The impact of recent climate change on the ecological productivity of forests in Romania

– Scientific report 2021 –

The main objective of this project is to analyze the potential impact of recent climate change on forest productivity in Romania, based on various climatic and remote sensing data, which will be processed over the past three decades (1987–2016) by means of complex geostatistical techniques.

According to the funding application, the project's **specific objectives** are:

1) acquisition of interannual climatic and satellite data in Romania for the 1987–2016 period, necessary to test the hypothesis of the recent climate change impact on forest productivity countrywide;

2) geostatistical processing of trends in forest vegetation density in Romania, in relation to the trends of the main climatic parameters over the past three decades;

3) geostatistical processing of trends in forest biomass in Romania, in relation to the trends of the main climatic parameters over the past three decades;

4) geostatistical processing of trends in net primary productivity of forests in Romania, in relation to the trends of the main climatic parameters over the past three decades;

5) raising awareness on the necessity of interdisciplinary scientific investigations of this important ecoclimatic issue in Romania's scientific/political spheres by disseminating the study's results.

In accordance with the overall scope and the specific objectives above, **in 2021 the first 2 objectives of the project were fully met**, i.e. acquiring satellite and climate data across Romania, and modeling forest vegetation density in relation to recent climate change, as detailed in the project proposal. While the first research report, submitted in late 2020, explained the detailed stages of acquiring and preprocessing Landsat satellite data within national forest boundaries, **this second research report will detail the stages of climate data processing (I), modeling forest vegetation density (II), and the investigation of statistical relationships between climate and ecological data for the country's forest environments (III)**. Thus, the most important information regarding the completion of the three major stages will be presented below, which pertain to the first (stage I) and the second (stages II and III) specific objectives of the project.

Climate data processing (I)

The climatic data used in this report consists of seasonal (summer period) air temperature (T, in °C), precipitation (P, in mm) and reference evapotranspiration (ETo, in mm), at 1 km × 1 km spatial resolution, using gridded observational data collected from all weather stations of Meteo Romania. The climatic parameters' data were computed based on daily values, which were averaged (T) or summed (P and ETo) for the summer season (June – August) of each year of the 1987–2018 period (compared to the original application, in the end it was considered necessary to update the interval by 2 years). T and P were collected directly from Meteo Romania's observational measurements, but ETo values were estimated (based on air temperature, relative humidity, sunshine duration and wind speed data – data also collected from Meteo Romania) using the FAO-56 Penman-Monteith method.

Considering that, similarly to Landsat data, the study required climatic data mapped, in order to detect the forests' response to the dynamics of climatic conditions, all climate data were spatialized by interpolations. Therefore, T, P and ETo summer values were spatialized for all 32 years through the Regression-Kriging interpolation method. Subsequently, the climatic data mapped were used in the analysis of the relationships between climate and the ecological state of Romanian forests, after 1987.

Modeling of forest vegetation density (II)

Forest density was estimated based on the Normalized Difference Vegetation Index (NDVI), which was computed (yearly, for the summer period, as previously mentioned) as the difference between near infra-red and red bands divided by their sum: NDVI = (NIR - Red) / (NIR + Red). These spectral bands were included in the Landsat satellite database, described in the first research report (2020). All yearly NDVI raster data were processed strictly at the level of Romania's forest boundaries (extracted from the CORINE Land Cover databases), at a final spatial resolution of 1 km × 1 km, similar to the resolution of climatic data.

Once the yearly raster series of NDVI were obtained, the non-parametric *Mann-Kendall* (MK) test and *Sen's slope* estimator were used to investigate the ecological trends of Romanian forests. The NDVI trends were explored at pixel level in terms of their direction (positive or negative), magnitude (the change per year) and statistical significance (at the significance level α = 0.1 or 90%). The same two statistical procedures were applied to climate data, in order to empirically examine the eco-climatic trend similarities and possible relationships between the two data sets.

NDVI was used in this project due to the high number of technical and practical advantages. NDVI's strengths include the low number of constituting spectral bands (only NIR and Red), simplicity in its computation method, easy availability of long-term spectral databases required for its calculation or its overall reliability in the analysis of vegetation density and productivity.

Investigation of eco-climatic relationships (III)

The statistical relationships between NDVI and climate (T, P, ETo and climatic water balance, CWB, expressed in mm and calculated based on the difference between P and ETo – CWB = P-ETo) data were quantitatively investigated, by correlating the two datasets. The statistical correlations were performed based on the mean values of NDVI and climate raster data, which were extracted for three spatial units of Romania (major geographical regions, major ecoregions and major landforms) that were considered natural homogeneous areas where the climate impact on NDVI can be investigated.

The temporal eco-climatic relationships were investigated through basic statistical correlation indices, like the adjusted coefficient of determination (R^2) and the Pearson linear correlation coefficient (r). Also, the statistical significance of eco-climatic relationships was assessed throughout the Romanian forests (of the three spatial units) by means of 0.05 and 0.1 p-value thresholds.

The results obtained in 2021

The use of the *Sen's slope* and *MK* procedures showed an overall greening of the Romanian forests (Fig. 1a), but with significant regional differences. Classifying *Sen's slope* values in decreasing (negative), increasing (positive) and null (stationary) trends, the results revealed that ~50% of Romania's forest area was affected by NDVI changes (decreasing and increasing, including statistically significant ones) in vegetation quality, while the other half remained unchanged or relatively unchanged (stationary trends highlighted in dark gray) (Fig. 1b). Statistically, of the total absolute NDVI changes (> 30.000 km^2) throughout the country's forests, ~65% experienced vegetation enhancement (positive NDVI trends, which indicate increases in vegetation density), while the remaining ~35% experienced vegetation degradation (negative NDVI trends, which indicate decreases in vegetation quality / density) (Fig. 1c). However, the two types of trends have limited statistical significance across the Romanian forests (Fig. 1c).

Regionally, by extracting percentage-based statistics for the three natural spatial units, it was found that, in terms of major geographical regions, the Carpathians region accounts for the most extensive greening trends (~35%) of the total NDVI changes of Romania (Fig. 2a). In terms of major ecoregions, the Carpathian montane coniferous forests experienced the greatest changes in vegetation density in Romania (~42% of the total), mostly consisting of positive NDVI trends (~28%) (Fig. 2b). Overall, the ecoregions of Romania were dominated by greening trends, except for forests located in the ecological units of Extra-Carpathians region (East European forest steppe and Pontic steppe), with general trends of vegetation degradation (Fig. 2b).

In the case of the 16 landform units of Romania, a general pattern of NDVI changes was also observed. All units overlapping Carpathian territories (Eastern, Curvature, Southern, Banatului and Western Carpathians) recorded a positive net balance of NDVI changes (positive trends more widespread than negative trends) (Fig. 2c). At the opposite pole, large relief units in the Extra-Carpathians area (Moldavian Plateau, Romanian Plain, Dobrogea Plateau) experienced dominant degradation (especially the Romanian Plain and Moldavian Plateau, each with ~4% decreasing trends of the total NDVI changes) or balanced mixed (Danube Delta) trends of NDVI (Fig. 2c). In landforms located in the Intra-Carpathians region forests experienced a slight ecological improvement, except for the Transylvanian Plateau, which recorded a general decline in forest vegetation density (Fig. 2c).

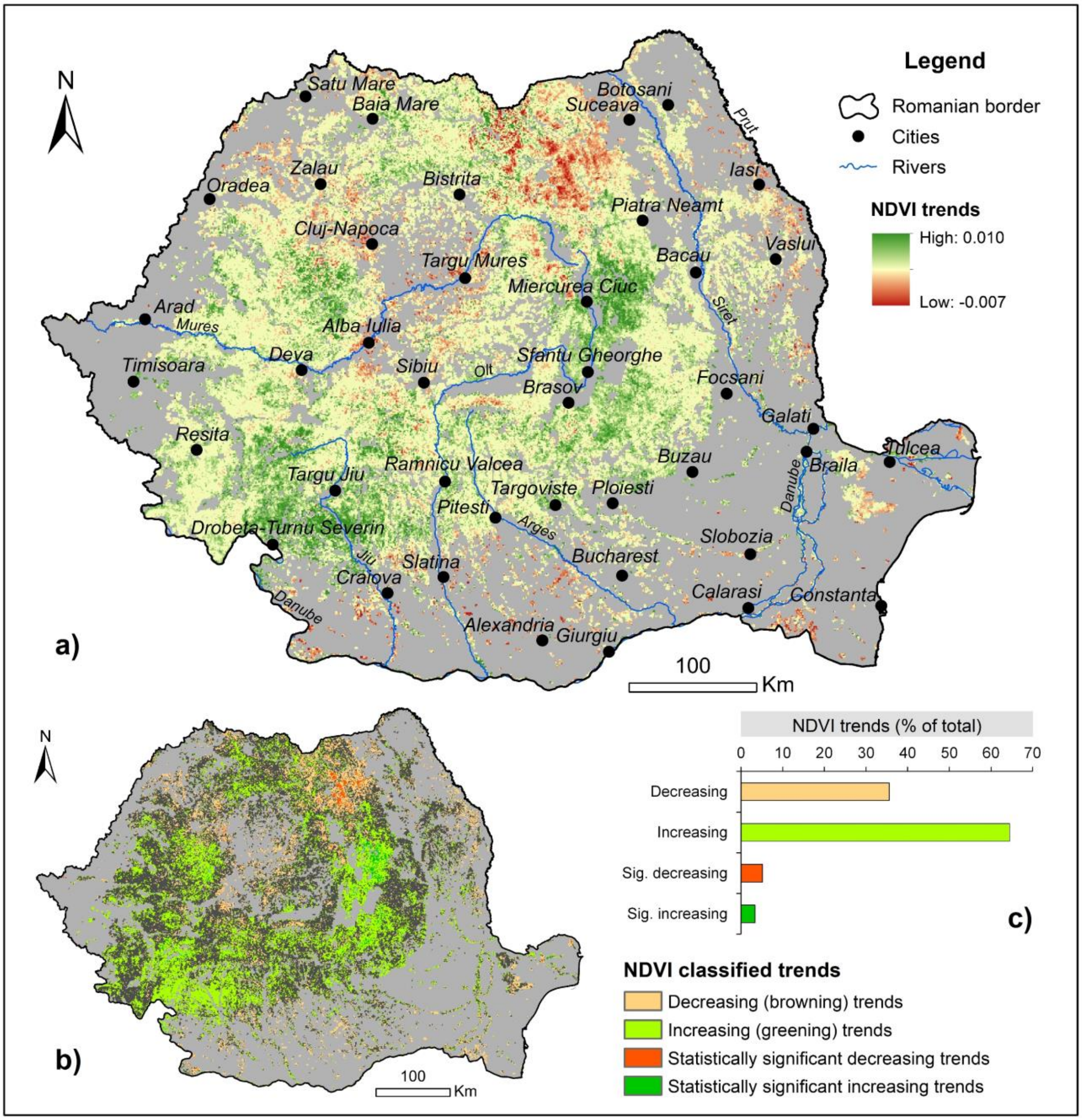

Fig. 1. General (a) and classified (b) NDVI annual trends (in the summer season) in Romania during 1987–2018 and extracted percentage-based statistics (c) of the two types of trends resulting from the NDVI trend classification. Note: more details about this figure can be consulted in the paper sent for publication (Prăvălie et al., 2021, see page 9).

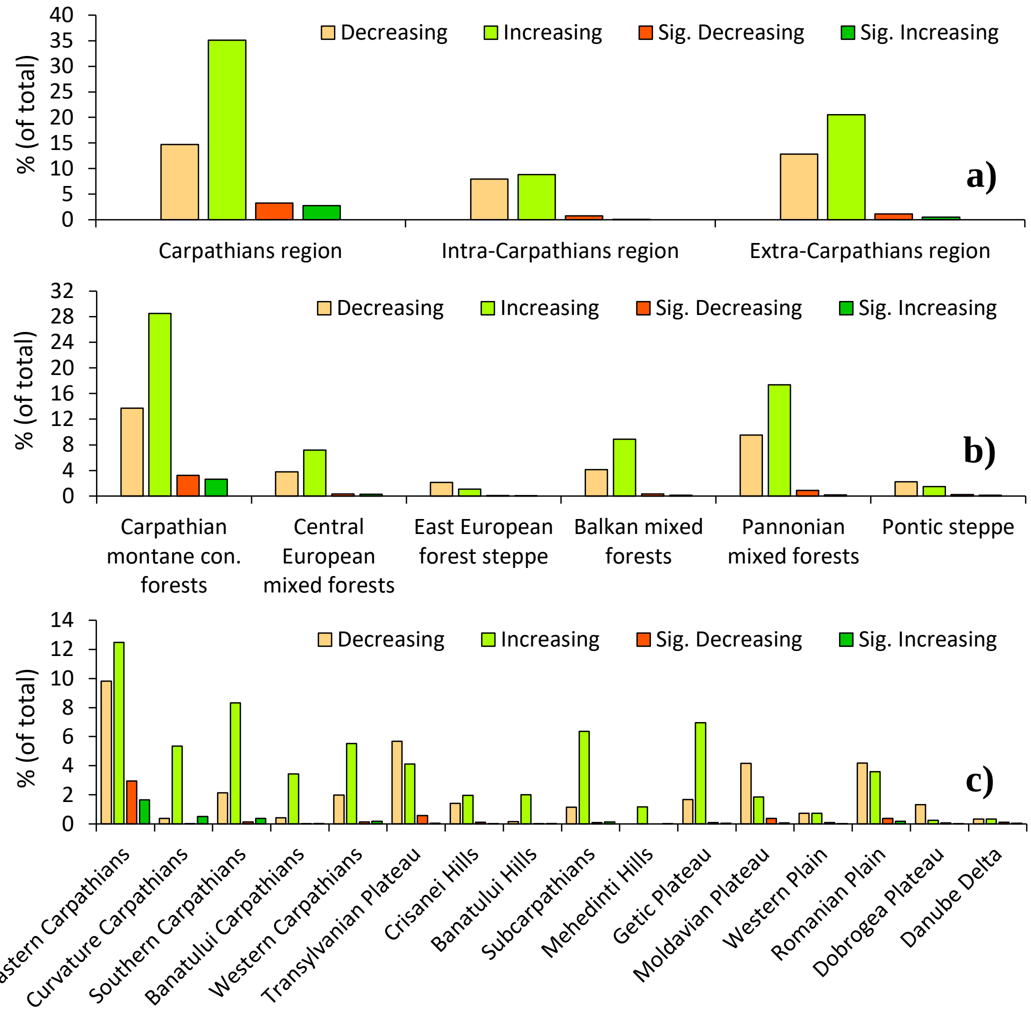

Fig. 2. Percentage-based areas of NDVI trends during 1987–2018, within major geographical regions (a), major ecoregions (b) and major landforms (c) of Romania. Note: more details about this figure can be consulted in the paper sent for publication (Prăvălie et al., 2021, see page 9).

The analysis of the climatic variable trends, which are potentially driving factors of NDVI dynamics, showed an exclusive warming statistically significant across 99% of Romanian forestlands, in case of T (Fig. 3). P recorded a more heterogeneous dynamics compared to T, characterized by wetter conditions throughout the Carpathians and some hilly and plain regions, and drier conditions in some parts of the Intra- and Extra-Carpathian regions (Fig. 3). ETo intensified across almost the entire territory of Romania, largely due to the exclusively positive trends of T (Fig. 3).

The analysis of the CWB highlighted that most of the country's forestlands became wetter during summer, although the statistical significance of CWB trends is relatively limited nationally, similar to P and ETo trends (Fig. 3). All these trends indirectly suggest that climate change is a driving force of NDVI changes, but the ecological response to climate dynamics must be concretely investigated through statistical correlations.

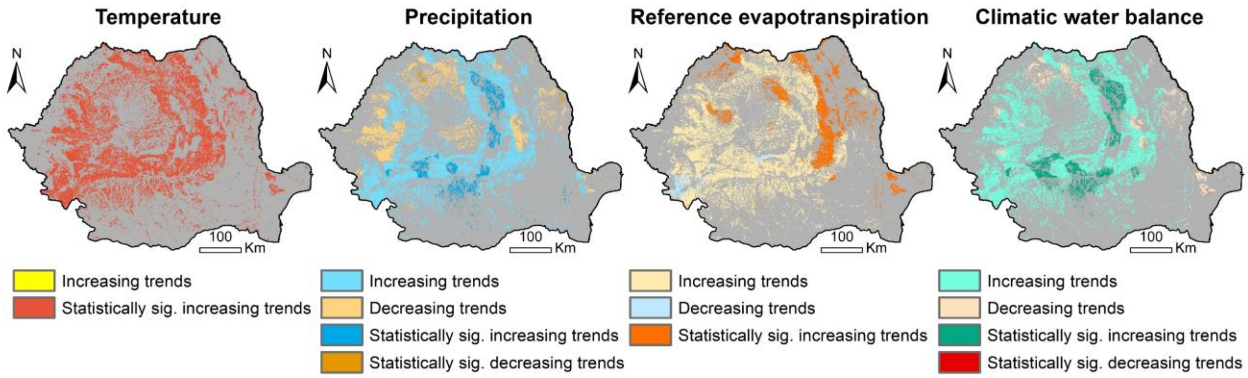

Fig. 3. Classified annual trends (in the summer season) for temperature, precipitation, reference evapotranspiration and climatic water balance (precipitation minus reference evapotranspiration), across the Romanian forestlands during 1987–2018. Note: more details about this figure can be consulted in the paper sent for publication (Prăvălie et al., 2021, see page 9).

The correlation of the annual climatic (T, P, ETo and CWB) and ecological (NDVI) datasets, for the three spatial units, revealed some interesting statistical relationships. With regard to the temperature – NDVI relationship, peak R^2 values in the Carpathians region, Carpathian montane coniferous forests and Eastern Carpathians showed that the NDVI dynamics can be explained by T changes in the three selected hotspots of the three natural unit categories (Table 1). While the R^2 values seem relatively low, their statistical significance is high, not only in these cases, but also in other cases generally located in mountainous areas (Table 1).

Also, given the computed *r* values in the three exemplified cases, it was found at least a moderate intensity (~50%, expressed as percentage) of eco-climatic relationships in the high-altitude areas, but also the fact that NDVI is significant positively correlated with T in the mountain regions (Table 1). This statistical clue reveals that forest vegetation density increased in temperature-limited mountainous areas of Romania, as a consequence of the recent climate warming that affected the country's high-altitude areas. The precipitation-NDVI statistical analysis showed a general lack of correlations between NDVI variability and that of P, due to the very low R^2 and *r* values and the general lack of statistical significance (Table 1).

In contrast, evapotranspiration seems to play a far more important role in the ecological dynamics of forests, mainly in the Extra-Carpathian areas. The R^2 and *r* findings showed a peak impact of Eto on NDVI in the Moldavian Plateau, Western Plain, Danube Delta, Romanian Plain, Dobrogea Plateau (landforms), East European forest steppe and Pontic steppe (ecoregions) (Table 2). Also, the negative *r* coefficient values indicate a significant negative correlation between Eto and NDVI (Table 2), which suggests that the amplification of the evapotranspiration regime in recent decades caused a decline in density and health of forest ecosystems, especially in the mentioned lowland and hilly areas. In the last case, although the statistical information indicated a positive impact of the CWB in the greening trends of NDVI, there still are many situations with relatively low R^2 and *r* values and with low statistical significance across the country.

Table 1. Statistical correlations between mean air temperature (°C) / precipitation (mm) and NDVI data, investigated across various natural spatial units in Romania in the 1987–2018 period.

No.	Spatial units	Temperature – NDVI				Precipitation – NDVI			
		R^2 adjusted	r	p-value	Significance[a]	R^2 adjusted	r	p-value	Significance[a]
1	Romania	0.179	0.453	0.009	high	0.041	0.268	0.138	not signif.
2	Carpathians region	0.220	0.495	0.004	high	0.030	0.248	0.171	not signif.
3	Intra-Carpathians region	0.175	0.449	0.010	high	0.002	0.186	0.309	not signif.
4	Extra-Carpathians region	0.062	0.303	0.092	low	0.070	0.317	0.077	low
5	Carpathian montane con. forests	0.236	0.510	0.003	high	0.036	0.259	0.153	not signif.
6	Central European mixed forests	0.062	0.304	0.091	low	0.041	0.269	0.137	not signif.
7	East European forest steppe	0.000	0.119	0.516	not signif.	0.060	0.301	0.095	low
8	Balkan mixed forests	0.015	0.216	0.236	not signif.	0.065	0.308	0.086	low
9	Pannonian mixed forests	0.158	0.430	0.014	high	0.015	0.215	0.236	not signif.
10	Pontic steppe	0.034	0.256	0.157	not signif.	0.182	0.457	0.009	high
11	Eastern Carpathians	0.261	0.533	0.002	high	0.023	0.233	0.199	not signif.
12	Curvature Carpathians	0.151	0.423	0.016	high	0.004	0.191	0.296	not signif.
13	Southern Carpathians	0.195	0.470	0.007	high	0.049	0.282	0.118	not signif.
14	Banatului Carpathians	0.098	0.356	0.045	high	0.007	0.160	0.382	not signif.
15	Western Carpathians	0.164	0.437	0.012	high	0.003	0.171	0.350	not signif.
16	Transylvanian Plateau	0.231	0.506	0.003	high	0.007	0.199	0.276	not signif.
17	Crisanei Hills	0.100	0.359	0.044	high	0.002	0.185	0.311	not signif.
18	Banatului Hills	0.043	0.271	0.133	not signif.	0.016	0.129	0.481	not signif.
19	Subcarpathians	0.083	0.336	0.060	low	0.048	0.281	0.120	not signif.
20	Mehedinti Hills	0.103	0.363	0.041	high	0.020	0.228	0.210	not signif.
21	Getic Plateau	0.022	0.232	0.201	not signif.	0.079	0.330	0.065	low
22	Moldavian Plateau	0.018	0.223	0.220	not signif.	0.019	0.117	0.524	not signif.
23	Western Plain	0.030	0.248	0.171	not signif.	0.078	0.328	0.067	low
24	Romanian Plain	0.015	0.215	0.236	not signif.	0.151	0.422	0.016	high
25	Dobrogea Plateau	0.002	0.184	0.313	not signif.	0.203	0.478	0.006	high
26	Danube Delta	0.115	0.379	0.033	high	0.008	0.200	0.272	not signif.

Note: signif. – significant; more details about this table can be consulted in the paper sent for publication (Prăvălie et al., 2021, see page 9).

Table 2. Statistical correlations between reference evapotranspiration (mm) / climatic water balance (mm) and NDVI data, investigated across various natural spatial units in Romania in the 1987–2018 period.

No.	Spatial units	Reference evapotranspiration – NDVI				Climatic water balance – NDVI			
		R^2 adjusted	r	p-value	Significance[a]	R^2 adjusted	r	p-value	Significance[a]
1	Romania	0.096	-0.354	0.047	high	0.120	0.386	0.029	high
2	Carpathians region	0.099	-0.358	0.044	high	0.105	0.366	0.039	high
3	Intra-Carpathians region	0.081	-0.333	0.063	low	0.091	0.346	0.052	low
4	Extra-Carpathians region	0.088	-0.343	0.054	low	0.138	0.407	0.021	high
5	Carpathian montane con. forests	0.108	-0.370	0.037	high	0.115	0.379	0.032	high
6	Central European mixed forests	0.074	-0.322	0.072	low	0.104	0.365	0.040	high
7	East European forest steppe	0.139	-0.408	0.020	high	0.160	0.432	0.014	high
8	Balkan mixed forests	0.065	-0.309	0.086	low	0.117	0.382	0.031	high
9	Pannonian mixed forests	0.074	-0.322	0.072	low	0.086	0.340	0.057	low
10	Pontic steppe	0.182	-0.456	0.009	high	0.261	0.533	0.002	high
11	Eastern Carpathians	0.100	-0.359	0.044	high	0.107	0.368	0.038	high
12	Curvature Carpathians	0.065	-0.308	0.086	low	0.052	0.288	0.110	not signif.
13	Southern Carpathians	0.088	-0.343	0.054	low	0.102	0.362	0.041	high
14	Banatului Carpathians	0.057	-0.296	0.100	not signif.	0.038	0.263	0.147	not signif.
15	Western Carpathians	0.085	-0.338	0.058	low	0.068	0.312	0.082	low
16	Transylvanian Plateau	0.063	-0.305	0.090	low	0.085	0.339	0.058	low
17	Crisanei Hills	0.096	-0.353	0.047	high	0.090	0.345	0.053	low
18	Banatului Hills	0.089	-0.344	0.054	low	0.069	0.314	0.080	low
19	Subcarpathians	0.060	-0.300	0.095	low	0.098	0.356	0.045	high
20	Mehedinti Hills	0.059	-0.298	0.097	low	0.073	0.321	0.073	low
21	Getic Plateau	0.045	-0.275	0.128	not signif.	0.117	0.381	0.032	high
22	Moldavian Plateau	0.122	-0.387	0.029	high	0.075	0.323	0.071	low
23	Western Plain	0.125	-0.391	0.027	high	0.186	0.461	0.008	high
24	Romanian Plain	0.151	-0.422	0.016	high	0.228	0.503	0.003	high
25	Dobrogea Plateau	0.166	-0.439	0.012	high	0.265	0.538	0.002	high
26	Danube Delta	0.137	-0.406	0.021	high	0.131	0.398	0.024	high

Note: signif. – significant; more details about this table can be consulted in the paper sent for publication (Prăvălie et al., 2021, see page 9).

Much more details about all these results explored for the first time in Romania, which were obtained in accordance with the first two specific objectives of the project, were featured in Prăvălie et al. (2021) – **Prăvălie R.**, et al., 2021. *NDVI-based ecological dynamics of forest vegetation and its relationship to climate change in Romania during 1987–2018*. Ecol. Indic. (in press). This study is already in an advanced stage of publication, and was recently revised for the prestigious journal **Ecological Indicators** (Impact Factor 5, Relative Influence Score 1.7, Article Influence Score 1). After the publication of the paper, all details about NDVI dynamics, in relation to climate change in Romania, can be consulted in this national study conducted within this postdoctoral project funded by UEFISCDI.

Other articles that have already been published under the project acknowledgments and that have a direct or indirect connection with the project theme are:

1) **Prăvălie R.**, 2021. *Exploring the multiple land degradation pathways across the planet*. **Earth Science Reviews** 220, https://doi.org/10.1016/j.earscirev.2021.103689, Impact factor 12.4, Relative Influence Score 5.1, Article Influence Score 3.8;

2) **Prăvălie R.**, et al., 2021. *Global changes in soil organic carbon and implications for land degradation neutrality and climate stability*. **Environmental Research** 201, https://doi.org/10.1016/j.envres.2021.111580, Impact factor 6.5, Relative Influence Score 2.1, Article Influence Score 1.3.

Also, other deliverables of the project obtained so far consist in the presentation of the results at 3 **international online conferences**, held **abroad** and in Romania:

1) **Prăvălie R.**, Bandoc G., 2021. *Analysis of forest ecological changes in Romania based on detecting recent trends in Normalized Difference Vegetation Index*. "9th Annual International Conference on Ecology, Ecosystems and Climate Change", 12–15 July, Athens, Greece;

2) **Prăvălie R.**, 2021. *Recent impact of climate change on forest productivity in Romania*. "27th International Conference on “Agriculture, Biological and Environmental Sciences” (MABES-21)", August 11–13, Barcelona, Spain;

3) **Prăvălie R.**, Bandoc G., 2021. *Detecting land-atmosphere carbon fluxes at global scale after 2001*. The 2nd International Conference "Geographical Sciences and Future of Earth", November 12, Bucharest, Romania.

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