onset of budding, onset and end of flowering, onset and end of mass flowering, setting of seeds, onset of maturation, and maturation of seeds, onset and end of seed dispersal, onset and end of plant dying off. Only the main indicators were used for the analysis:

- *Sprouting (Spr)* – the emergence of seedlings from underground organs, onset of bud opening or leaf growth in overwintering rosettes.
- *Leafing (Leaf)* – unfolding of the first true leaf.
- *Flower buds become visible (Bud)* – appearance of the first flower buds.
- *Onset of flowering (OF)* – appearance of the first flowers, onset of pollen production.
- *End of flowering (EF)* – date when most of the plants drop all petals from flowers or pollen production ceases.
- *Fruit set; onset of ovary growth (OG)* – the date when the first ovaries are found in most plants.
- *Fruit maturation (FM)* – day when the first mature fruit (seeds) appear.
- *Onset of seed dispersal (OD)* – the first day of seed dispersal or fruit fall.
- *End of seed dispersal (ED)* – the last day of seed dispersal or fruit fall.
- *Onset of dying off (DO)* – the first day when in 10% of plants in the population, the first signs of dying off of shoots are manifested.
- *End of dying off (DE)* – the day when 90% of the plants in the population have died off (dried out shoots).

In addition, the following parameters were calculated: *duration of budding (DBud)*, *duration of flowering (DF)* and *duration of vegetation (DV)*. The du-

ration of budding was calculated as the number of days from the onset of budding to the onset of flowering; flowering duration as the difference between the onset and the end of flowering; the duration of the growing season was calculated as the time interval between the sprouting and the end of dying off.

Data on the average monthly air temperature, maximum and minimum soil temperatures, as well as the amount of precipitation per month were obtained from a meteorological station located within the reserve and constantly operating since 1972.

For statistical processing of data on plant phenology and the effect of climatic factors, calculations were performed using the STATISTICA 6.1 software package (Ivanter, 2003).

Results

Meteorological research

The long-term mean annual air temperature (over 38 years of observations) was 5.3 °C. The coldest year was 1987, when the mean temperature was 3.1 °C. The warmest year was 1995 with an average annual value of 7.2 °C. A general increase in the average annual air temperature is observed during the period of research (Fig. 1).

Rainfall also changes from year to year. The average annual precipitation is 573.1 mm. The maximum amount (more than 700 mm) of precipitation was recorded in 1987, 1990, 2006, 2007, 2011 and 2013, the minimum was recorded in 1996, 2009, 2010 and 2014. In general, for 38 years, the amount of precipitation has remained at about the same level (Fig. 2).

Phenological observations

Laser trilobum

L. trilobum sprouts and leaves in the second ten days of April, the onset of flowering is observed in the first ten days of June, and the seeds mature in the second half of July. Hence, *L. trilobum* can be classified as a mid-spring species in terms of sprouting and leafing and an early summer species in terms of the onset of flowering (Voroshilov, 1960).

Statistical data on the duration of the phenological phases of *L. trilobum* and the dates of their onset on the phenological routes 2 and 7 are shown in Table 1. The degree of variability of all dates was estimated by the coefficient of variation V (%), interpreted using G.F. Lakin's (1980) method. According to this method, V values up to 10% show low variability, from 10 to 25% – medium variability, more than 25% – high variability. These data show that *L. trilobum* shows low variability in the onset of budding, onset and end of flowering, and fruit setting. Duration of budding and flowering on both routes, as well as the end of dispersal and the onset of dying at PR no. 2 show high variability; for other indicators, the degree of variability is medium.

The obtained parameters are reliable due to high reliability of the arithmetic mean ($t_m \gg 2$) (Zaitsev, 1984). The statistical significance (p -value) of the observations was less than 5% in all parameters, except for the duration of budding and flowering (7.5, 9.4 and 6.2, 6.6 on both routes, respectively), and it is these two phases that have the greatest variability ($V > 25\%$).

Note that almost all phenological phenomena along PR no. 7 occurs several days earlier than those in PR no. 2. Perhaps this is due to the diversity of the

Fig. 1. Mean annual air temperature (1979–2017).

Fig. 2. Mean annual precipitation (1979–2017).

microrelief and, accordingly, different climatic characteristics.

The duration of the growing season of *L. trilobum* varies from year to year (Fig. 3). On both routes, the shortest growing seasons were recorded in 2010 (97 and 78 days). This summer was noted as extremely hot and dry (Letopis' prirody, 2010). The longest growing season was in 1980 (188 days) on PR no. 2. This year was characterized by a significant decrease in the average monthly air temperature in the spring (by 2.1 °C) and an increased amount of precipitation in the spring (1.5 times higher than the norm) and summer (2.5 times higher than the norm in August) (Letopis' prirody, 1980).

The longest growing season on PR no. 7 was in 2011 (158 days). This year, the amount of precipitation in spring was 1.3 times higher than the norm, and autumn precipitation exceeded the long-term average values by more than 5 times and amounted to 378.9 mm (Letopis' prirody, 2011).

Thus, it can be assumed that the duration of the growing seasons of *L. trilobum* is influenced by the precipitation regime. Thus, an increase in precipitation in spring by 1.5 times leads to an increase in the growing season on PR no. 2, and an increase in autumn precipitation leads to an increase in the duration of the growing season on PR no. 7.

The graph of changes in the duration of the growing season for 38 years of observations is shown in Fig. 3. The trend line shows a gradual decrease in the length of the growing season on both routes.

On PR no. 7 in some years *L. trilobum* lacked flowering and fruiting phases (Fig. 4). Analysis of weather conditions shows the presence of spring-sum-

mer droughts in the years preceding this phenomenon. Thus, in 1995, three waves of spring-summer droughts were observed (13.04–10.05, 05.06–02.07, 02.09–23.09) (Letopis' prirody, 1995), which led to a complete absence of the generative phase of plants in 1996 and 1997.

The same effect was observed in 1999 after the 1998 drought, which began at the end of April and continued until June 25 (Letopis' prirody, 1998, 1999). A drought lasting 30 days occurred in August 2005; also, insufficient precipitation (17.2% of the norm) was recorded in August 2007, which, in turn, led to the absence of fruits in *L. trilobum* in 2006 and 2008. (Letopis' prirody, 2006, 2008). In addition, the severe drought of 2010 (Letopis' prirody, 2010) (20.06–23.08) affected the fruiting of *L. trilobum* at PR no. 7, which was absent for the next two years. However, all these droughts did not have a significant effect on flowering and fruiting of plants on PR no. 2, where the habitat conditions for *L. trilobum* are less extreme.

Euphorbium zhiguliensis

Statistical data on the duration of the developmental phases of *E. zhiguliensis* are presented in Table 2. In terms of phenological dates, it is a mid-spring species. The average dates of sprouting and leafing are in mid-April, the flowering phase begins in late April-early May, fruiting begins on average in the first decade of June. The onset of the seed dispersal of this species varies in different years, the amplitude of fluctuations of this indicator is quite high (55 days); on average, this phase begins on July 2.

Compared to *L. trilobum*, *E. zhiguliensis* was shown to be more sensitive with respect to environmental conditions. For the latter species, a low de-

Table 1. Statistical parameters of the duration of phenological phases and the dates of their onset for *Laser trilobum*. Above the line are the values for PR no. 2, below the line for PR no. 7. X – the average value of the indicator; m_x – error of the mean; X_{min} – the minimum value of the parameter; X_{max} – maximum value of the parameter; σ^2 – variance; σ – standard deviation; m_σ – the standard deviation error; t_m – value of reliability of the arithmetic mean; V – the coefficient of variation; p – statistical significance (p-value).

Parameters of phenological phases	X	m_x	X_{min}	X_{max}	σ^2	$\sigma \pm m_\sigma$	t_m	$V, \%$	$P, \%$
<i>Spr</i> (date)	15.04	1.2	09.04	04.05	53.9	7.3 ± 0.9	51.0	14.2	2.4
	20.04	2.1	30.03	30.04	168.8	13.0 ± 1.5	21.7	28.5	4.6
<i>Leaf</i> (date)	26.04	1.1	12.04	09.05	51.3	7.2 ± 0.8	49.4	12.6	2.0
	24.04	1.1	10.04	05.04	46.5	6.8 ± 0.8	49.9	12.3	2.0
<i>Bud</i> (date)	28.05	1.2	17.05	12.06	53.3	7.3 ± 0.9	72.3	8.2	1.4
	25.05	1.6	09.05	18.06	78.6	8.9 ± 1.2	54.2	10.3	1.8
<i>DBud</i> (days)	12	0.9	2	26	34.2	5.9 ± 0.7	13.3	49.1	7.5
	12	1.1	3	27	73.8	6.2 ± 0.8	10.5	53.4	9.4
<i>OF</i> (date)	09.06	1.1	25.05	19.06	49.5	7.0 ± 0.8	84.8	7.0	1.2
	06.06	1.6	24.05	26.06	74.1	8.6 ± 1.1	61.4	8.7	1.6
<i>EF</i> (date)	21.06	1.3	02.06	07.07	63.6	8.0 ± 0.9	86.9	7.1	1.2
	19.06	1.6	03.06	10.07	38.3	8.6 ± 1.1	69.5	7.1	1.4
<i>DF</i> (days)	13	0.8	4	22	21.1	4.6 ± 0.5	16.2	35.4	6.2
	14	0.9	3	25	22.4	4.7 ± 0.6	15.2	34.3	6.6
<i>OG</i> (date)	14.06	1.1	28.05	29.06	46.5	6.8 ± 0.8	96.4	6.4	1.0
	14.06	1.7	29.05	07.07	89.9	9.5 ± 1.2	62.6	8.9	1.6
<i>FM</i> (date)	23.07	2.8	22.06	22.08	27.4	16.6 ± 1.9	51.8	11.4	1.9
	19.07	4.0	01.06	28.08	482.6	21.9 ± 2.9	35.2	15.6	2.8
<i>OD</i> (date)	30.07	4.6	12.07	07.09	795.0	28.2 ± 3.3	33.1	18.5	3.0
	31.07	2.4	21.06	28.08	168.1	13.0 ± 1.7	63.7	8.5	1.6
<i>ED</i> (date)	02.09	8.6	16.07	30.10	276.2	52.6 ± 6.2	21.6	28.3	4.6
	01.09	5.9	26.07	28.10	753.1	27.4 ± 4.2	31.7	14.6	3.2
<i>DO</i> (date)	28.07	6.6	27.06	20.10	1630	40.4 ± 4.7	22.3	27.5	4.5
	26.07	3.0	21.06	08.09	358.6	18.9 ± 2.2	50.6	12.4	1.9
<i>DE</i> (date)	05.09	6.5	01.08	26.10	1574	39.7 ± 4.7	29.0	21.0	3.5
	27.08	3.3	12.07	04.10	407.8	20.2 ± 2.3	54.6	11.2	1.8
<i>DV</i> (days)	143	3.9	97	189	559	23.7 ± 2.8	36.7	16.5	2.7
	132	3.2	78	161	400	20.0 ± 2.3	41.3	15.1	2.4

Fig. 3. Length of the growing season of *Laser trilobum*.

Рис. 4. Phenological spectrum of *Laser trilobum* on PR no. 7

Table 2. Statistical parameters of the duration of phenological phases and the dates of their onset for *Euphorbia zighuliensis*. Above the line are the values for PR no. 2, below the line for PR no. 6. X – the average value of the indicator; m_x – error of the mean; X_{min} – the minimum value of the parameter; X_{max} – maximum value of the parameter; σ^2 – variance; σ – standard deviation; m_σ – the standard deviation error; t_m – value of reliability of the arithmetic mean; V – the coefficient of variation; p – statistical significance (p-value).

Parameters of phenological phases	X	m_x	X_{min}	X_{max}	σ^2	$\sigma \pm m_\sigma$	t_m	$V, \%$	$P, \%$
<i>Spr</i> (date)	23.04	1.6	9.04	4.05	59.9	7.7 ± 1.6	32.7	14.3	3.0
	14.04	1.0	2.04	1.05	39.7	6.3 ± 0.7	44.5	13.8	2.2
<i>Leaf</i> (date)	26.04	1.6	13.04	11.05	59.7	7.7 ± 1.6	34.3	13.6	2.9
	18.04	1.1	03.04	05.05	48.6	6.9 ± 0.7	42.9	14.2	2.3
<i>Bud</i> (date)	02.05	2.0	20.04	21.05	63.3	8.0 ± 1.4	31.3	12.8	3.2
	22.04	1.2	07.04	08.05	59.4	7.7 ± 0.8	42.0	14.6	2.3
<i>DBud</i> (days)	8	1.2	3	20	22.5	4.7 ± 0.8	6.3	62.5	15.9
	10	1.0	2	29	40.1	6.3 ± 0.7	10.0	62.0	10.0
<i>OF</i> (date)	09.05	2.1	26.04	25.05	68.9	8.3 ± 1.5	32.9	11.8	3.0
	02.05	1.2	19.04	19.05	60.9	7.8 ± 0.8	49.9	12.4	2.0
<i>EF</i> (date)	26.05	2.4	05.05	07.06	99.4	9.9 ± 2.4	35.0	11.4	2.8
	21.05	1.4	29.04	06.06	82.2	9.0 ± 1.0	55.9	11.0	1.7
<i>DF</i> (days)	18	2.5	4	34	94.2	9.7 ± 2.5	7	55.5	14.3
	19	1.3	2	37	72.6	8.5 ± 0.9	14	44.1	7.1
<i>OG</i> (date)	22.05	2.6	03.05	05.06	104.1	10.2 ± 1.8	32.0	12.2	3.1
	14.05	1.3	25.04	30.05	70.4	8.3 ± 0.9	55.6	11.0	1.7
<i>FM</i> (date)	19.06	3.4	29.05	03.07	127.2	11.3 ± 2.4	32.6	10.1	3.0
	09.06	1.3	21.05	27.06	67.5	8.2 ± 0.9	76.0	8.1	1.3
<i>OD</i> (date)	23.06	3.2	04.06	05.07	117.0	10.8 ± 2.3	35.9	9.4	2.8
	12.06	1.4	24.05	28.06	80.7	8.9 ± 1.0	71.9	8.6	1.3
<i>ED</i> (date)	29.06	2.7	14.06	11.07	82.0	9.0 ± 1.9	44.8	7.5	2.2
	23.06	1.4	05.06	14.07	81.4	9.0 ± 1.4	78.9	7.8	1.2
<i>DO</i> (date)	02.08	4.9	27.06	10.09	535.5	23.1 ± 3.5	31.7	14.8	3.1
	05.07	3.9	01.06	15.09	607.2	24.6 ± 3.9	31.8	19.4	3.1
<i>DE</i> (date)	31.08	6.4	4.07	17.10	964.5	31.1 ± 4.6	28.7	16.9	3.4
	03.08	6.5	12.06	31.10	1651	40.6 ± 6.5	23.8	25.8	4.2
<i>DV</i> (days)	130	7.9	86	190	1325	36.4 ± 5.6	16.5	27.9	6.0
	111	6.3	65	194	1533	39.1 ± 6.3	17.5	35.1	5.7

Fig. 5. Length of the growing season of *Euphorbia zighuliensis*.

Fig. 6. Phenological spectrum of *Euphorbia zighuliensis*.

degree of variability is observed only at the onset of fruit maturing, as well as at the onset and end of seed dispersal. The duration of budding, flowering, and vegetation show high variability on all routes, while the rest of the parameters are characterized by an average degree of variability. All data are statistically reliable ($t_m \gg 2$). The measure of statistical significance of the experiment (as in *L. trilobum*) is less than 5%, except for the duration of the budding, flowering and vegetation phases (Zaitsev, 1984).

All phenological phenomena on PR no. 6 start a few days earlier than PR no. 2. Presumably, this is because on PR no. 6, this species is found in an open steppe area, and not in a forest community, where there is less sunlight, and the grass roots are sodded.

The duration of the growing season for *E. zhiguliensis* varies from 45 (1988) to 184 days (2008) and averages 113 days. Sprouting of plants in 1988 was recorded on April 17 (on average 14.04), and dying off already occurred on June 30, and thus the duration was 40% of the average. The weather conditions of this year were distinguished by an increased air temperature in June, which exceeded the long-term average values by 2.2 °C, and the amount of precipitation in May – June exceeded the long-term average values by 17.1 and 39.1 mm (Letopis' prirody, 1988).

Over 38 years of phenological observations of *E. zhiguliensis* showed a general tendency to an increase in the duration of the growing season, which has been especially noticeable since 2003 (Fig. 5).

The shortest period in the life cycle of *E. zhiguliensis* is fruit maturing, which takes from 2 to 10 days, but in 2007 this phase lasted 20 days. Most likely, this was due to the cool weather in June, when the average air temperature was 17.7 °C (0.8 °C lower than the long-term mean), while the air temperature on the soil dropped to 0.0 °C, which is the absolute minimum for the second decade of June.

The duration of the main phenological phases of *E. zhiguliensis* is shown in Fig. 6.

Conclusions

The process of plant development is affected by many factors: from the growing conditions to the microclimatic conditions of the plant habitats. Some species have highly specific environmental, climatic and phytocenotic needs. We studied the degree of climate influence on the life and development of two rare plant species.

L. trilobum reacts sharply to periods of drought, with no fruiting phase in subsequent years. Almost all stages occur several days earlier on PR no. 7 than PR no. 2. In different microclimatic conditions, the duration of the growing season changes (in the fo-

rest community at PR no. 2 it is 10 days longer than at forest PR no. 7); also, the duration of the growing season of *L. trilobum* is influenced by the precipitation regime. Thus, an increase in precipitation in spring leads to an increase in the growing season on PR no. 2, and an increase in the amount of autumn precipitation leads to an increase in the duration of the growing season on PR no. 7. At the same time, there is a tendency to a decrease in the duration of the growing season on all routes.

The development of *E. zhiguliensis* is most influenced by the precipitation regime in summer and the temperature regime during the budding and flowering phases. All phenological phenomena on PR no. 6 start a few days earlier than PR no. 2. In general, over 38 years of phenological observations of *E. zhiguliensis*, there is a trend toward an increase in the duration of the growing season.

In the future, the Nature Reserve plans to continue researching the links between plant phenological processes and climatic changes, which, can reveal new potential indicator species of the state of the environment.

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