Landscape basis for the formation of phenological network in steppe provinces of the Urals

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Abstract. The article describes the formation of a regional phenological network that can be used as a basis for landscape-dynamic studies of the steppe natural complexes of the Urals. The functional-dynamic approach was used as a methodological basis of the study. The phenological network was reviewed within a period since 1925 till recent times. We performed a landscape structure analysis and determined the hierarchical levels of natural complexes specific for the territory that serve as geographical markers of the regional phenological network. Analyzing long-term archive data collected by the Russian Geographical Society and the Ural Reserves Chronicles of the nature data in the 20-21th centuries, we uncovered some negative trends in the onset of spring-summer phenomena in the steppe provinces of the Urals. In addition, we present several key criteria, that should be used to determine how geographically representative a phenological network is, such as: typicalness, landscape diversity, anthropogenic differentiation. The structural and spatial analysis of the phenological network of the steppe landscape provinces of the Southern Urals allowed revealing its peculiarities, such as its branched structure, irregularity, and its inconsistency with the landscape diversity of the region. Quantitative analysis and modeling of the phenological network allow developing recommendations for its expansion. A scientifically profound phenological network will optimize dynamic monitoring of the steppe natural complexes of the Urals and collecting data that is crucial for the long-term sustainable development of the region.

1. Introduction
The modern landscape structure of the territory is formed in the process of changing states in the course of dynamic and evolutionary development. According to the functional-dynamic approach, the mosaic structure is caused by the factors of formation and emergent effects, the heterogeneity of the geographical context, expressed by different states belonging to one or more dynamic trajectories. The state of the geosystem is considered as a spatial-temporal homogeneity, distinguished by the criteria for preserving the composition and ratio of system-forming elements and leading processes [1]. One of the important characteristics of geosystems is seasonal dynamics, which is expressed in the rhythmic change of short-term states within the annual cycle, caused by intra-annual changes in thermal and water regimes. On a logarithmic scale, seasonally dynamic states are short-term and are measured over a period of 100 years [2]. The fundamental problem that phenological research is aimed at solving is the identification of the mechanisms of spatial-temporal organization and dynamics of landscapes. When studying climate dynamics, it becomes relevant to study phenological phenomena that reflect
the seasonal rhythm of nature, which serve as complex indicators of physical and geographical conditions and allow us to trace the trends of their changes [3].

The study of seasonal-dynamic states involves the use of research methods based on the collection, processing and analysis of a significant array of primary data selected by a number of parameters. Information is collected within a phenological network, which is a collection of geographically representative reference points and key sites, evenly distributed in typical regional conditions. The duration of the series of observations and the geographical representativeness of the network of observation points serve as a criterion for reliability of the information received and the conditionality of the results of the studies performed [4]. To date, the basis for obtaining data for studying seasonal dynamics is the Phenological Network of the Russian Geographical Society (RGS), which unites correspondent observers from among initiative researchers and nature lovers in Russia and the countries of the former USSR. They collect the results of observations according to a single program for each geographical area. The data of long-term phenological observations of the voluntary phenological network that existed in the XX century is the only mass and comparable source of information on the response of wildlife to climate changes in Russian regions [5], including the steppe zone of the Urals. The results of long-term observations of the phenological network are stored in the Archives of the Russian Geographical Society, located in the A. L. Komarov Phenological Center of the BIN RAS in St. Petersburg and provide information on the steppe zone of the Urals and the Cis-Ural region for the period from 1925 to 1994. The inventory of archival materials, even at the initial examination, allows us to state the insufficient density of observation points, the fragmentary information on the series and elements of the biota. Thus, despite the importance of the accumulated factual material, its insufficient completeness is due to the empirical nature of the network formation without a special landscape justification.

2. Models and Methods
The functional-dynamic and historical approaches serve as the theoretical basis for the landscape justification of the phenological network. The relative complexity of creating a geographically representative model is determined by the specifics of the modern spatial organization that has developed historically. The projected phenological network is formed on the basis of permanent or temporary observation points, which are linked either to the locations of correspondent observers (network territories), or are located within specially protected natural areas that carry out phenological research. When describing the seasonal rhythms, the most valuable are long series of observations that are comparable to the characteristic time of the development of geosystems. Such series of phenological observations are accumulated by the classical or primary method of the group of time recorders, the essence of which is to fix the date of occurrence of the phenomenon in a certain territory. The best results can be obtained when the seasonal phenomenon is clearly visible and the object is located near the observer's place of residence [6]. In the latter case, the duration of the study depends on the continuity of phenological studies, i.e. it is associated with subjective factors. The termination of the researcher's activity leads to the end of the phenological series.

More complete and stable information is provided by specially protected natural areas that do not act on their own initiative, but in accordance with the work plan of the institution. Located in typical natural conditions, they reflect the landscape diversity and operate according to a single observation program. Among the most reliable sources are nature reserves, whose mandatory scientific activities are carried out under the program of the Annals of Nature [7]. The accumulated factual material of a documentary nature contains information about the state and dynamics of natural phenomena and processes, meets the requirements of reliability, mass character, representativeness and long-term continuity.

The implementation of geographical representativeness in the design of the phenological network is achieved through the landscape justification of the rational placement of reference points. The leading role is played by the landscape principle, the initial theoretical position of which is the need to reflect in it all the characteristic natural complexes of a certain type and taxonomic rank from the
standpoint of taking into account landscape diversity [8]. A prerequisite for the deployment of a phenological network is the study of the landscape structure of the territory: The scheme of physical and geographical zoning and the landscape map reflecting the landscape diversity of the region are used as an objective basis for the selection of accounting units. However, in modern conditions, there is no landscape map of the Urals. The available landscape maps of administrative regions differ in their approaches to the classification of geosystems and their content [9-12].

The practical implementation of the landscape principle is achieved through the simultaneous application of the following "key" criteria for the location of reference points: typicality, landscape diversity, and consideration of anthropogenic differentiation. At the planning stage of the phenological network, 3 stages of landscape research are mandatory: inventory, evaluation and target.

Inventory stage includes: 1) study and analysis of the landscape structure, including the structure of anthropogenic modifications of landscapes which is carried out based on existing maps of physical and geographical zoning and landscape maps; 2) collection, digitization and analysis of phenological data-linking observation points, establishing phenomenon indicators and determining the duration of the series; 3) studying the existing network of reference points in order to identify the features of structural and spatial organization; Evaluation stage includes: 1) an estimated multivariate analysis based on the results of landscape mapping or physical-geographical zoning; 2) assessment of the representativeness of the existing phenological network in order to identify landscape units that are not represented by reference points and need their priority allocation; 3) determination of the data conditionality, based on the duration of the presented series of observations and phenological indicators. Target stage includes: 1) justification of plots that meet the criteria of the landscape principle; 2) development of a methodology that ensures the regularity of data collection, scientific analysis and modeling based on qualitative and quantitative indicators.

An inventory study of the phenological network formed in the steppe complexes of the Urals was carried out based on an analysis of archive documents of the RGS phenological network, that we performed in year 2020. We examined over 600 phenological forms, filled out during a period from 1925 to 2019 by volunteer observer correspondents at fixed observation points in the steppe regions of the Urals and the adjacent East European Plains. We also analyzed phenological data collected in the Shulgan-Tash and Orenburg nature reserve, stored in their Chronicles of nature reports.

At the stage of inventory analysis of the existing phenological network, the study of the geographical context was carried out on the basis of the results of the physical and geographical zoning of the Urals. There exist recognized Ural zoning schemes created by representatives of different landscape schools, such as L. D. Dolgushin (1955), A. M. Olenev (1959), A. G. Chikishev (1966), A. A. Makunina (1974), V. I. Prokaev (1983), A. A. Chibilev (2011), A.V. Shakirov (2011), etc. [13; 14]. However, according to the authors [9], the genetic classification and the scheme of physical and geographical zoning of the New Earth-Ural plain-mountain country by V. I. Prokaev is the most complex and fundamentally justified one [2]. The landscape province is used as the main physical and geographical unit for the analysis of geographical representativeness. The spatial analysis of the phenological network was carried out by distributing the reference points and observation points by landscape provinces allocated within the landscape areas. The landscape province combines natural complexes similar in subzonal, sector, and neotectonic-orographic features. Their geological and geomorphological basis is characterized by the predominance of one morphometric type of mountain or plain relief, due to the common neotectonic regime; and in the mountains, the similarity of the structure of the high-altitude zone.

In the study of anthropogenic changes in natural complexes, the principles of classification of modifications of indigenous and conditionally indigenous facies, proposed by V. I. Prokaev and modified by the authors, were used [9]. Based on the recognition of the leading role of geological, geomorphological and climatic factors, all natural complexes, depending on the degree of transformation, are divided into three types: indigenous, derived and anthropogenic.

Studying seasonal regularity requires revealing phenological indicators, typical for the types of natural complexes: 1) zonal natural-territorial complexes, 2) interzonal natural-territorial complexes
(floodpalains, creaks, of swamps), 3) anthropogenic. The phenomena, listed in the phenological forms are easy to detect, and commonly observed by a wide range of observers [15; 16]. Among them are blooming of Gagealutea Ker-Gawl., Tulipaschrenkii, Adonis vernalis, Caraganaarborescens, Syringa vulgaris, Rosacanina, Rosa majalis, SorbusaucupariaPadus.; beginning of pollination of AlnusglutinosaGaertn., the beginning of leaf growth of Betulapubescent, Betula Pendula Roth. and Padusavium. On the average the herbaceous species are typical of the conditions of the zonal natural-territorial complexes, while the woody species are typical of the interzonal natural-territorial conditions [17]. The anthropogenic complexes usually present a combination of herbaceous, shrubby, and woody indicator species.

The original data has a varied completeness in terms of key natural phenomena. Due to the developing multifactor relationships, we analyzed data not solely from the Urals, but from the adjacent East European Plains as well. The comparative analysis of the dynamics of the steppe natural complexes of the plains and mountains are essential for studying global processes and mapping of natural phenomena.

The study used materials on 22 points in the landscape provinces of the Urals and the south-eastern part of the East European Plain. The following periods of continuous series are distinguished: 1937 – 1944; 1963 – 1978; 1981-2019. The longest rows are in the Shulgan-Tash nature reserves – 39 years, from 1981 to 2019, and Orenburg (the Burtinskaya Steppe and Aituarskaya Steppe sections) - 16 years from 1998 to 2014. The observation forms in the archives of the RGS vary in degrees of preservation and completeness of the presented material. The data was studied by preliminary digitization and entering qualitative and quantitative parameters in spreadsheets. As a result, a register of the results of observations for the steppe provinces was compiled, presented in table 1.

Table 1. Availability of phenological data in the steppe landscape provinces.

|                      | Russian Plain | South Ural Upland | Ural-Tobolsk province of the Trans-Ural peneplain | Isetsko-Uisk province of Trans-Ural peneplain | Western foothill mid-mountainous South Urals |
|----------------------|---------------|-------------------|---------------------------------------------------|------------------------------------------------|-----------------------------------------------|
| **Strong points**    | Orenburg,    | Khalilovo,        | Jabyk station,                                    | Verhniaya Sanarka                               | Shulgan-Tash reserve                          |
|                      | Volostnovka, | Kuvandyk,         | Kasselsky village,                                |                                                |                                               |
|                      | Buzuluk,     | Aydarbak,         | Troitsk,                                          |                                                |                                               |
|                      | Syrt,        | Shaitan-Tau reserve | Orsk,                                             |                                                |                                               |
|                      | Chebenki,    |                   | Orenburg reserve                                  |                                                |                                               |
|                      | Shaposhnikovo, |                 | (Aytuarskaya steppe)                              |                                                |                                               |
|                      | Ponomarevka, |                   | (Burtinskaya steppe)                              |                                                |                                               |
|                      | Krasniy Holm, |                   |                                                  |                                                |                                               |
|                      | Donetskoe,   |                   |                                                  |                                                |                                               |
|                      | Abdulino,    |                   |                                                  |                                                |                                               |
|                      | Orenburg reserve |             |                                                  |                                                |                                               |
| **The beginning of blooming of Tulipaschrenkii** | 4 (10) 1970-1973 | - | 28 (2) 1998-2013 | - | 34 (1) 1981-2019 |
The beginning of blooming of *Adonis vernalis* 8 (2) 1925, 1928 1931-1932 1969-1972 38 (1) 1981-2019

The beginning of blooming of *Tussilágo* 53 (17) 1951-1963 10 (2) 1933-1941 - 39 (1) 1981-2019

The beginning of blooming of *Fragáriavésca* 48 (8) 1963-1978 - 12 (3) 1937-1944 - 37 (1) 1981-2019

The beginning of blooming of *Padusavium* 48 (8) 1965-1978 - 12 (3) 1936-1944 - 36 (1) 1981-2019

The beginning of pollenation of *Alnus glutinosa* Gaertn. 3 (3) 1934, 1936, 1939 - 12 (1) 1999-2014 - 44 (1) 1995-2020

The beginning of blooming of *Sorbus aucuparia* 46 (12) 1961-1965 27 (3) 1934 1998-2013 1998-2014 1932 39 (1) 1961-2020

The beginning of blooming of *Rosacanína, Rosa majalis* 93 (24) 1963-1978 2 (2) 1974, 2017 14 (3) 1962-1975 - 35 (1) 1981-2019

The beginning of blooming of *Caraganaarborescens* 48 (8) 1965-1978 - 12 (3) 1937-1944 - -

The beginning of blooming of *Syringa vulgaris* 50 (14) 1926-1935 6 (1) 1962-1967 2 (1) 1962, 1964 2 (1) 1932, 1936 -

The beginning of leaf growth of *Betulapubescens, Betula Pendula* Roth. 110 (30) 1962-1972 7 (2) 1964-1974 11 (3) 2002-2014 1 (1) 1932 36 (1) 1981-2019

For the phenological characteristics, linear trends are calculated over a long-term series of observations. Their reliability is directly related to the representativeness of the sample, it significantly
depends on the number of omissions in the studied series. In this regard, estimates of the statistical significance of trends are informative. Table 2 shows only items with the series lasting more than 7 years, in which the estimates are statistically significant at the 10% level, since in some cases there is not enough information available for all years. The archive data for the periods from 1 to 6 years is not significant, but it can serve as an indicative one. The trend was estimated using the least squares method, i.e., a linear time function was found: \( d^*(t) = At + B \), which best approximates the time series \( \{d(t)\} \). Here \( d(t) \) is the date (day in the calendar year) of the seasonal phenomenon in the \( t \)-th year (where \( t \) is the year of observation). The value of the coefficient \( A \) gives the average rate of change of the considered characteristic (day/year) over the studied time interval [18].

Calendar dates were translated into continuous series by counting from March 1 [19]. For example, March 31 – 31, April 1 – 32, etc. Earlier occurrence of phenomena is recorded by a negative trend, later – by a positive one. The rate of change in the dates of occurrence of phenomena, which characterizes the trend over decades, was calculated as the average for within a province.

We calculated long-term data linear trends. The data reliability is related to the representativeness of the sample and significantly depends on the number of omissions in the data ranges and the assessment of the statistical significance of trends is relevant. Table 2 presents solely continuous data with series of more than 7 years that are statistically significant at the 10% level, with the exclusion of the cases lacking sufficient information for the period. The archive data series shorter than 7 years (from 1 to 6) is not statistically significant but can be used as a reference. The trend assessment was carried out by the least squares’ method, i.e, the linear function of time was determined: \( d^* (t) = At + B \), which best approximates the time series \( \{d(t)\} \), with \( d(t) \) as the date (day in a calendar year) of the seasonal phenomenon in the \( t \)-th year (\( t \) as the year of observation). The rate of the coefficient \( A \) represents the average rate of change of the studied characteristic (day/year) over the inspected period [18].

The calendar dates were converted into continuous series by counting from March 1 [19]. For example, March 31 equals 31, April 1 equals 32, etc. The earlier onset of the phenomena is recorded by a negative trend, the later one by a positive number. The rate of change in the dates phenomena occurrence, which characterizes the trend over decades, was calculated as the average for within a province.

Table 2. Average rate of change of dates of occurrence of events.

| The observed phenomenon \ Province | Russian Plain | South Ural Upland | Western foothill mid-mountainous South Urals | Ural-Tobolsk province of the Trans-Ural peneplain |
|-----------------------------------|--------------|------------------|---------------------------------------------|-----------------------------------------------|
| The beginning of blooming of Tulipaschrenkii Period, years | 2000-2014 | - | 1981-2019 | 1998-2013 |
| A, day/year | -1.1 | - | -3.9 | -2.2 |
| Blooming of Tussilágo Period, years | 1963-1951 | 1933-1941 | 1981-2019 | - |
| A, day/year | -2.6 | -1.9 | -6.5 | - |
| The beginning of blooming of Fragáriavésca Period, years | 1963-1978 | - | 1981-2019 | 1937-1944 |
| A, day/year | -0.4 | - | -2.6 | 0.1 |
3. Results and Discussion
The analyzed volume of long-term phenological information allowed us to identify unidirectional trends in the shift in the timing of the beginning of spring-summer events in plants in the studied provinces.

Spatial analysis of the existing phenological network allows us to conclude that the location of the observation points at the level of landscape provinces of the steppe zone of the Urals is unrepresentative. Observation points have different temporary forms of organization: temporary objects (places of residence of observers) and permanent points (state nature reserves). The number of observation points by province varies from one to six. The Iset-Uy province of the Trans-Ural peneplain is represented by a single point located in the floodplain of the Sanarka River, which does not reflect the landscape diversity in typical zonal conditions on the plakors. A similar situation is developing in the Western foothill-mid-mountain region of the Southern Urals, where there is also only one observation point, but its reliability is higher, due to its status – it is located on the territory of the Shulgan-Tash Reserve. A more extensive network of phenopoints is typical for the South Ural Upland Province, where there are 6 observation points in all genetic types of natural complexes – 4 upland, 1 floodplain and 1 anthropogenic. Within the Ural-Tobolsk province, there are also rows of 6
points, but the accounting data in the conditions of residential anthropogenic complexes – 2 prevail; zonal and intrazonal types are each represented by one point, which also does not reflect the landscape diversity of the conditions of this province. In the Cis-Ural region, 11 observation points were analyzed – 4 in upland conditions, 5 in floodplain conditions, and 1 in anthropogenic conditions.

In all studied provinces we detect the shift in spring-summer phenological dates towards earlier dates. The maximal phenological rates from 3.2 to 6.5 days per 10 years were detected for the beginning of blooming of a list of herbaceous species - *Tulipa schrenkii*, *Tussilago*, *Fragaria vesca*, *Adonis vernalis* in the Western pre-mountainary and moderate mountainary provinces of the Southern Urals during the period between 1981 to 2019. The minimal phenological shifts were detected for the beginning of blooming of *Fragaria vesca* and *Caragana arborescens* during the period between 1937 to 1944 in the Ural-Tobol province of the Eastern Ural plains (0.1 days per 10 years) and for the beginning of leaf growth of *Padus avium* Mill. in the South-Eastern part of the Russian plains. In the steppe zone of the Russian plains, during years 1960-1970 the beginning of blooming of *Tussilago*, *Syringa vulgaris* and *Sorbus aucuparia* is characterized by stable negative trends with the rates between 2.3 days per 10 years to 4.7 days per 10 years, the beginning of leaf growth of *Betula pubescens*, *Betula pendula* Roth. is characterized by negative trends with the rates of 1.2 days per 10 years. At several observation plots (Syrty, Abdulino, Donskoe Orenburg oblast) in the beginning of the XXI century we detected a light positive trend of the beginning of leaf growth of *Betula pubescens*, *Betula pendula* Roth., however, statistically insignificant. In the steppe regions the seasonal dynamics of the herbaceous species is most indicative, because the shrubby and woody species are representatives of the interzonal natural-territorial complexes and inhabit aberrant moisty floodplains. Possibly the multidirectional trends indicate the appearance of different adaptational mechanisms of natural complexes in the current changing climatic conditions.

4. Conclusion

The results of the inventory and the assessment of the phenological network in the steppe provinces of the Urals allow identifying its flaws and defying the directions and ways of its optimization. The lack of bound landscape justification results in unreasonable spatial organization. The formed phenological network does not have a fixed organizational structure, and therefore it has a spontaneous, uncontrollable character, and is not fully hierarchically structured. The phenological network of the steppe landscape region of the Urals does not reflect the landscape diversity of the region, therefore, impedes studies of the vital trends in seasonal dynamics that are important for the development of the socio-economic structure of the region, which, in turn, negatively affects the efficiency indicators.

The present data contained in the RGS’s archives can serve as a basis for revealing trends in the onset of phenomena; however, in current rapidly changing conditions, there is a need to increase the number of observation points of the phenological network in typical natural complexes of a certain type and taxonomic rank in accordance with the landscape diversity of the provinces. A detailed landscape study and analysis of landscape maps could help to construct a more geographically profound network. Quantitative analysis, for example, the establishment of an index of landscape diversity, may allow determining the rational sufficiency of observation points required for each landscape province.

A specialized organization such as the Steppe Institute of the Ural Branch of the Russian Academy of Sciences, could manage the phenological network in the steppes of the Urals, developing methodology, research methods and analyzing trends in the dynamics and evolution of natural complexes. The organization of an effective system of phenological monitoring in the Urals and in
Russia will be facilitated by the creation and activation of the regional phenological commissions playing a coordinating role in all regional branches of the Russian Geographical Society. The regional branches of the Russian Geographical Society can collect and process data, propagate phenological observations and publish “weather calendars”. Coordination and structuring data processing and analysis, including hydrometeorological information, will allow to assess and forecast changes in the seasonal rhythms of natural complexes, as well as to assess the rate of the anthropogenic impact on changes in the rhythms of seasonal processes and phenomena.

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