Dynamics of phytoproductive functioning of low-mountain steppe landscapes of the Southern Urals

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Abstract. We tested the hypothesis that landscape spatial pattern controlled the range of possible dynamic states. We used NDVI values in 1984-2019 in the low-mountain-steppe landscape in the Southern Urals and calculated Getis-Ord statistic to detect hot and cold spots of high and low green phytomass, respectively. We assessed the stability of hot and cold spots before and after establishment of protective regime and evaluated the contribution of the matter circulation in a catchment geosystem to the stability of phytoproductive functioning. The dynamics of the areas of spots of increased and decreased phytomass in the steppe landscape has a clearly pronounced seasonal variation, determined by the time of increased or decreased evaporation. The frequency of spots of high phytomass increases in the larger catchments. The mode of phytoproductive functioning in small catchments can be more holistic without the persistent areas with a meadow type of functioning. Sub-vertical and inclined bedding of sedimentary rock layers distorts the dependence of hot spots on catchment area. The protective regime in the zonal steppe phytocoenoses stabilizes the dynamics of green phytomass.

1. Introduction
Self-organization of a landscape as a tool for adjusting the spatial structure to environmental fluctuations is one of the priority topics of current and future landscape research. It is associated with the forecast of dynamism and sharpness of boundaries between natural units, which can significantly affect the reliability of land use conditions. As follows from the basics of landscape science and landscape ecology, the spatial pattern is both a consequence of landscape processes and a driver in the further development of processes [1, 2, 3].

The bioproduction process has long been considered in the literature as the core of landscape functioning. It largely determines the resistance to disturbances and can create preconditions for the self-development of the component structure due to the accumulation of syngenic formations in the case of imbalance between matter input and output [4]. The dependence of phytoproductivity on climatic fluctuations is well known. It is especially well-manifested in areas of insufficient moisture supply, including the steppe zone. The temporal aspect of the phytoproduction dynamics has been studied well enough. However, this is not true for the dynamics of the boundaries between areas with different modes of functioning. Since measuring phytomass, taking into account all fractions, is extremely labour-consuming and complete studies are quite rare [5], in recent decades, vegetation indices calculated from satellite images are commonly used as a surrogate for the aboveground green phytomass [6, 7, 8]. Though accuracy is obviously lower than in direct ground measurements, an equally obvious advantage of this approach is the opportunity to integrate the temporal and spatial aspects of the phytoproductive functioning of the landscape. Analysis of the time series of the NDVI
maps provides the opportunity to assess the stability of shape of zones with uniform type of functioning, the presence of zones with transient and unstable modes of functioning.

Numerous case studies have established relationships between the extreme environmental conditions and the temporal variability of phytomass [9, 10]. Errors in determining the dynamics of phytomass may be associated with spatial and temporal nonlinearity and nonstationarity of climatic factors [11, 12]. It follows that the analysis of time series of functional indicators (including bioproductivity) should be performed in different versions: separately for time intervals with different climatic conditions, areas with different landscape structures or contrasting systems of matter circulation.

Among the methods of spatial analysis, the Hot spots analysis is seen as especially relevant. However its potential is clearly not fully used in studying the landscape functioning. This method is used to identify the clusters of high and low values of any functioning parameter (e.g., agricultural productivity, urban heat islands, fires, etc.) and to explain the causes of this phenomenon, including the spatial pattern and related synergistic effects [13, 14]. The fluctuations in both occurrence and area of clusters with extremely high and low NDVI values is interpreted as an indicator for the sensitivity of the water and soil to climatic and weather fluctuations, which allows obtaining a comprehensive picture of the spatio-temporal landscape organization.

We hypothesize that landscape spatial pattern can control the modes of functioning, including the range of possible states. In conditions of insufficient moisture supply and a summer break in phytomass, which is typical for steppes, the configuration and stability of zones of increased phytomass should depend on the structure of the catchment geosystem. The purpose of our research is to assess the stability of zones with high and low green phytomass in the low-mountain-steppe protected landscape and to evaluate the contribution of the matter circulation in a catchment geosystem to the stability of phytomass productivity.

2. Material and Methods
The case study was conducted in the low-mountain steppe landscape of the "Aytuarskaya steppe" which is the part of the "Orenburgsky" state nature reserve. The study area is located in the Kuvandyk district of the Orenburg region near the state border with Kazakhstan (figure 1). The territory is provided with 216 integrated descriptions in representative types of natural units and catena elements. In June 2019, we measured green herbal phytomass at 64 plots. The results confirmed significant correlations between the NDVI values in this period and the green phytomass, which allows using this index as a fairly reliable indicator [15].

Most area belongs to the landscape of structural-erosional low mountains with ridges and valleys, composed of alternating layers of Carbon and Permian sandstones, conglomerates, limestones and siltstones, with remnants of Eocene flat interfluve, with Stipa and Festuca dominated steppes on Chernozem soils [16]. A part of the territory north of the Aktobe plateau is a system of deep valleys, stretching along the strike of rock layers, and separated by asymmetric ridges of stable layers of conglomerates and sandstones [17]. The characteristic alternation of exposures of different layers on the ridges and slopes results in a mosaics of steppe communities differing in degree of geologic effect.

To study the spatial contrasts of phytomass we analyzed 38 cloudless Landsat satellite images with radiometric corrections, obtained for the period 1984–2019. One image was taken in April (when, as a rule, there is still snow in valleys), 9 – in May, 8 – in June, 5 – in July, 5 – in August, 6 – in September, 4 – in October. For each image, the Normalized Difference Vegetation Index (NDVI) was calculated using the conventional formula: NIR-RED / NIR + RED.
After converting the data to the vector form the NDVI values were used to calculate Getis-Ord statistics for 38 dates in 1984-2019 in GIS ArcMap 3.0. This enabled us to map spots of increased phytomass (Hot spots, HS below) and spots of low phytomass (Cold spots, CS below). This means that clusters of pixels with peak values (high and low, respectively) differ significantly from the neighborhood within a radius of 300 m. The size of the selected radius corresponds to the typical distances between the water divides as well as to the width of ridges and bottoms of valleys. HS and CS were calculated using the Euclidean distance and the method "inverse quadratic distance", which decreases the weight with distance.

The frequency of HS and CS occurrence was evaluated for the periods:
- 1984-1998 (17 survey dates), when plowing and grazing were carried out on the territory that currently belongs to the nature reserve, and since 1989 traces of this activity have been preserved;
- 2007-2019 (21 dates), when the natural mode of functioning was restored after arable and pasture loads;
- 1984-2019 (38 dates).

For each pixel, we calculated the frequency of HS and CS regardless of the significance level for the Getys-Ord statistics, i.e. the repeatability of the very fact of occurrence of a spot of increased and decreased phytomass. Then, the configurations of spots of increased and decreased green phytomass were compared for the periods before 1998 and after 2007.

For each of the 38 dates from 1984 to 2019, we compiled the maps of the HS and CS significance. Index 1 was assigned to HS with $p < 0.10$, 2 – for $p < 0.05$, 3 – for $p < 0.01$. CS significance scores were coded as -1, -2, -3, respectively. The zero frequency of HS and CS was coded as 0. To obtain a more detailed map of HS and CS, we summed up the significance scores separately for the periods 1984-2019, 1984-1998, and 2007-2019. It was assumed that the higher the total significance score, the higher the frequency of spots of increased phytomass (HSS), i.e. plots significantly differing in green phytomass from the neighborhood with a radius of 300 m. Analogously, a large negative absolute value corresponds to a high frequency of highly significant spots of low phytomass (CSS). A zero sum of significance scores corresponds to zero recurrence of hot or cold spots, i.e. constantly insignificant difference from the average phytomass in the neighborhood. Small values or 0 were considered to correspond to the coinciding sums of positive and negative values. However, this was possible only...
for spots with a low level of significance: a small number of pixels could at different times be in the category of both increased and decreased phytomass relative to the vicinity.

At the next step we compared 53 catchments by the stability of the location of the HSs and CSs, the possible distance of their displacement, and size fluctuations. The persistence of spots of increased and decreased phytomass was understood as the high frequency of their occurrence at a high level of significance in the same place during most of the observation periods. The size of catchments varied from 11 to 298 hectares. The catchments differ in the ratios of landforms, which were subsequently used as explanatory variables. Descriptive statistics of the frequency of occurrence of HS and CS in pixels were calculated for the catchments: mean, median, quartiles, deciles (10% and 90%), maximum value, and standard deviation. We used GIS ArcMap 3.0 and Statistica 7.0 software to calculate the percentage of pixels in which HSs occur: a) ever without taking into account the frequency, b) with a frequency of more than 0.7 (stable spots of increased phytomass), c) with a frequency of less than 0.3 (unstable spots that appear at least sometimes). The ratio of the total area of pixels with a frequency of more than 0.7 and less than 0.3 was also calculated: the larger the number, the more stable the spots of increased phytomass. Small values of this ratio were interpreted as the possibility of a strong expansion of a small number of persistent hot spots in some years. All mentioned indicators were calculated separately for the periods 1984-1998, 2007-2019 and 1984-2019.

We tested the hypothesis that the stability of HSs and CSs in space and in time was determined by the features of the drainage catchment: size, shape, and terrain ruggedness. All morphometric features were calculated using the SRTM digital model (resolution 30 m after downscaling by the bicubic interpolation method) in SAGA GIS 7.0 software. We tested the hypotheses:

- If a drainage area is large, the runoff of groundwater discharging in valleys and gullies is always sufficient to form a permanently existing patch of increased phytomass;
- If a drainage area is small, the dependence on the weather conditions of a particular year increases and the spot with increased phytomass may not appear in some years when moisture conditions are unfavorable.

After that, we tested the hypothesis that as the steppe phytocoenosis was being restored after the plowing in the 1980s the difference between the phytomass of the old arable plots from the neighboring ones was disappearing with time. For this purpose, the CSs configurations were compared for the periods before 1998 and after 2007. In addition, the frequencies of HSs and CSs occurrence were compared for these two periods.

To quantify the dependence of HSs stability on the properties of relief, vegetation cover, and soils, we used correlations, crosstabulation, and analysis of variance using Statistica 7.0 software.

3. Results and Discussion
The study of the seasonal dynamics of spots with increased and decreased phytomass (HS and CS, respectively) and their location in space provided the following results.

In the second half of April the background phytomass forms homogeneous pattern with small CSs in the bottoms of deeply incised sectors of gullies and valleys. They are induced by the slowest snowmelt and, accordingly, the delay in vegetation. Rapid drying out and warming up of slopes manifests itself at an earlier beginning of the growing season. The only HS occurred in the area with the strongest pastoral loads near the northern outskirts of the Aytaur village, possibly associated with the development of nitrophilic plants.

In the first ten days of May, spots of increased phytomass begin to form on pasture to the north of the reserve, on steep west-facing and north-facing slopes that have higher heat supply as well as in some gullies. By mid-May, HSs in the pasture shrink and disappear. In the 1980-1990s by the end of May this HS was being transformed into CS due to increased grazing, but by the 2010s it differed little from the background. By the second half of May, a wide, fragmented HS expands and disappears on the gentle eastern slopes and hills in the Tyshkak valley. By the end of May this HS shrinks and is preserved in the gullies only. In some years, CSs also persist in catchment depressions and valleys due to vegetation delay. During the plowing period of the 1980s large CS was being formed within the
boundaries of arable lands, which, in a fragmented and blurred form, appears on the plateau even after 30 years. In the second half of May, more or less continuous strips of HSs are formed along the thalweg of the largest valleys, with a delay in some years. By the end of May, small CSs begin to form on steep slopes along the shoulders. This indicates the depletion of spring moisture reserves in soils of the most drained units.

In June, the HS strips are stable along the thalweg of valleys and gullies (figure 2). They are formed mainly by mesophytic and xeromesophytic communities dominated by Bromopsis inermis, Phleum phleoides, Galatella rossica, Sanguisorba officinalis, Serratula gmelini. Shrub communities with Amygdalus nana, Cerasus fruticosa, Spiraea hypericifolia occupy a significant area. CSs are disappearing on former arable lands, though until the 1990s CSs were also pronounced in June. CSs along steep slopes and ridges may appear in some years (for example, 1988), but more often they do not differ significantly from the surroundings. In the 1980s CSs along the crests could appear already at the beginning of June (possibly due to grazing), but in the 2010s under the reserved regime – not earlier than the second half of June.

![Figure 2](image2.png)

**Figure 2.** Significance scores of the existence of hot (red tones) and cold (green tones) spots of increased phytomass on June 22, 2019. ± 1 - significance level <0.10, ± 2 - significance level <0.05, ± 3 - significance level <0.01. The “+” sign corresponds to spots of increased phytomass (HS), the “-” sign - to spots of low phytomass (CS).

![Figure 3](image3.png)

**Figure 3.** Frequency of Hot spots of increased phytomass for the vicinity with a radius of 300 m for the period 1984-2019. (38 dates).

During July, the NDVI values in the steppes decrease due to the lower photosynthetic activity of cereals. There is a gradual reduction in the length of the HS strips along the thalweg of the largest valleys at the expense of the lower courses. The width of HS strips decrease as well due to the transition to a pause in the vegetation of the Stipa dominated steppes in wide terrace-like valley
bottoms. In some years (2014), there was a break in the continuity of the HS strips in the largest valleys (Karagashty, Shinbutak). At the same time, the HSs in the upper sector of the gullies at the northern slopes of the Aktobe plateau disappear or decrease. This indicates a significant depletion of the groundwater supply by the middle of summer, which can approach the surface only in the middle part of the catchment.

During August, there is a gradual reduction in the length and width and a break in the continuity of the HSs along the gullies.

By the beginning of October, the continuity of the HS strips is finally lost even along the thalwegs in valleys. By the second half of October, the number and area of CSs increases. The largest CSs appear in the narrowed bottoms of steep-sloping deeply-incised gullies, probably because of the accumulation of cold air and weak heating due to shading.

Figure 3 shows the frequency of HSs for the period 1984-2019. The average frequency of HSs in the catchments varies in the range from 0.01 to 0.17, that of CS – from 0.01 to 0.06. The share of the catchment area, on which spots of increased phytomass may ever appear, ranges from 4 to 59%, on average for 53 catchments - 25%. In 36 out of 53 catchments, no HSs with a frequency of more than 0.7 occur. The maximum ratio of the area of stable HSs (the frequency of occurrence is more than 0.7) to the area of the unstable HSs (the frequency of occurrence is less than 0.3) was 0.45. The most stable configurations of HSs can be achieved in catchments with area of 50-150 ha.

Geology is one of the controls over the HS stability. The most stable highly significant (p <0.01) HSs develop along the thalwegs of valleys, which indicates the stability of the intrazonal meadow mode of functioning with constant summer moisture. Nevertheless, in the bottoms of even the largest valleys, a continuous strip of constantly increased phytomass is not formed. Instead, the sectors with various frequencies of HSs alternate. In valleys stretching across the strike lines of sedimentary layers, HSs are stable and highly significant. They are not confined to the lower courses, as might be expected from the maximum catchment area, but to the middle courses at the intersection of sandstone or limestone layers. The instability of the HSs in the lower courses is associated with a significant loss of moisture due to the subsurface flows encouraged by the sub-vertical bedding of sedimentary rock layers in many areas. According to crossstabulation, zones of stable functioning (with a HS frequency close to 0) are more often confined to the astructural slopes with numerous end faces of sedimentary strata. In contrast, on structural slopes (most of them east-facing), the proportion of pixels with unstable functioning increases (with HS frequency about 0.5). This, obviously, should be explained by the periodic inflow of additional moisture from the neighboring catchment along the dip of the strata. This testifies that the real boundary of catchments does not actually coincide with the formal geomorphic boundary along the watershed which. This is a common situation in areas with monoclinal bedding.

Nevertheless, we detected a dependence of the HSs and CSs stability on the area and relief of a catchment. In most catchments, the share of the territory where HSs can occur with a nonzero frequency is 15-30%. In the small catchments (up to 50 hectares), the increase in terrain ruggedness is accompanied by an increase in the share of the area of HSs (figure 4), which testify a more intensive discharge of groundwater in the bottoms. In the larger catchments, there is no such relationship. In the catchments with an area of more than 100 hectares, the maximum HS frequency is always high, more than 0.7. Hence, in large catchments almost at any time the catchment area provides a steady water supply in the bottoms despite some outflow of moisture into adjacent catchments along the dip of the strata. Small valleys and gullies have reduced stability of the HSs. This is partly due to the loss of moisture due to the outflow into adjacent catchments along the dip if the strata. Thus, in small drainage catchments, a relatively integral low-contrast mode of functioning of steppe phytocenoses prevails over time. In contrast to the bottoms of the valleys, in the gullies a well-manifested meadow type of phyto-production functioning, with the preservation of phytomass during the dry summer period, does not exist constantly and occurs only in wet years.
Figure 4. Relationship between the share of the area with ever emerging patches of increased phytomass (without taking into account the frequency) and the average Terrain ruggedness index for the neighborhood 330 m in drainage catchments with an area of up to 50 hectares.

Figure 5. Relationships between the stability of spots of increased phytomass (the ratio of the area of "hot spots" with a frequency of more than 0.7 to the area of "hot spots" with a frequency of less than 0.3) and the distribution of slopes in the catchment (the ratio of the proportions of slopes over 15° and less than 10°).

In the catchments where the proportion of steep slopes (more than 15 degrees) highly exceeds the proportion of gentle ones (less than 10 degrees) we either detected no stable HSs at all or detected a very small proportion compared to the proportion of unstable spots (figure 5). The most persistent HSs occur in the catchments with more than 70% gentle slopes. Note that although spots with increased phytomass can occupy a large area at high dissection (TRI) (figure 4), for their stability in time an additional condition is the presence of a sufficiently high proportion of gentle slopes in a catchment.

Comparative analysis of the HS frequencies in 1984-1998 and 2007-2019 showed significant changes in the units that were exposed to anthropogenic or natural disturbances. An increase in the HS frequency is characteristic mainly for the upper courses of the gullies draining the Aktobe plateau, especially those related to the catchment of the Tyshkak valley. The area of regular occurrence of HSs has expanded due to its upward movement towards catchment depressions. Obviously, this is due to the restoration of aspen tree growth after fires \[18\]. In the deeply dissected section of the landscape, the changes are less significant. Due to the establishment of the protected regime, the frequency of HSs associated with tree and shrub thickets along the thalwegs increased. The CS frequency decreased on the plateau and in flat wide valley bottoms formerly subjected to plowing. In the lower reaches of the valleys, on the contrary, a decrease in the HS frequency occurred, which, apparently, is due to a decrease in the runoff, which is able to reach the mouths. Most likely, this is explained by an increase in summer temperatures and a weakening of the water-preserving and runoff-regulating role of the strongly reduced thickets. The latter is associated with an increase in the frequency of fires at 4-5 years interval \[18\] as a result of the accumulation of dead biomass, which previously was being destroyed by cattle.

Areas of the Aktobe plateau and the wide bottoms of some valleys that were plowed up until the 1980s (Karagashty, Tyshkak) are distinguished by low phytomass even 30 years after the termination of plowing. Within the plots that were plowed in the 1980s the average frequency of CSs decreased markedly in 2007-2019 compared to 1984-1998 (figure 4). The CSs configuration of the formerly cultivated areas is generally preserved, but the area is gradually fragmented. The units that do not differ in phytomass from the surroundings (shown in green in figure 6), develop, though their proportion is lower than the proportion of CSs.
Figure 6. Frequency (%) of formation of cold spots (Cold spots) of low phytomass for the neighborhood with a radius of 300 m: a) 1984-2019, (38 Landsat survey dates); b) 1984-1998 (under the conditions of recent anthropogenic impact, 17 dates); c) 2007-2019 (in the conditions of a long-term reserve regime, 21 dates). Black lines and numbers show the contours and numbers of the studied catchments.

4. Conclusion

As a result of the study, the following conclusions were obtained.

- The dynamics of the areas of spots of increased and decreased phytomass in the steppe landscape has a clearly pronounced seasonal variation, determined by the hydrothermic conditions.
- The frequency of spots of high phytomass increases in the larger catchments. This is associated with a more stable influence of groundwater. The mode of phytoreproductive functioning in small catchments can be more holistic without the persistent areas with a meadow type of functioning.
- Sub-vertical or inclined bedding of sedimentary rock layers distorts the dependence of the stability of spots of increased phytomass on the catchment area due to the alternation of local discharge sites and increased water infiltration as well as periodic flows between catchments along the dip of the strata.
- The protective regime in the zonal steppe phytocoenoses stabilizes the dynamics of green phytomass due to the higher frequency of the background dynamics, i.e. the formation of a uniform regime of phytoreproductive functioning characteristic of a holistic landscape-scale geosystem.

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