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Estimation of forests productivity response on local climatic variations within territory of Ukraine with satellite data using

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Forests biomass is a significant carbon pool. And the dynamic of forest productivity is directly related to climatic factors of the territories. In the paper the analysis of the terrestrial forest productivity and climate drivers on regional levels has been done. The gross primary production (GPP) and net primary production (NPP) from a global satellite-based terrestrial production efficiency model MOD17 as the forest productivity indicator and meteorological data from the weather station network as climatic indicators were used. Correlation analysis between forest productivity and climatic indicators for different growing seasons and landscape-climatic zones of Ukraine has been done. Multiple linear regression models for corresponding seasons and zones have been simulated using the principal component analysis (PCA).

Keywords: forest, carbon cycle; climate change; gross primary productivity; remote sensing; principal component analysis

1. Introduction

Forest ecosystems comprise a significant terrestrial carbon pool. They play a substantial role in the carbon exchange between the land and the atmosphere through the processes of photosynthesis, respiration and decomposition. Therewith, forests have important resource, recreation and conservation functions. Therefore, study and assessment of the forest productivity are underlying issues for rational forest management under changing world conditions. Currently, global climate changes are an enormously challenging issue for humanity [8–10]. These changes are closely linked with the carbon cycle [2]. Accordingly, in this work, it is hypothesized that a part of the spatial variation in forest productivity trends can be associated with the trends of climatic factors. The previous studies [3, 15, 19, 27] showed that there is a statistically significant relationship between the plant productivity and climatic factors. Therefore, understanding of forest response on climate system fluctuation is important for our better understanding of contribution and role of forest in the carbon cycle. This study is aimed to estimate the trends of climatic drivers and their relations with the forest productivity for different landscape-climatic regions of Ukraine.

The methods of ground forests inventory [22–25, 13] provide results with quite high accuracy. However, they require considerable time and effort on the part of humans to inventory vast areas. Moreover, these methods are hard to use in territories that are difficult to reach geographically. In this case, the remote sensing methods can be very useful and facilitate the solution of this problem. Among all methods, only satellite observations provide a global spatially continual observation of land cover parameters. Production efficiency models (PEMs) are the most commonly used group of models of the gross primary productivity (GPP) (the amount of organic matter synthesized by producers per unit area in unit time) that based on remote sensing data.

The PEMs have been developed to monitor the primary production, taking advantage of the available satellite data [16]. The PEMs are based on theory of the light use efficiency LUE [4, 6, 14, 17, 20, 21] which states that a relatively constant relationship exists between the photosynthetic carbon uptake and radiation absorption by vegetation at the canopy level [1]. The typical equation for the GPP calculation is:

$$GPP = \varepsilon \cdot FPAR \cdot PAR \cdot S_{\text{Tmin}} \cdot S_{\text{VPD}} \qquad (1)$$

where, GPP — Gross Primary Productivity (g C m^{-2}); PAR — Photosynthetically Active Radiation (MJ m^2); FAPAR — Fraction of Absorbed PAR (dimensionless %); ε — Light Use Efficiency (g C MJ^{-1}); S_{Tmin} — Daily Minimum Temperature Scalar, S_{VPD} — Vapour Pressure Deficit Scalar (0–1) [16].

2. Data and Methods

2.1. Forest productivity data

The Numerical Terradynamic Simulation Group (NTSG) (http://www.ntsg.umt.edu/) provides long-term time series of global estimates of the terrestrial GPP (MOD17) since March 2000. The data from the Collection 5 of the MOD17A2 model were used. The MOD17A2 is an 8-day summation of the GPP. The model is based on the data obtained from the MODIS spectrometer located on board of the Terra and Aqua spacecrafts. The spatial resolution of the model

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is 1×1 *km*, which allows assessing of the GPP at the regional and local levels. The temporal resolution is 8 days that is applicable for assessment of the seasonal features. The data set contains the observations for 13 years (from 2000 to 2012). The uncertainty of the model was estimated about 13–15% [12]. There are two main sources of the uncertainty. Firstly, the MOD12Q1 land cover product used in the model has accuracy in the range of 70–80%, and most of mistakes are between similar classes [26]. Secondly, large-scale meteorological data are provided by the NASA Data Assimilation Office (DAO). These data are derived using a global circulation model (GCM). Preliminary studies done by the NTSG suggest that the relationship between surface observations and DAO data across the U.S. appears reasonable, but comparisons have yet to be made on a global scale [7]. As a result, it may contain systematic errors in some regions. The uncertainties in meteorological data are mainly responsible for the unrealistic GPP in some small regions. For these pixels located in harsh environments, overestimated temperature alone, for example, can be enough to produce underestimation of the GPP due to the higher Vapour Pressure Deficit (VPD). A detailed discussion about the MOD17 algorithm sensitivity to meteorological inputs can be found elsewhere [28].

2.2 Climatic data

The World Meteorological Organization (WMO) collects the meteorological data from a global network of weather stations. The meteorological parameters that were available in the data sets and have been used in the study are listed in the Table 1. A total number of the weather stations over the territory of Ukraine presented in the WMO station list is 169. Nevertheless, only 33 of them (Table 2) have continuous measurements of the weather parameters for certain period.

Table 1
Meteorological parameters from the WMO data set used in the study

Data	Description
TEMP	Mean daily temperature, degree Celsius (°C)
DEWP	Mean daily dew point, degree Celsius (°C)
MAX	Maximum daily temperature, degree Celsius (°C)
MIN	Minimum daily temperature, degree Celsius (°C)
PRCP	Precipitation, mm
RH	Relative humidity, %

These weather stations were grouped according to landscape-climatic zoning (Fig. 1, Table 2). The data were spatially averaged for each region. A temporal harmonization has been done for data coincidence with 8-day data set of the forest productivity.

2.3 Data analysis

Figure 2 shows general description of the data analysis. MOD12Q1 Land Cover Product [5] has been used for creation of forest mask. MOD17A2 Product has been masked by the forest mask and medians of GPP spatial distribution for different landscape-climatic zones [18] have been calculated. The weather stations data have been grouped according to landscape-climatic zoning and spatial statistic has been calculated. Finally, the statistical data analysis and modeling have been done.

The full time series analysis was performed to estimate the dynamics and trends of all parameters for each region. The next stage of the study was the analysis of the environmental factors and their impact on the for-

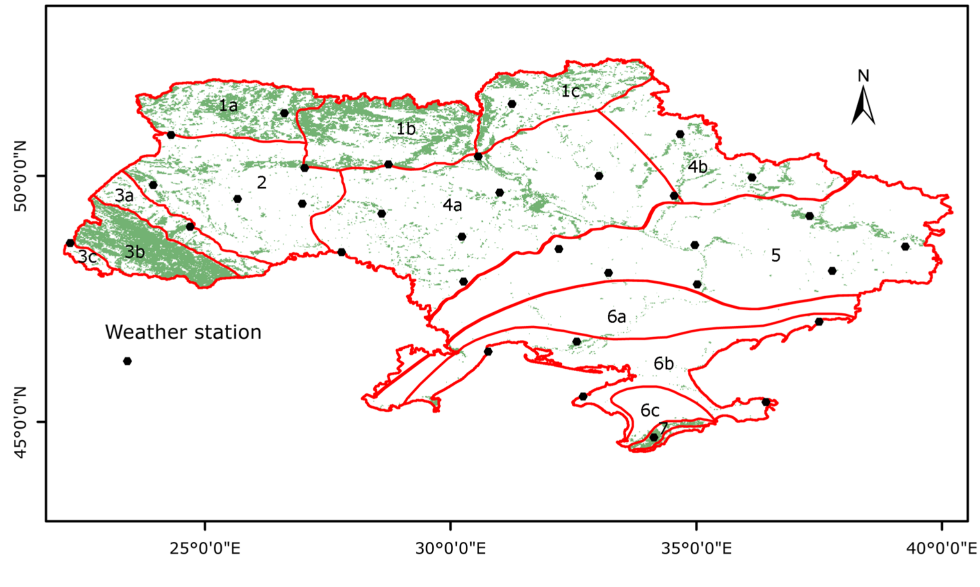

Fig. 1. Forest mask, landscape-climatic zoning and weather stations position for the territory of Ukraine 1 — the mixed forests zone (MF); 2 — the broadleaf deciduous forests zone (LF); 3 — the Carpathian mountains (KRP); 4a — the western forest-steppe subzone (WFS); 4b — the eastern forest-steppe subzone (EFS); 5 — the north steppe subzone (NS); 6 — the south steppe subzone and coastal lands (SS); 7 — the Crimean mountains and southern coast of Crimea (SC) (According to the National Atlas of Ukraine)

Table 2
List of the weather stations and theirs grouping according to landscape-climatic zoning

USAF	STATION	LAT	LON	ELEV
1. Mixed forests zone:				
330880	SARNY	51.283	26.617	156
331770	VOLODYMYR-VOLYNSKYI	50.833	24.317	194
333250	ZHYTOMYR	50.233	28.733	224
333450	KYIV	50.4	30.567	167
331350	CHERNIHIV	51.467	31.25	141
2. Broadleaf deciduous forests zone:				
334290	KHMELNYTSKYI	49.433	26.983	350
333170	SHEPETIVKA	50.167	27.033	278
334150	TERNOPIL	49.533	25.667	329
333930	LVIV	49.817	23.95	323
3. Carpathian mountains zone:				
336310	UZHHOROD	48.633	22.267	124
335260	IVANO-FRANKIVSK	48.967	24.7	280
4a. Western forest-steppe subzone:				
334660	MYRONIVKA	49.667	31	153
333770	LUBNY	50	33.017	158
335620	VINNYTSIA	49.233	28.6	298
336630	MOHYLIV-PODILSKYI	48.45	27.783	78
335870	UMAN	48.767	30.233	216
337610	LIUBASHIVKA	47.85	30.267	183
4b. Eastern forest-steppe subzone:				
332750	SUMY	50.85	34.667	181
335060	POLTAVA	49.6	34.55	160
343000	KHARKIV	49.967	36.133	155
5. North steppe subzone:				
345190	DONETSK	48.067	37.767	225
345230	LUHANSK	48.567	39.25	62
337910	KRYVYI RIH	48.033	33.217	124
337110	KIROVOHRAD	48.517	32.2	171
345040	DNIPROPETROVSK	48.6	34.967	143
344150	IZIUM	49.183	37.3	78
346010	ZAPORIZHZHIA	47.8	35.017	112
6. South steppe subzone and coastal lands:				
338370	ODESA	46.433	30.767	42
339020	KHERSON	46.633	32.567	54
339830	KERCH	45.4	36.417	49
347120	MARIUPOL	47.033	37.5	70
339460	SIMFEROPOL	44.683	34.133	181
7. Crimean mountains and southern coast of Crimea:				
339460	SIMFEROPOL	44.683	34.133	181

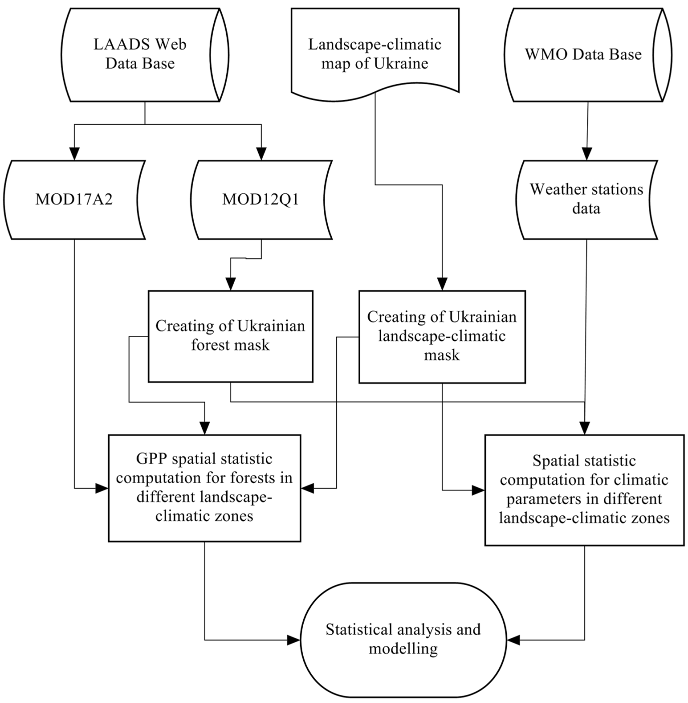

Fig.2. Flow chart for the data collection, processing and analyzing

est productivity. For this propose the method of principal component analysis (PCA) [11] was used. Using of this method give a possibility, firstly, to reduce the dimension of the output parameters, and secondly, to identify the hidden but objectively existing relations.

The growing season in Ukraine has a clear seasonality. Therefore the data were analyzed by seasons (DOY (days of year) 64–152 — spring; DOY 153–248 — summer; and DOY 249–336 — autumn) to assess seasonal characteristics.

3. Results and Discussion

In order to assess the general trends of the climatic drivers and the forest productivity, the time series for each region was analyzed. Fig. 3 shows a comparison of slope coefficients of the trend lines for each climatic driver in different regions of Ukraine. It was found a clear increasing of the temperature parameters for all regions. The strongest growth of the temperatures took place in the southern regions (Crimea, the northern and southern steppe subzones). Slightly lower growth of the temperatures was observed in the forest-steppe zone and the lowest one was evaluated for the forest zones and the Carpathians. It should be noted that the maximum temperatures had stronger positive trend among all temperatures parameters especially for the southern regions. The trends of the precipitation had opposite tendency. A slight increasing was observed only for the mixed forests zone and the Carpathian Mountains. In other regions the precipitation amount had decreasing trends. And the most intense decline was evaluated for Crimea, the southern steppe and forest-steppe zones. The relative humidity has the most heterogeneous trends. Significant increasing was observed for the Carpathian and Crimea Mountains and the forest zones, in comparison to other regions, where decreasing trends took place. The analysis of the forest productivity (GPP) showed slight positive trends for the Carpathians and the forest zones (mixed and deciduous forests). The forest GPP of other regions had decreasing trends. The most significant decreasing of the forest GPP took place in the eastern steppe subzone and the steppe zone.

The next step of the study was an analysis of correlation between each climatic driver and the forest GPP. As it was mentioned above, the growing season in Ukraine has a clear seasonality. Taking it into account, the correlation coefficients for the seasons (spring, summer, autumn) (Fig. 4) has been calculated. The results showed that the forest GPP had strong positive correlation with temperature parameters for spring and autumn (r > 0.7) and had not one for summer (r = –0.2–0.2). In southern regions, such as the steppe zone and Crimea, the correlation had small negative value. The correlation with precipitation was found to be not so strong. The seasonal analysis demonstrated more significant role of precipitation in spring for the forest and forest-steppe regions, while the steppe zone forest productivity was more sensitive to the precipitation amount in summer. The relative humidity had the small negative correlation with the forest GPP for all regions. However, for the steppe and forest-steppe zones it had a positive relationship in summer.

Since all climatic parameters have a good correlation with each other, the PCA was used to avoid the parameter saturation. This method also reduces the data set dimensionality. All parameters are grouped in several components, which essentially are a linear combination of the parameters. Such comprehensive assessment makes it possible to identify the hidden relations because there is no correlation between the principal components at all. The contribution of each component to the data description was estimated after analyzing the residual variance. Thus, the number of prin-

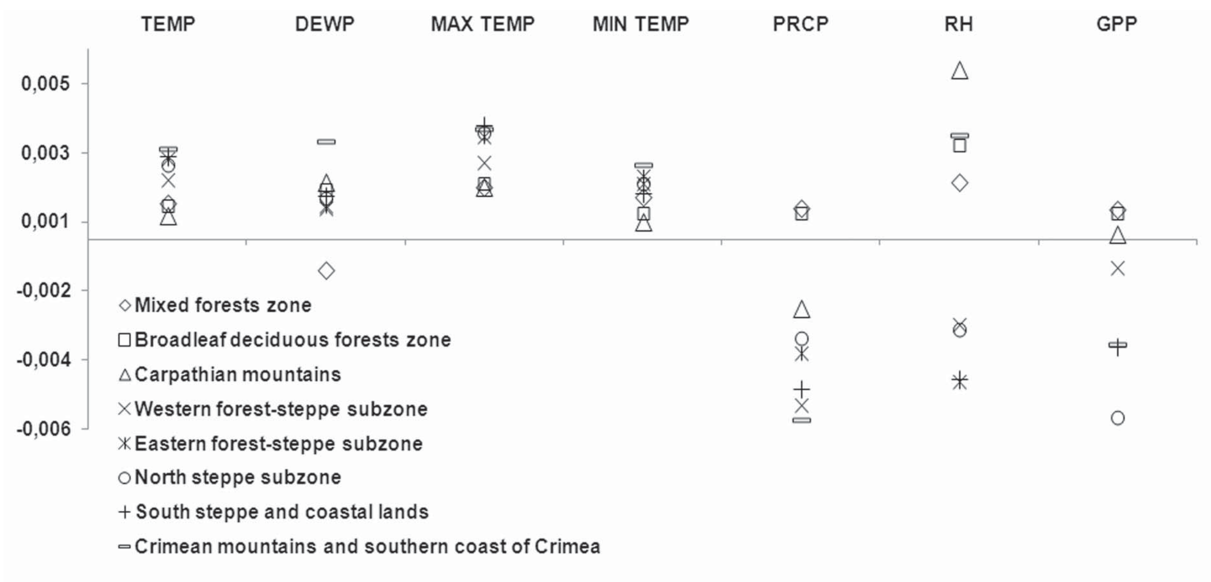

Fig.3. The slope coefficients of the trend lines (2000–2012) for the main climatic drivers regarding landscape-climatic regions of Ukraine

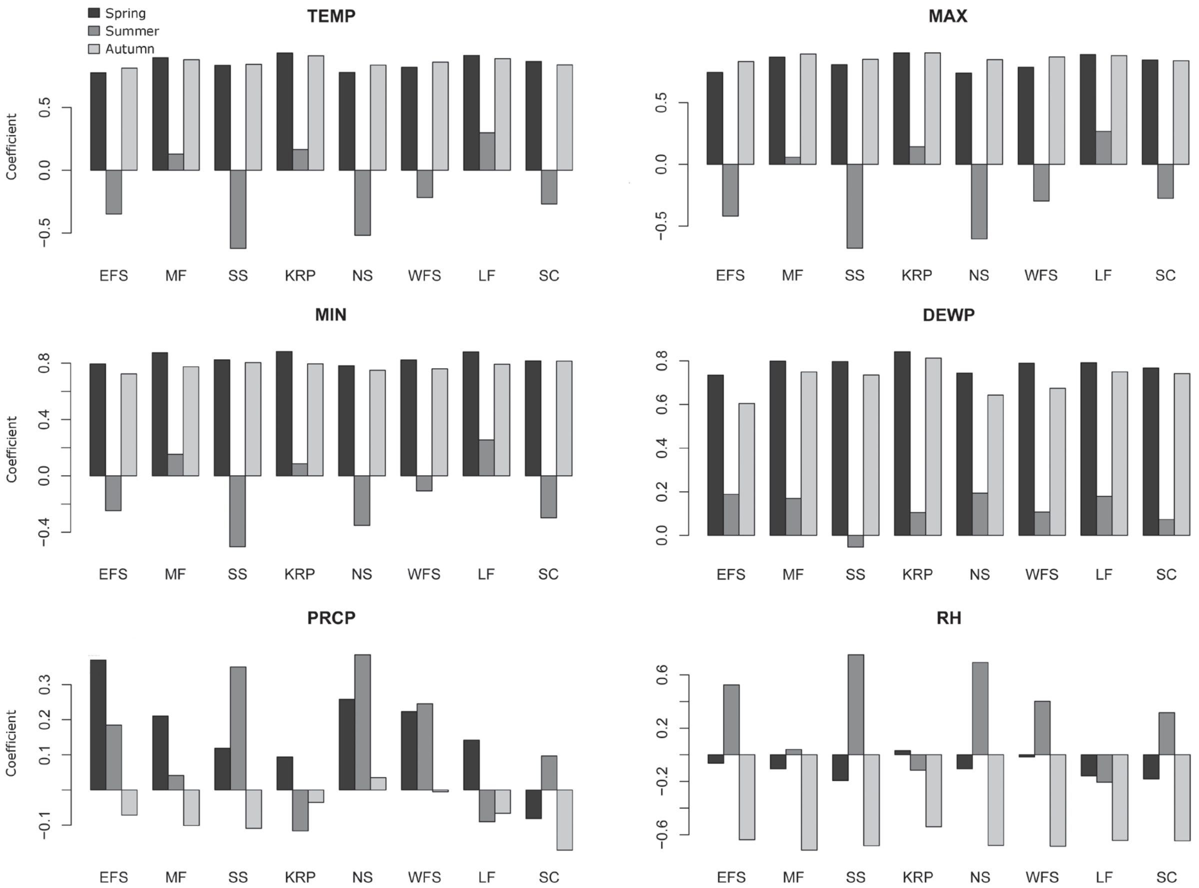

Fig.4. The correlation coefficients between the GPP and climatic drivers for the seasons

cipal components (PC) necessary to describe the data was determined. It should be noted that, in general, all PC residuals have a similar distribution for all landscape-climatic zones. And the first three components describe an average of 55–65%, 20–30% and 5–10% of the data respectively. The rest of the components have insignificant effect on the data and can be considered as the influence of measuring errors, noise and other additional factors not considered in the study. In the sequel analysis it was considered only first two components, as far as the ones together describe from 80 to 90% of the data. An analysis of the PC loadings shows how factors related each other and how ones influence on the principal components. The residual variance analysis provides more detail information about the PC1 and PC2 (Tables 3, 4) which describe the temperature regime and moisture availability respectively. A seasonal analysis showed significant changes in the component loadings through the growing season.

The PC loadings of the variances can be considered as a correlation between the PC score and correspondent variance. It was above mentioned, the first component is determined by the temperature parameters: averaged, maximum and minimum daily air temperatures and dew point. Table 3 shows a good positive correlation between the PC1 and the temperature parameters for spring and summer and negative one for autumn for all climatic zones. Meanwhile, minimum temperatures had a slightly higher correlation than other temperature variances for spring when the averaged temperatures correlation predominates for summer and autumn.

The moisture availability is defined by the PC2 determined mainly by precipitation and relative humidity. Analysis of the PC2 loadings (Table 4) showed following results. There was a good positive correlation between the PC2 scores, precipitation and relative humidity in spring for all climatic zones except South Crimea where correlation was negative. For summer, there was a good negative correlation between ones except the Carpathian region and the western forest-steppe subzone where the correlation was positive. The autumn was characterized by a negative correlation for the broadleaf deciduous forests zone and South Crimea and positive one for all other climatic zones.

In order to assess the effect of the temperature and moisture regimes on the forest GPP for different seasons and climatic zones a multiple linear regression model based on the first two PCs was used:

$$GPP_{i,j} = \beta_0 + \beta_1 PC1_{i,j} + \beta_2 PC2_{i,j} + \varepsilon_{i.j} \qquad (2)$$

where i and j are climatic zone (subzone) and season respectively.

Table 3.
The PC1 loadings of the variables

Zone	TEMP	DEWP	MAX	MIN	PRCP	RH
			Spring			
EFS	0.499	0.469	0.488	0.508	0.182	− 0.030
MF	0.489	0.489	0.467	0.503	0.221	0.053
SS	0.507	0.474	0.501	0.501	− 0.007	− 0.129
KRP	0.491	0.501	0.458	0.506	0.141	0.149
NS	0.512	0.462	0.498	0.513	0.069	− 0.093
WFS	0.503	0.485	0.484	0.512	0.126	0.005
LF	0.497	0.490	0.475	0.509	0.165	0.032
SC	0.513	0.478	0.498	0.507	− 0.033	− 0.046
			Summer			
EFS	0.525	0.274	0.521	0.491	− 0.190	− 0.317
MF	0.519	0.451	0.505	0.493	− 0.107	− 0.135
SS	0.509	0.333	0.505	0.482	− 0.235	− 0.295
KRP	0.529	0.459	0.500	0.479	− 0.142	− 0.103
NS	0.521	0.219	0.520	0.470	− 0.257	− 0.350
WFS	0.524	0.393	0.511	0.488	− 0.155	− 0.219
LF	0.521	0.460	0.500	0.491	− 0.130	− 0.096
SC	0.528	0.225	0.523	0.487	− 0.209	− 0.339
			Autumn			
EFS	− 0.503	− 0.414	− 0.492	− 0.479	0.021	0.322
MF	− 0.489	− 0.443	− 0.481	− 0.457	0.097	0.339
SS	− 0.480	− 0.437	− 0.478	− 0.469	0.128	0.338
KRP	− 0.507	− 0.475	− 0.489	− 0.468	0.019	0.242
NS	− 0.497	− 0.414	− 0.487	− 0.475	0.013	0.344
WFS	− 0.498	− 0.427	− 0.485	− 0.469	0.016	0.337
LF	− 0.499	− 0.447	− 0.488	− 0.460	0.085	0.307
SC	− 0.478	− 0.423	− 0.476	− 0.464	0.141	0.360

Table 4.
The PC2 loadings of the variables

Zone	TEMP	DEWP	MAX	MIN	PRCP	RH
			Spring			
EFS	0.499	0.469	0.488	0.508	0.182	− 0.030
MF	0.489	0.489	0.467	0.503	0.221	0.053
SS	0.507	0.474	0.501	0.501	− 0.007	− 0.129
KRP	0.491	0.501	0.458	0.506	0.141	0.149
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The analysis of the regression coefficients allows to estimate the power and direction with which these principal components effect on the forest GPP for the corresponding season and climate zone. The comparison of the coefficients with the PC loadings provides the understanding of specific climatic drivers influence on the forest productivity. The regression coefficients for the first two components are presented in Table 5. The table illustrates that PC1, which describes the temperature regime, is statistically significant in all cases except of summer for the western forest-steppe subzone. The statistical significance of the regression coefficient for the PC2 (i. e. moisture regime) is not so straightforward. The PC2 for spring is statistically significant only for forest zones, and for all other climatic zones is not. The opposite situation was observed for summer. The PC2 for the forest-steppe and steppe zones is statistically significant, and for forest zones is not. For autumn the PC2 is not statistically significant for all zones. The coefficient of determination (R^2) indicates a very good fitting of the model for spring and autumn (especially for forest zones ($R^2 > 0.8$)) and negligible fitting for summer. Meanwhile the steppe zone had worse fitting for spring and autumn and much better one for summer in comparison with forest ones. This indicates that the forest productivity of the steppe region is more affected by extreme climatic drivers during summer.

Analysis of the PCs regression coefficients (Table 5) with their loadings (Tables 3, 4) shows that the forest zones were characterized by a significant positive impact of the temperatures on the forest productivity in spring ($в_1$ = 7.05, 8.63, 9.36, 12.74 for mixed and deciduous forests, the Carpathian and Crimean Mountains respectively). This effect almost disappears in summer. In autumn effect of the temperature regime again increases, but it is about 2 times weaker compared to spring. The influence of the moisture regime was not observed. The PC2 correlation coefficients for summer and autumn were not statistically significant for the mixed and deciduous forests zones and the Carpathians. For spring it had a slight negative effect. For the Crimean Mountains $в_2$ was not statistically significant for all seasons.

The effect of the temperature regime for the forest-steppe zone was somewhat lower than for forest areas. The moisture regime had no effect for spring and autumn ($в_2$ was not statistically significant) and had a good positive impact for summer ($в_2$ = 2.36 and 2.84 for the WFS and EFS respectively). The steppe zone is very similar to the forest-steppe one. Although it had a stronger negative effect of the temperature regime on the forest productivity ($в_1$ = –3.28 and –3.25 for the NS and SS respectively) and had a stronger positive relation with the moisture regime for summer.

4. Conclusions

Consequence of the PCA about the sensitivity of the forest productivity in different landscape-climatic zones of Ukraine to changes in climatic drivers and their trends discussed above (Fig. 3) showed clear patterns. The forest ecosystems of the forest zones were found to be the most resistance to climatic variations for the territory of Ukraine. The positive relations of the forest productivity to the temperature regime were observed for these zones. The correlation between the forest productivity and moisture regime was not detected. Obtained results could indicate the absence of any stable limiting climatic conditions for these areas. It was found a slight trend to increase of the forest GPP for the mixed and deciduous forests zones and the Carpathians (Fig. 3). It can be explained by a slight increasing trend in the temperature parameters. The steppe zone and eastern forest-steppe subzone have the opposite trend to decreasing

Table 5.
Regression coefficients and R^2 of the multiple linear regression model (2) for different seasons and climatic zones

Zone (subzone) / Season	β_1	β_2	R^2
1. Mixed forests:			
Spring	7.0549	-2.5451	0.8011
Summer	SNS	SNS	SNS
Autumn	-5.1997	SNS	0.7771
2. Broadleaf deciduous forests:			
Spring	8.6274	-2.7743	0.8286
Summer	1.1205	SNS	0.08681
Autumn	-5.3147	SNS	0.7874
3. Carpathian mountains:			
Spring	9.3615	-3.5161	0.8644
Summer	SNS	SNS	SNS
Autumn	-6.8784	SNS	0.8349
4a. Western forest-steppe:			
Spring	6.64473	SNS	0.7008
Summer	-1.1370	-2.3553	0.1488
Autumn	-4.3639	SNS	0.7454
4b. Eastern forest-steppe:			
Spring	6.7335	SNS	0.647
Summer	-2.3385	-2.8380	0.2256
Autumn	-4.3699	SNS	0.6794
5. North steppe:			
Spring	5.4771	SNS	0.6466
Summer	-3.2762	-3.1019	0.4511
Autumn	-3.7522	SNS	0.7059
6. South steppe and coastal lands:			
Spring	5.4416	SNS	0.7044
Summer	-3.2459	-2.9998	0.5346
Autumn	-3.6186	SNS	0.7207
7. Crimean mountains and southern coast of Crimea:			
Spring	12,7428	SNS	0.7366
Summer	-2.3651	SNS	0.1007
Autumn	-6.9112	SNS	0.7104

Notes: SNS — Statistically non significant (p-value > 0.05) of the forest GPP. And for these areas the results of the PCA showed a very strong positive relation of the productivity to the moisture regime and a negative one to the temperature regime for summer. It was suggested that these climatic drivers in summer become limiting for the corresponding areas. Taking into account a trend to increasing of the temperature parameters and decreasing of the precipitation amount in these zones, decreasing of the forest productivity seems logical.

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ОЦІНКА РЕАКЦІЇ ПРОДУКТИВНОСТІ ЛІСОВОГО ПОКРИВУ НА ЛОКАЛЬНІ КЛІМАТИЧНІ КОЛИВАННЯ В МЕЖАХ ТЕРИТОРІЇ УКРАЇНИ З ВИКОРИСТАННЯМ СУПУТНИКОВИХ ДАНИХ

Д. М. Мовчан

Ліси утримують в собі значну кількість вуглецю у вигляді накопиченої біомаси. Динаміка продуктивності лісів безпосередньо залежить від кліматичних факторів відповідних територій. У роботі проведений аналіз надземної продуктивності лісів і кліматичних чинників на регіональних рівнях. Валова первинна продуктивність (ВПП) і чиста первинна продуктивність (ЧПП), отримані з глобальної моделі MOD17, як індикатор продуктивності лісів і метеорологічні дані з мережі метеостанції, були використані для аналізу. Кореляційний аналіз між продуктивністю лісів і кліматичними показниками був проведений для різних періодів вегетаційного сезону і ландшафтно-кліматичних зон України. Лінійна регресійна модель на основі аналізу головних компонент (PCA) була використана для оцінки впливу основних кліматичних чинників на продуктивність лісових територій України.

Ключові слова: ліси; вуглецевий цикл; зміни клімату; валова первинна продуктивність; дистанційне зондування; аналіз головних компонент

ОЦЕНКА РЕАКЦИИ ПРОДУКТИВНОСТИ ЛЕСНОГО ПОКРОВА НА ЛОКАЛЬНЫЕ КЛИМАТИЧЕСКИЕ КОЛЕБАНИЯ НА ТЕРТОРИИ УКРАИНЫ С ИСПОЛЬЗОВАНИЕМ СПУТНИКОВЫХ ДАННЫХ

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Леса удерживают в себе значительное количество углерода в виде накопленной биомассы. Динамика продуктивности лесов напрямую зависит от климатических факторов соответствующих территорий. В работе проведен анализ надземной продуктивности лесов и климатических факторов на региональных уровнях. Валовая первичная продуктивность (ВПП) и чистая первичная продуктивность (ЧПП), полученные из глобальной модели MOD17, как индикатор продуктивности лесов и метеорологические данные из сети метеостанций, были использованы для анализа. Корреляционный анализ между продуктивностью лесов и климатическими показателями был проведен для различных периодов вегетационного сезона и ландшафтно-климатических зон Украины. Линейная регрессионная модель на основании анализа главных компонент (PCA) была использована для оценки влияния основных климатических факторов на продуктивность лесных территорий Украины.

Ключевые слова: леса; углеродный цикл; климатические изменения; валовая первичная продуктивность; дистанционное зондирование; анализ главных компонент