FORECAST CHANGES IN THE PRODUCTIVITY OF PLANT COMMUNITIES IN THE PRE-URALS STEPPE SITE OF ORENBURG STATE NATURE RESERVE (RUSSIA) IN EXTREME DROUGHT CONDITIONS USING NDVI

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The normalised-difference vegetative index (NDVI) seasonal dynamics of 15 types of vegetation communities in dry 2010 and in 2016 with favourable weather conditions was studied in the Pre-Urals Steppe site where the Programme on establishing a semi-free population of the Przewalski's horse *Equus ferus przewalskii* in Orenburg State Nature Reserve started. The NDVI seasonal dynamics in a year with normal weather conditions includes four main phases including the 1st phase of spring NDVI increasing, the 2nd phase of the productivity maximisation of the dominant vegetation, the 3rd phase of the summer progressive decrease in photosynthetic activity in response to the heat and lack of moisture, the 4th phase of low photosynthetic activity lasting from midsummer to the late autumn. The dependence of NDVI on vegetation productivity during its maximum development in the Pre-Urals Steppe in 2016 was described by the linear regression equation. Vegetation productivity on 20 June 2010 and that on 20 June 2016, calculated by the linear regression equation, were compared. The comparison revealed that in 2010, the decline in productivity during vegetation maximum development varied between 19% and 65% depending on the type of plant community. The following plant communities were the least resilient to drought: communities of fallow lands on the locations of previous true steppes, communities which appeared under the influence of overgrazing in the locations of the previous true steppes and the communities of meadow-steppes. Good moistening resulted in a slight decline in productivity communities located in topographical depressions. Productivity of plant communities with early-spring growth of dominating species declined to a lesser degree as the communities are located on a well-warmed surface. Some biological features of the *Caragana frutex* + *Spiraea crenata* vegetation type also result in the less decline in productivity. The NDVI coefficient does not accurately reflect productivity at the end of the growing season. Therefore, patterns of declines in productivity of similar vegetation types during the drought in Trans-Urals region in 1998 were used to project the autumn decline in vegetation productivity during the drought in the Pre-Urals Steppe. Based on these findings, the average vegetation productivity in the Pre-Urals Steppe in autumn in dry 2010 were four to five times lower than that during the maximum plant development in 2016 which had favourable weather conditions. As the height of vegetation considerably reduces during drought, the availability of pasture forage may sharply drop in winter, especially if a deep snow cover accumulates and unevenly distributes according to terrain relief. In the Pre-Urals Steppe, only some steppe communities, covering about 20% of the area, are the most accessible to supply Przewalski's horses with dry pasture forage in winter. Projecting the winter supply of pasture forage after a severe drought should be based on the assumption that the forage availability may reduce by 8 to 10 times as compared with calculated summer productivity in a year with favourable weather conditions. In this regard, there is a need to make stocks of hay for feeding horses in winter after a drought. For potentially repeated droughts the sufficient amount of hay to feed Przewalski's horses in the Pre-Urals Steppe over two winter seasons should be stocked in years with normal precipitation as it will be difficult to make the stock in a dry year. For a final assessment of the accessibility of winter pasture forage stock for Przewalski's horses in the Pre-Urals Steppe, some additional field studies of productivity of the main vegetation types at the end of the growing season using the harvest method are necessary as well as an analysis of the distribution and height of snow cover on the territory in years with high winter precipitation.

Key words: *Equus ferus przewalskii*, Landsat 5, Landsat 8, monitoring, Przewalski's horse, remote sensing, seasonal dynamics, Sentinel 2, vegetation, vegetation indexes

Introduction

The understanding of the relationship between certain animal species and the conditions of their habitats is crucial for wild management (Michaud et al., 2014). Predictors of pasture forage stocks and their possible changes in extreme weather years are necessary when fulfilling projects on reintroduction of endangered herbivorous species to strictly Protected Areas. In 2015, the Programme on establishing a semi-free population of the Przewalski's horse *Equus* *ferus przewalskii* Poliakov, 1881 in Orenburg State Nature Reserve started in the Pre-Urals Steppe site.

The Pre-Urals Steppe site goes through periodically extreme droughts, the last one occurred in 2010. Various vegetation indices derived from remote sensing data are used to assess the impact of drought on the ecosystem's primary productivity (Bayarjargal et al., 2006; Zhang & Jia, 2013). Some research have shown that NDVI can be used as a surrogate for ecological productivity, and in fact reflects net primary productivity of an ecosystem because it is highly associated with photosynthetically active radiation that drives photosynthesis (e.g., Numata et al., 2003, 2007; Li et al., 2013). The average vegetation productivity during its maximum development in dry 2010 were assessed using the linear model of correlation between the Normalised Difference Vegetation Index (NDVI) and vegetation productivity in model-scientific plots studied in 2016 (Fedorov et al., 2019). However, the calculated decrease in the average productivity in dry years does not reflect the changes in productivity of some particular vegetation types as well as the amount of pasture forage available for Przewalski's horses in autumn and winter, because the different vegetation types are disproportionately affected by drought and they are very diverse with respect to accessibility for the animals in winter. For example, the vegetation is better preserved in topographically low areas but it may be inaccessible due to a deep snow cover.

The aim of this study is the projection of possible changes in productivity of different vegetation type in the Pre-Urals Steppe during dry years using NDVI for 2010.

Material and Methods

The Pre-Urals Steppe is a fenced area measuring approximately 16 × 14 km and totalling 165.38 km^2. The centre of the site is located at 51.182600°N and 56.181700°E. Grasslands occupy more than 95% of the area, representing rich bunchgrass, psammophytic, petrophytic, halophytic steppes, and their anthropogenic derivatives. The productivity of grassland for grazing in the main types of grassy vegetation was analysed, mapping of the plant communities was conducted, and calculation of grassland forage stocks was calculated for 2016 which had favourable weather conditions (Fedorov et al., 2018).

As a typological framework for the analysis of the vegetation seasonality, we used the typology drafted by Yamalov et al. (2016). However, the authors of this study have consolidated closely related groups of plant communities such as psammophytic, petrophytic, halophyte, meadow-steppe and some others. In this way the number of the types was reduced from 25 to 15. Their brief descriptions are shown in Table.

To analyse the NDVI seasonal dynamics, Landsat-8 and Sentinel-2 satellite images were used to analyse 2016 with normal precipitation. Landsat-5 images were used to analyse dry 2010. Most of the images were cloudless. A few of them had 5–7% of cloud cover in the study area. When NDVI was calculated, pixels in cloud areas were not used.

The calculations were conducted for vegetation polygons of a GIS-map of vegetation of the Pre-Urals Steppe with the use of the zonal statistics plugin of QGIS. To assess the average productivity of different types of vegetation during their maximum development in 2010, a linear predictive model on the correlation between NDVI and vegetation productivity in model-scientific plots studied in 2016 was used (Fedorov et al., 2019):

$$\text{Productivity (g/m)} = 8.89615 + 571.8 \times NDVI$$

The dependence of NDVI on vegetation productivity during its maximum development was described by the linear regression equation in the Pre-Urals Steppe in 2016. The correlation coefficient of +0.76 was found between NDVI and vegetation productivity (Fedorov et al., 2019). This made it possible to compare vegetation productivity on 20 June 2016 and that on 20 June 2010 calculating by the linear regression equation (Table).

The vegetation in the Pre-Urals Steppe mainly consists of dry grasses at the end of the growing season. Thereby the NDVI coefficient does not accurately reflect productivity over this period. Therefore, patterns of declines in productivity of the similar vegetation types during the drought in Trans-Urals region in 1998 (Yunusbaev, 2001) were used to project the autumn decline in vegetation productivity during the drought in the Pre-Urals Steppe.

To assess precipitation in 2010 and 2016, the data obtained from the meteorological station No 35127 which is located in the city of Akbulak, Orenburg Region, 35 km south-west of the Pre-Urals Steppe were used (http://aisori-m.meteo.ru/waisori/ – specialised sets for climate studies).

Results and Discussion

The NDVI seasonal dynamics for plant communities in the Pre-Urals Steppe site for dry 2010 and 2016 with normal precipitation is shown in Fig.

Table. Brief descriptions of the main vegetation types of the Pre-Urals Steppe site

Vegetation type	Description of community	Size, km^2	Productivity, tons/km^2	
			2016*	2010**
A – Steppe communities on thin-layer sandy and gravelly soils				
1. *Stipa borysthenica* Klok. ex Prokud.	Psammophytic steppes on rather flat topography	9.249	215	129
2. *Galatella villosa* (L.) Reichenb. fil.+ *Artemisia lercheana* Weber ex Stechm.	Steppes influenced by moderate grazing are located in the lower and middle part of smooth and moderately steep slopes of various exposure and on the top of small hills and ridges	13.07	228	123
3. *Festuca valesiaca* Gaudin+ *Artemisia lerchiana* Weber ex Stechm. + *Galatella villosa* (L.) Reichenb. fil. petrophytic	Petrophytic steppes on the top of small hills and ridges, rocky outcrops, moderately steep slopes with insolation	3.954	142	107
B – Relatively mesophytic vegetation communities of meadowlands, meadow-steppes and shrubs				
4. *Alopecurus arundinaceus* Poir.	Meadowlands on terraces of deep and moderate gullies	0.352	454	247
5. *Poa transbaicalica* Roshev. + *Stipa zalesskii* Wilensky	Meadow-steppes in small topographical depressions, along hollows and temporary watercourses, as well as on flat-land sites if the soils are sufficiently moisture-provided	19.762	344	162
6. *Poa transbaicalica* Roshev. motley-grass	Long-standing fallow lands mostly on the sites of formerly ploughed meadow-steppes	13.1	421	146
7. *Stipa capillata* L.	Steppes with the dominance of *Stipa capillata* on the sites with moderate moisture-providing formerly influenced of intensive grazing including those along hollows	21.058	181	147
8. *Caragana frutex* (L.) K. Koch+ *Spiraea crenata* L.	Shrubs in hollows, beginnings of gullies and in small topographical depressions, rarely on stony slopes	0.432	190	***
C – Halophytic steppes and alkali meadowlands				
9. *Artemisia lerchiana* Weber ex Stechm. + *Stipa lessingiana* Trin. et Rupr. motley-grass	Halophytic steppes predominantly on rather flat topography	13.885	173	118
10. *Artemisia pauciflora* Weber	The community which appeared under the influence of overgrazing in the locations of the previous communities *Artemisia lerchiana* + *Stipa lessingiana* motley-grass	0.736	165	99
11. *Puccinellia distans* (Jacq.) Parl.	Alkali meadowlands which appeared under conditions of alternating moistening	0.064	193	142
D – Fallow lands in the locations of the previous true steppes				
12. *Agropyron pectinatum* (Bieb.) Beauv.	Fallow lands in the locations of the previous cultivation of *Agropyron pectinatum* and surrounding plots with formerly affected vegetation	10.799	350	136
13. *Stipa lessingiana* Trin. et Rupr.+ *Festuca valesiaca* Gaudin	Advanced stages of rehabilitation of formerly ploughed or overgrazed steppes	17.947	329	124
14. *Festuca valesiaca* Gaudin + *Poa crispa* Thuill.	Relatively recent fallow lands which appeared under the influence of overgrazing on rather flat topography and smooth slopes	23.003	204	133
15. *Festuca valesiaca* Gaudin + *Falcaria vulgaris* Bernh.+ *Pastinaca clausii* (Ledeb.) Pimenov	Communities which appeared under the influence of combined anthropogenic effect such as ploughing, livestock grazing and frequent fires	12.450	253	110

Note: * – The average vegetation productivity calculated by the harvesting method for 2016, which had favourable weather conditions (Fedorov et al., 2018).
** – The average productivity of different vegetation types calculated with the use of a regression analysis between NDVI and vegetation productivity in the Pre-Urals Steppe for extremely dry 2010 (Fedorov et al., 2019).
*** – The productivity of grassy vegetation was not calculated.

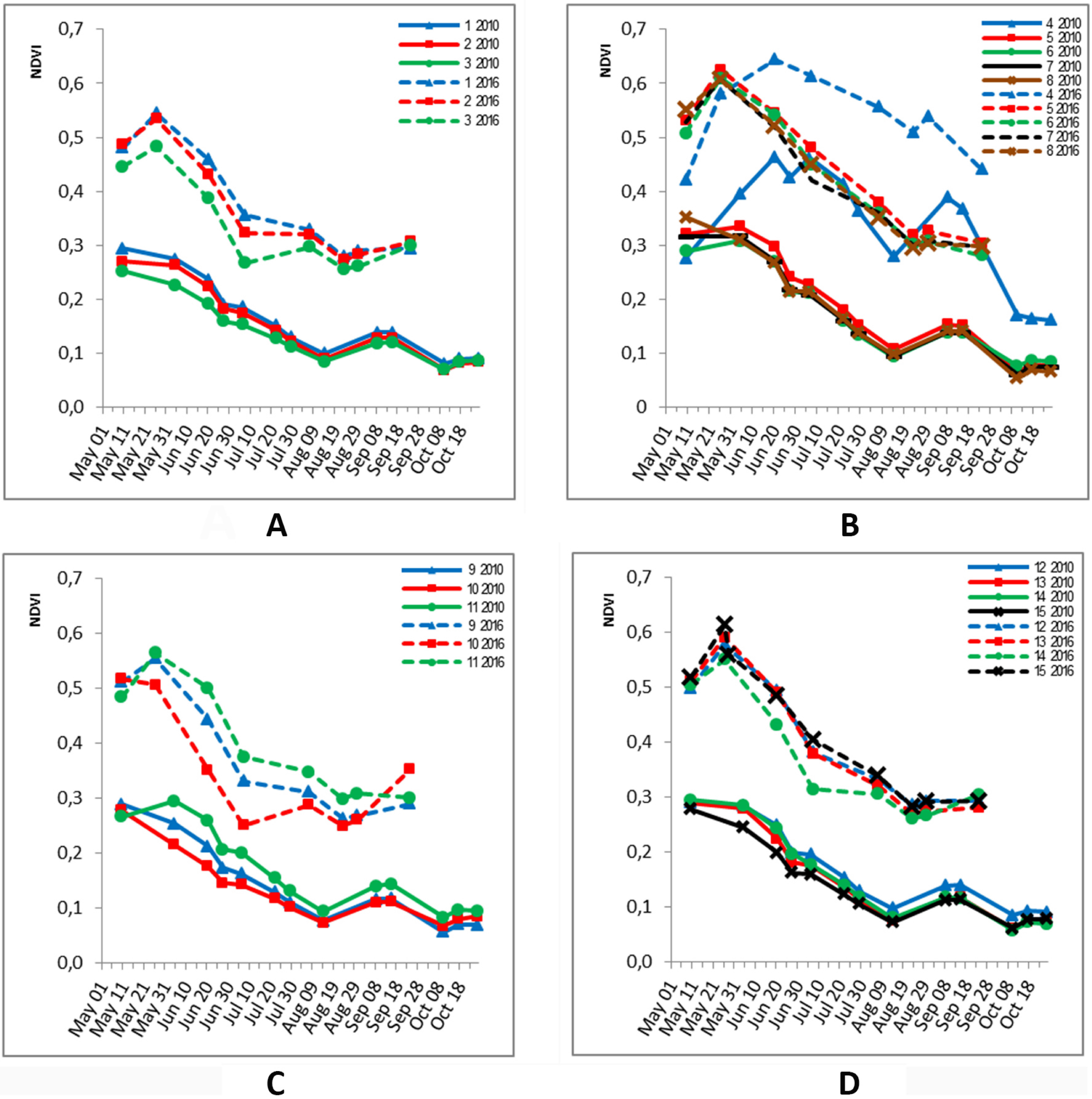

Fig. The NDVI seasonal dynamics for plant communities in the Pre-Urals Steppe site for dry 2010 and 2016 with normal precipitation. Designations: **A** – Steppe communities on thin-layer sandy and gravelly soils: 1 – *Stipa borysthenica*, 2 – *Galatella villosa* + *Artemisia lercheana*, 3 – *Festuca valesiaca* + *Artemisia lerchiana* + *Galatella villosa* petrophytic; **B** – Relatively mesophytic plant communities of meadowlands, meadow-steppes and shrubs: 4 – *Alopecurus arundinaceus*, 5 – *Poa transbaicalica* + *Stipa zalesskii*, 6 – *Poa transbaicalica* motley-grass, 7 – *Stipa capillata*, 8 – *Caragana frutex* + *Spiraea crenata*; **C** – Halophytic steppes and alkali meadowlands: 9 – *Artemisia lerchiana* + *Stipa lessingiana* motley-grass, 10 – *Artemisia pauciflora*, 11 – *Puccinellia distans*; **D** – Fallow lands in the locations of the previous true steppes: 12 – *Agropyron pectinatum*, 13 – *Stipa lessingiana* + *Festuca valesiaca*, 14 – *Festuca valesiaca* + *Poa crispa*, 15 – *Festuca valesiaca* + *Falcaria vulgaris* + *Pastinaca clausii*.

The NDVI seasonal dynamics in a year with normal weather conditions include four main phases. The first one is the phase of spring NDVI increasing corresponding to the period of intensive vegetation growth. The phase ended in the third decade of May in 2016. The second phase starts from the maximum NDVI value and lasts to the productivity maximisation of the dominant vegetation as a rule corresponding to the fruiting phase in gramineous plants. Representatives of Poaceae usually decrease photosynthetic activity in their leaves over the fruiting phase and consequently NDVI decreases. In 2016, the second phase ended between the third decade of June and the beginning of July depending on the vegetation type. The second phase passes smoothly into the third phase which is characterised by a progressive yellowing of gramineous plants and forbs in response to the heat and lack of moisture resulted in the NDVI decrease. The speed of the process depends on soil moistening. The third phase passes faster in halophytic strongly affected plant communities such as *Artemisia pauciflora* and in petrophytic steppes (*Festuca valesiaca* + *Artemisia lerchiana* + *Galatella villosa* petrophytic). Changes in moistening as a result of erosion and soil compaction incurred by overgrazing form a reason of the accelerated third phase in the halophytic strongly affected plant communities. Thin-layer and heavily gravelly of the soils on the top of hills, ridges and steep slopes with insolation also accelerate changes in moistening and consequently the passing of the third phase in petrophytic steppes. Slowly yellowing occurs in meadowland, meadow-steppe and shrub communities. The fourth phase is characterised by a low photosynthetic activity in the most steppe plants. It lasts from midsummer to the late autumn. In 2016, the NDVI values in the fourth phase were 0.30–0.35 when the rain failed. NDVI increased after precipitation.

During the growing season in the dry year of 2010, the average temperature was higher. The precipitation was lower than the annual average values during the last 50 years (http://aisori-m.meteo.ru/waisori). Efficient precipitation did not occur in May and June 2010 when grasses intensively grew. The drought followed the low snowfall winter affecting negatively the soil moistening at the beginning of the vegetation seasonal growth. This influenced significantly the vegetation seasonal growth and its NDVI dynamics. During the drought in 2010, the relatively normal vegetation development occurred only in meadowland communities, the *Alopecurus arundinaceus* types on temporary watercourse beds and terraces of deep and moderate gullies (Fig.). Due to the lack of moistening the development of steppe and meadow-steppe vegetation types stopped between the end of the first decade and the beginning of the second decade of May. The NDVI values for steppe and meadow-steppe types were approximately equal or even lower than the NDVI values for the same types in autumn 2016. Many plants species did not blossom or blossomed without fruiting, that is why the second phenological phase was not expressed in a number of steppe vegetation types. The third phenological phase when photosynthetic activity decreased was of longer duration. Differences between NDVI values of closely related groups of steppe vegetation decreased over the third phase. In the third decade of June 2010, NDVI fell to 0.2, which meant the vegetation was almost completely dry. Some dry plants further crumbled and were disperse by wind, some others lost partly their dry leaves. NDVI as a consequence were less than 0.2 in late July and less than 0.1 in October. Some rainfalls occurred in August and September. It improved the state of meadowland vegetation of the *Alopecurus arundinaceus* type but meadow-steppe and steppe vegetation did not notably recover.

The comparison of vegetation productivity in 2016 and in 2010 revealed that in 2010, the vegetation productivity during its maximum development was on average 42% lower than that in 2016. The decline in productivity varied between 19% and 65% depending on the type of plant community.

Plant communities of fallow lands on the locations of previous true steppes were the least resilient to drought. An exception was the community of the *Festuca valesiaca* + *Poa crispa* type with dominating gramineous species characterised by an early growth. Also, there was a high decline in productivity of meadow-steppe vegetation types such as *Poa transbaicalica* + *Stipa zalesskii* and *Poa transbaicalica* motley-grass with plant species poorly adapted to drought.

The *Stipa capillata* type declined in productivity only by 19%, this was probably due to the good snow-retaining by last year's dry plants of the dominate species. Better moistening of soils in topographical depressions led to a lower decrease in the productivity of the *Puccinellia distans* type located there. Productivity of plant communities with early-spring growth of dominating species declined to a lesser degree as the communities are located on a well-warmed surface (*Festuca valesiaca* + *Artemisia lerchiana* + *Galatella villosa* petrophytic). Some biological features of the *Caragana frutex* + *Spiraea crenata* type also result in a lower decline in productivity.

During the drought in the Trans-Urals region in 1998, the vegetation productivity of true steppe of the feather-grass-forb type and petrophytic steppe of the feather-grass-forb type during their maximum development were lower by 60% and 70% accordingly than their perennial average productivity (Yunusbaev, 2001). Based on these findings, it can be assumed that the decline in the vegetation productivity in autumn in the drought of 2010 averaged not less than half of the productivity during the maximum plant development in that year in the Pre-Urals Steppe. Thus, the average vegetation productivity in the Pre-Urals Steppe in autumn in the dry year were four to five times lower than that during the maximum plant development in 2016, which had favourable weather conditions.

As the height of vegetation considerable reduces during drought, the availability of pasture forage may sharply drop in winter especially if deep snow cover accumulates and unevenly distributes according to terrain relief. The following steppe communities on thin-layer gravelly soils provide the most available pasture forage for Przewalski's horses in winter: *Galatella villosa + Artemisia lercheana and Festuca valesiaca + Artemisia lerchiana + Galatella villosa* petrophytic types, covering about 10% of the Pre-Urals Steppe site. Also, the accessible dry forage of winter pastures preserves in halophytic steppes of *Artemisia lerchiana + Stipa lessingiana* motley-grass and *Artemisia pauciflora* types on slopes comprising 9% of the area. But at the same time, the accessibility of dry vegetation of meadowlands, meadow-steppes and fallow lands on the locations of previous true steppes covering 34% and 40% of the Pre-Urals Steppe accordingly may reduce significantly. A definitive conclusion about the possible accessibility of pasture forage in the winter period can be made only after analysing the distribution and height of snow cover in years with high levels of winter precipitation.

Conclusions

Projecting the winter supply of pasture forage after a severe drought should be based on the assumption that the forage availability may reduce twice as compared with that in autumn and by 8 to 10 times as compared with calculated summer productivity in a year with favourable weather conditions. In this regard, there is a need to make stocks of hay for feeding horses in winter after a drought. For potentially repeated droughts the sufficient amount of hay to feed Przewalski's horses in the Pre-Urals Steppe over two winter seasons should be stocked in years with normal precipitation as it will be difficult to make any stock in a dry year.

For a final assessment of the accessibility of winter pasture forage stock for Przewalski's horses in the Pre-Urals Steppe, some additional field studies of productivity of the main vegetation types at the end of the growing season using the harvest method are necessary as well as an analysis of the distribution and height of snow cover on the territory in years with high winter precipitation.

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ПРОГНОЗ ИЗМЕНЕНИЯ ПРОДУКТИВНОСТИ РАСТИТЕЛЬНЫХ СООБЩЕСТВ НА ТЕРРИТОРИИ УЧАСТКА «ПРЕДУРАЛЬСКАЯ СТЕПЬ» ОРЕНБУРГСКОГО ГОСУДАРСТВЕННОГО ЗАПОВЕДНИКА (РОССИЯ) ПРИ ЭКСТРЕМАЛЬНОЙ ЗАСУХЕ С ИСПОЛЬЗОВАНИЕМ NDVI

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Проанализирована сезонная динамика NDVI 15 типов растительных сообществ в засушливом 2010 г. и нормальном по увлажнению 2016 г. на участке «Предуральская степь», где стартовала Программа создания полувольной популяции лошади Пржевальского *Equus ferus przewalskii* в государственном природном заповеднике «Оренбургский». В нормальный по погодным условиям год динамика изменения NDVI включает четыре основные фазы: первая фаза весеннего повышения NDVI; вторая фаза достижения наибольшей продуктивности доминирующей растительности; третья фаза летнего постепенного снижения фотосинтетической активности под влиянием жары и недостатка влаги; четвертая фаза низкой фотосинтетической активности, длящейся с середины лета до поздней осени. Зависимость NDVI от продуктивности растительности в период ее максимального развития в Предуральской степи в 2016 г. описывалась уравнением линейной регрессии. Сравнивались продуктивность 20 июня 2016 г. и 20 июня 2010 г., рассчитанная по уравнению линейной регрессии. Сравнение показало, что в 2010 г. снижение продуктивности во время максимального развития растительности колебалось от 19% до 65% в зависимости от типа растительного сообщества. Наименее устойчивы к засухе были сообщества растительности залежей на месте настоящих степей, сильно сбитых производных настоящих степей и луговых степей. Лучшее увлажнение в понижениях привело к меньшему снижению продуктивности находящихся там сообществ. Продуктивность растительных сообществ с ранневесенним ростом доминирующих видов снизилась в меньшей степени, так как эти сообщества произрастают на хорошо прогреваемых поверхностных объектах. Некоторые биологические особенности типа *Caragana frutex* + *Spiraea crenata* также приводят к меньшему снижению их продуктивности. Коэффициент NDVI не может быть корректно использован для оценки продуктивности травостоя в конце периода вегетации. В связи с этим для прогноза осеннего снижения продуктивности в Предуральской степи были использованы закономерности снижения продуктивности в аналогичных типах растительности в засуху 1998 г. в Зауралье. Выяснено, что средняя продуктивность растительности Предуральской степи в осенний период в засушливом году была в 4–5 раз ниже, чем в аналогичный период благоприятного по погодным условиям 2016 г. В связи со значительным снижением высоты травостоя в засуху, может резко падать доступность пастбищного корма в зимний период, особенно при большой высоте снежного покрова, который в зависимости от рельефа распределяется неравномерно. В Предуральской степи зимой для лошадей Пржевальского наиболее доступны пастбищные корма только на нескольких степных сообществах, занимающих около 20% площади. При прогнозировании зимней обеспеченности пастбищными кормами после сильной засухи необходимо исходить из того, что она может сократиться в 8–10 раз по сравнению с известной летней обеспеченностью в благоприятном по погодным условиям году. Поэтому будут необходимы страховые запасы сена для подкормки лошадей зимой после засухи. На случай нескольких засушливых лет в нормальный по осадкам год должно быть заготовлено сено в количестве, достаточном для подкормки лошадей Пржевальского в течение двух зимних сезонов. Для окончательной оценки доступности зимних запасов пастбищного корма необходимы дополнительные полевые исследования с взятием укосов в основных типах растительности в конце периода вегетации, а также анализ распределения и высоты снежного покрова в годы с высоким уровнем зимних осадков.

Ключевые слова: *Equus ferus przewalskii*, Landsat 5, Landsat 8, Sentinel 2, вегетационные индексы, дистанционное зондирование, лошадь Пржевальского, мониторинг, растительность, сезонная динамика