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# NDVI-based ecological dynamics of forest vegetation and its relationship to climate change in Romania during 1987–2018

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# ABSTRACT

Forests have become increasingly stressed by climate change, including in Romania over recent decades, but their response to climate dynamics has not yet been analysed in this country. This study aims to investigate, for the first time, recent ecological changes in forests across Romania, in relation to climate dynamics that affected the country from 1987 to 2018. To this end, countrywide remote sensing (Landsat) data were processed for forest boundaries over the 32 years, in order to compute annual (summer season data) Normalized Difference Vegetation Index (NDVI) datasets, which were subsequently investigated as trends using the Mann-Kendall test and Sen's slope estimator. Simultaneously, various climatic data (temperature, precipitation and reference evapotranspiration) were processed through interpolation techniques and via the same two statistical tools, and were subsequently used for exploring the impact of climate change on Romanian forestlands after 1987. The results highlighted general greening (increasing NDVI) trends of forests nationally (65% of all NDVI changes, which total over 30.000 km<sup>2</sup> across Romania), which were dominated by widespread positive NDVI trends detected in the Carpathians region of Romania. This general ecological dynamic suggests a possible enhancement in vegetation productivity in the country's high-altitude areas. Contrasting browning (decreasing NDVI) trends were found for 35% of Romanian forestlands marked by NDVI changes, especially apparent in the Extra-Carpathians (lowland) region, which indicates that in these cases forests were degraded or devitalized. However, the statistical significance of both greening and browning trends is limited across the country. The analysis of climatic trends and of correlations between annual NDVI and climate data indicated that recent warming throughout Carpathians may be an important driving force of forest greening in temperature-limited mountain regions. This finding is supported by an at least moderate intensity of air temperature - NDVI relationships (r correlation coefficient values of ~50%, the highest of all eco-climatic relationships analysed), generally detected throughout mountain environments. At the same time, it seems that evapotranspiration increase accounted at least in part for forest browning in lowland areas, while the impact of precipitation in forest ecological dynamics remains unclear. All these findings can be useful for a better forest management under the future climate change conditions in Romania.

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# 1. Introduction

With a vast presence worldwide and a multidimensional ecological role, the Earth's forests are vital for human society through their ecosystem services (Masiero et al., 2019). Moreover, the importance of forests is projected beyond the benefits they provide to humanity, considering they stabilize the overall functioning of the Earth's systems, by protecting global biodiversity or by regulating the climate system, through carbon sequestration and evaporative cooling processes (Prăvălie, 2018).

However, many forests and their ecosystem services have been intensely disrupted over the past decades, either by climate change, direct anthropogenic pressure or by both these general factors simultaneously (Prăvălie, 2018). Climate change, which has materialized through many pathways across the globe – such as changes in temperature and precipitation (IPCC, 2021), but also in evapotranspiration or in other meteorological/hydrometeorological parameters (Prăvălie et al., 2016a; Rosmann et al., 2016; Zhang et al., 2016; Ostad-Ali-Askar et al., 2018; Liu et al., 2021a; Talebmorad et al., 2021; Zhao et al., 2021) –, has become an important driver for various types of forest changes, like phenological shifts, die-off events or large-scale productivity shifts (Prăvălie, 2018).

Therefore, changes in forest productivity have become a major pathway of climate-induced forest changes, according to many global studies that used the Normalized Difference Vegetation Index (NDVI) and highlighted both greening and browning trends across the planet, through this remote sensing tool that is considered a reliable ecological indicator for vegetation health and productivity (Sobrino and Julien, 2011; Eastman et al., 2013; Liu et al., 2015; Tian et al., 2015; Yang et al., 2019). Thus, NDVI is a widely applied method for estimating vegetation cover and greenness across the world, but also forest and non-forest vegetation productivity dynamics in relation to climate change (Chu et al., 2019; Ols et al., 2019; Zhao et al., 2020; Jiang et al., 2021; Li et al., 2021; Liu et al., 2021b, 2021c; Zhe & Zhang, 2021).

Recent changes in the ecological productivity of forests, as a consequence of climate change, are most likely an environmental reality in Romania as well, considering that this country has recently experienced various forms of climate change, such as certain notable changes in temperature (Ionita et al., 2013; Dumitrescu et al., 2015; Prăvălie et al., 2017), precipitation (Marin et al., 2014; Dumitrescu et al., 2015; Prăvălie et al., 2019) or evapotranspiration (Croitoru et al., 2013; Prăvălie et al., 2019) parameters. Both annually and seasonally (summer, the season of major interest, considering it overlaps, for the most part, with the season of peak biological activity in Romania), the aforementioned studies showed a general warming coupled with an overall increase in evapotranspiration across the country, simultaneously with a partial decrease in precipitation in several areas, like southeastern and southwestern Romania. Considering these parameters are generally known as key climatic drivers for forest (and non-forest) vegetation changes, as well as the fact their dynamics indicate certain important changes in climate conditions over the past decades, it is reasonable to consider a potential climatic impact on the ecological state of the country's forests.

This potential impact becomes all the more credible given the context that climatic changes are also apparent in most of Romania's Carpathian mountainous areas (Cheval et al., 2014; Prăvălie et al., 2019), where the country's forests have the largest spatial footprint. A recent study, which tackled climatic water balance trends (a general picture of climate change), showed that Romania's territory had become overall drier over the past ~50 years (Prăvălie et al., 2019). The results of this national study indicated that Romania recorded (between 1961 and 2013) a general increase of the climatic water deficit both annually and seasonally, when the maximum biological activity of vegetation can be particularly affected in this country. The findings of the aforementioned study, as well as those of numerous other national climate studies (Croitoru et al., 2013; Cheval et al., 2014; Dumitrescu et al., 2015; Sfică

et al., 2017; Cheval et al., 2020; Nita et al., 2020; Micu et al., 2021), indirectly suggest a possibly high reaction of forests (and of other ecosystems) to climate change, although the concrete relationship between climate change and the forests' ecological dynamics was not previously explored nationally in any of the aforementioned studies.

This study aims to fill this knowledge gap regarding potential changes in the ecological state of forests, as a response to the climate change that has recently affected Romania. In line with this goal, the paper is based on the analysis of NDVI data, processed for the past three decades across the entire forested area of Romania. At the same time, this study focuses on the detection of possible relationships between climate change and forestry changes, using some representative statistical tools. Essentially, this is the first national study that aims to explore forest ecological changes in relation to recent climate dynamics, based on the analysis of large-scale NDVI and climate data, collected and processed within Romanian forestland boundaries. By investigating NDVI trends and relating them to national climatic conditions, the resulting data is expected to be highly useful for ensuring a better adaptation of these ecosystems to future climate change, or even for combating the effects of climate change in Romania, which depends on the maintenance of healthy forests at national scale.

#### 2. Data and methods

#### 2.1. Study area

Romania is the largest country in southeastern Europe (almost 240,000 km<sup>2</sup>) (Fig. 1). According to the official definition, Romanian forests comprise all lands that exceed 0.5 ha covered by trees with a minimal height of 5 m upon reaching maturity, and with a canopy cover of over 10% (NFI, 2021). These ecological systems cover extensive areas in Romania, of almost 7 million ha (or almost 70,000 km<sup>2</sup>) or just below 30% of the national territory (NFI, 2021). In terms of distribution per major landforms, they are mostly located in mountainous areas (~60% of the total), as well as in hilly (~34%) and plain (~6%) regions (MEWF, 2019).

In terms of composition, there is a high diversity of forest species. According to the official data (late 2019), beech (*Fagus sylvatica*) is the country's main forest species ( $\sim$ 31% of national forest area), followed by softwood species ( $\sim$ 25%), which are mainly represented by spruce (*Picea abies*, 19%) and fir (*Abies alba*, 4%) (MEWF, 2019). In addition to beech, Romanian forests also feature many other hardwood species ( $\sim$ 21%, with various acacia, hornbeam, ash species etc.), oak species ( $\sim$ 16%, sessile oak, pedunculate oak etc.), and various deciduous softwood species ( $\sim$ 7%, linden, poplar, willow etc.) (MEWF, 2019).

Romanian forests span across various climatic and ecological conditions nationally (Geacu et al., 2018; Dumitrașcu et al., 2020; Kucsicsa et al., 2020). The temperate climate of Romania is highly influenced by the Carpathian mountain range (Fig. 1a) and is characterized by cooler (temperature < 1 °C) and wetter (precipitation > 1300 mm and reference evapotranspiration < 500 mm) conditions in mountainous areas, considering the mean multiannual climatic values from the 1961-2013 period (Prăvălie et al., 2019; 2020a). At the opposite pole, warmer (up to 11-12 °C) and drier (precipitation even as low as 400 mm, and evapotranspiration even higher than 800 mm) characteristics are found in extra-Carpathian regions (the same 1961-2013 period), especially in the country's southeastern parts (Prăvălie et al., 2019; 2020a). All these very briefly presented climatic characteristics, alongside other environmental elements, such as various altimetry levels (ranging from 0 to 2,544 m a.s.l., from the Danube Delta region to the Carpathian mountains) or diverse soil types, shape the territorial distribution of forests nationally.

Ecologically and socio-economically, Romania's forest ecosystems are classified into two functional groups, i.e. forests with special protection functions, and forests with production and protection functions (MEWF, 2017). In the first group, the main functions of forests are the



Fig. 1. Main geographical characteristics of Romania (a), satellite scenes across Romania (for which remote sensing data was downloaded) (b) and the major natural spatial units for which various geostatistics were extracted in this study, namely major geographical regions (c), major ecoregions (d) and major landforms (e). Note: the general land cover and use classes in Romania were collected from the CORINE Land Cover database, 2018 version; abbreviations: agric. – agricultural; con – coniferous.

protection of soils, water and biodiversity, the protection against harmful climatic and industrial factors, social recreation, scientific interest and the protection of forest genetic heritage. The second group of forests focuses on biomass production (but also on environmental protection), for various economic purposes (MEWF, 2017).

Considering the importance of forests in Romania, assessed through the classification into the two functional groups or through the ecosystem services they provide, it is essential to understand the dynamics of their health / productivity state, in relation to the climate change that affected Romania over the past decades. Such knowledge, as previously mentioned, is not yet available, which is why detailed analyses are required in this respect, based on representative ecological and climatic data.

#### 2.2. Data acquisition

The data used in this paper is classified into two categories, satellite data and climatic data. Both datasets cover the period 1987–2018, which was chosen considering its statistical (at least three decades investigated, generally recommended in environmental trend analysis studies), temporal (multiannual interval updated up to 2018) and climatic relevance. For this final aspect, it was considered that climate warming generally intensified after the 1980–1990 decade both globally (Wu et al., 2019) and nationally (Prăvălie et al., 2017; 2020a), and this increase in air temperature could account for some possible recent ecological changes in Romanian forests.

#### 2.2.1. Remote sensing data

The satellite data used for the Romanian territory consisted of multitemporal Landsat imagery, which were downloaded for the 32 years via the Google Earth Engine (GEE) platform (GEE, 2021a), using the tools provided by this international platform. In order to cover the 1987-2018 period, three collections of satellite imagery were used, i.e. LANDSAT 5 TM Surface Reflectance Tier 1 (LANDSAT/LT05/C01/ T1 SR), for the period 1987–2011, LANDSAT 7 ETM + Surface Reflectance Tier 1 (LANDSAT/LE07/C01/T1\_SR), for 2012-2016 (in the context of the LANDSAT 5 satellite mission activity shutdown), and LANDSAT 8 OLI/TIRS (LANDSAT/LC08/C01/T1\_SR), for 2017-2018 (GEE, 2021a). The imagery featured in these satellite data collections represents the reflectance of the Earth's surface (corrected atmospherically and radiometrically) and contains 4 spectral bands in the visible (Red, Green, Blue) and near-infrared (NIR) spectral ranges (Red and NIR were used in this study), 2 bands in short-wave infrared (SWIR) range, and one in the thermal infrared (TIR) range.

All these data were downloaded for the summer season (months of June, July and August) of each year (the season with peak biological activity in Romania), as a multispectral mosaic composed of 22 satellite scenes across Romania (Fig. 1b). Considering the number of multispectral satellite scenes and the 16-day temporal resolution of LANDSAT data, on average, 129 satellite images resulted annually for the summer period. This number varied however in certain cases, as some images were unavailable in the repository due to various sensor-related technical issues or to the unsatisfactory quality of the remote sensing data (Table 1). In total, for the 32 analysed years, 4126 satellite images were used across Romania's entire territory.

# 2.2.2. Climate data

The climatic data consists of gridded, seasonal air temperature (T, in °C), precipitation (P, in mm) and reference evapotranspiration (ETo, in mm), at 1 km  $\times$  1 km spatial resolution, using observational data collected from all weather stations of Meteo Romania (NMA, 2021). The three climatic parameters' data were computed by Meteo Romania 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. While T and P were collected directly from Meteo Romania's observational measurements, ETo values were estimated by Meteo

#### Table 1

Number or satellite	e images	processed	every	year	across	Romania,	based	on
remote sensing data	quality	downloade	d in th	e 198	7-2018	3 period.		

Year	Number of satellite images	Year	Number of satellite images	Year	Number of satellite images
1987	135	1998	126	2009	151
1988	125	1999	149	2010	111
1989	102	2000	116	2011	113
1990	128	2001	100	2012	147
1991	121	2002	137	2013	140
1992	130	2003	103	2014	136
1993	144	2004	109	2015	155
1994	138	2005	92	2016	133
1995	141	2006	118	2017	166
1996	133	2007	143	2018	151
1997	138	2008	95		

Note: number of valid satellite images (which were processed in order to extract final annual satellite data, based on the median value of satellite pixels) for every year nationally, which depended on various technical (errors) or atmospheric (cloud cover) obstacles encountered throughout Romania in the 1987–2018 period.

Romania based on a series of detailed climate data (air temperature, relative humidity, sunshine duration, and wind speed data) using the FAO-56 Penman-Monteith method (Allen et al., 1998), which is the best in ETo computation (Mokhtari et al., 2018; Prăvălie et al., 2020c). T, P and ETo parameters, which are generally known to have a major influence in forest (and non-forest vegetation) productivity dynamics across the world and also in Romania (Liu et al., 2015; Bandoc et al., 2018; Chu et al., 2019; Yang et al., 2019; Meng et al., 2020), were mapped via interpolation methods and subsequently used in the analysis of the relationships between climate and the ecological state of Romanian forests, after 1987.

#### 2.2.3. Other geospatial data

This study also used the CORINE Land Cover (CLC) databases (CLC, 1990-2018), in order to delimit forest areas for which satellite and climatic data was extracted and analysed. Other geospatial data used in this research included boundaries in vector format of various spatial units (major geographical regions, major ecoregions or major landforms), which were used for analysing possible relationships between climatic and ecological conditions.

# 2.3. Data processing

## 2.3.1. LANDSAT and NDVI data computation

The annual remote sensing data was obtained based on the median values for each pixel of all satellite images selected for the summer season, within the same satellite scene. Considering that, in certain situations, the number of valid images in a collection was not sufficient for a high degree of spatial coverage, it was necessary to manually process each year individually in order to choose the most appropriate option. Therefore, in two cases (2002 and 2005), it was necessary to replace the images in collection TM5 with the corresponding ones of TM7, as a result of the fact that, in 2002 and 2005, there was no reliable TM5 satellite data across large areas in Romania (technical errors, extended cloud coverage or other causes).

All remote sensing and NDVI data were obtained by completing five phases. In the first phase (I), Romania's boundary was uploaded onto the GEE platform, which was subsequently used for the selection of satellite scenes and for obtaining the final mosaic. In the second phase (II), the necessary function for applying the cloud-masking to the LANDSAT TM5–TM7–8 OLI/TIRS image collection was created by adapting the template provided by the GEE platform (GEE, 2021b). This function consists of applying two distinct masks – the first removes pixels classified as "clouds" and their shadow in the Spectral Indices Pixel Quality Band, and the second removes fixed-pattern noise from the border of

#### each satellite scene.

Both the boundary and the masking function were used in the third phase (III) – satellite imagery selection and processing. In this phase, the cloud-masking function (in the summer season, 01.06.–31.08., of each year) presented in the previous phase (II) was applied by selecting a filter for a cloud cover degree of 100%. This filter value was chosen in order to select as large a number of satellite images as possible in the chosen timeframe, considering that in the end the median value of each pixel was computed from the annual collections in order to obtain a mosaic for each spectral band. In the fourth phase (IV), each mosaicked spectral band was then exported for each year at a spatial resolution of 30 m in a WGS84 projection, and subsequently reprojected into Pulkovo 1942 (58)/Stereo70 (EPSG: 3844), representative for Romania's territory.

In the final phase (V), the NDVI was computed (annually, 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) (Rouse et al., 1974). The computation was performed using R 4.0.3 (R Core Team, 2020) and the RStoolbox package (v0.2.6) (Leutner et al., 2019). Spectral and technical characteristics of TM and ETM +sensors are identical - the red band (band 3 in both sensors) has the wavelength 0.63-0.69 nm, while the near-infrared band (band 4 in both sensors) is 0.77-0.90 nm (USGS, 2012; 2014). The OLI sensor has a slightly different bandwidth: 0.64-0.67 nm in the red band (band 4), and 0.85-0.88 in the near infra-red one (band 5). Moreover, the way of rescaling radiance to digital number (DN) varies between 8-bit (TM/ ETM+) and 12-bit (OLI) unsigned integers (Huang et al., 2021). As the OLI's near infra-red band is much narrower than the TM/ETM+'s one, the NDVI values computed using OLI are higher, by 0.0164 on average (Roy et al., 2016). This difference is less significant than the relative impact of the atmosphere on the NDVI values obtained from the ETM +sensor (Roy et al., 2014; 2016). If the 0.0164 correction is applied to ETM + -derived NDVI, this would result in an overestimation of about 2% of vegetated ground cover (Thieme et al., 2020). Taking into consideration the construction of the model used, which uses median pixel values instead of real ones, the reported difference in NDVI values is comparable to the noise in the data used.

NDVI was used in this study as it is a reliable ecological indicator. Due to its spectral characteristics, as well as to its rather long history, NDVI has become the most commonly used tool for assessing forest and non-forest vegetation worldwide (Adole et al., 2016; Huang et al., 2021; Soubry et al., 2021). While this satellite index may feature some technical disadvantages (shortcomings), which include the saturation phenomenon or certain sensor issues and which were discussed in depth in a recent study (Huang et al., 2021), NDVI was used in this study due to the higher number of technical and practical advantages it delivers. NDVI's strengths include the low number of constituting spectral bands (only NIR and Red, as previously mentioned), easy availability of long-term spectral databases required for its calculation, simplicity in its computation method, its overall reliability in the analysis of vegetation density and productivity, or its maturity resulting from its extensive use (historical and current) in the forestry or non-forestry fields (Huang et al., 2021; Soubry et al., 2021). Even in the last years of ever increasing use of unmanned aerial systems with high spatial resolution data products, the NDVI, derived from thoroughly calibrated satellite-borne sensors, remains a useful, up-to-date and precise tool in the assessment of the extent, density, productivity and health of vegetation (Huang et al., 2021).

# 2.3.2. Climatic data interpolation

Similarly to satellite data, the study required climatic data mapped (via interpolation) in order to detect the forests' response to the dynamics of climatic conditions. T, P and ETo summer values were spatialized every year and provided by Meteo Romania (NMA, 2021), using the Regression-Kriging (RK) interpolation method. This method was finally deemed the fittest, using the cross-validation procedure and several error indicators, after testing the reliability of several climate data interpolation methods (Dumitrescu et al., 2017). RK is a multivariate method that includes one or more variables with a spatially continuous distribution in computations (Hengl et al., 2007). It results from summing the surface determined through the least squares method (applied to multiple regression) and the surface obtained through the spatial interpolation of regression residuals, by means of the Kriging method (Dumitrescu et al., 2016; 2017; 2020).

With this method, the first step consists of statistically validating the deterministic model, in the sense of verifying the intensity of the relationships between predictors and dependent variables (T, P and ETo). The best regression model could be determined by applying the stepwise regression method. In the case of the RK method, the matrix of the multiple regression grid points represents the large-scale variability of the analysed parameter modelled by explanatory variables. In order to tackle the collinearity effect, various predictors (altitude, mean altitude in a 20-km radius, latitude, distance from the Black Sea, distance to the Adriatic Sea and mean monthly multiannual climatic values) were filtered by means of principal component analysis (PCA). The predictors were derived from the Digital Elevation Model (2013 version) cropped for Romania (for the first five predictors) (EEA, 2014) or purchased from Meteo Romania (for the last predictor, with mean climate data recorded over a long period of approximately five decades) (NMA, 2021). The filtering of predictors through PCA was performed by Meteo Romania, by transforming the initial variables into a new set of variables, uncorrelated and of a smaller size. Hence, the newly obtained dataset contains most of the original dataset variability.

Once the T, P and ETo data were interpolated and provided by Meteo Romania (as previously mentioned), climatic water balance (CWB, in mm) values were obtained across Romania based on the difference between precipitation and reference evapotranspiration (CWB = P-ETo). Thus, in addition to the three climatic parameters, the CWB was used in this study as a synthetic picture of climatic changes with potential recent effects in the Romanian forests' ecological state. The CWB values are therefore relevant in climate or interdisciplinary approaches, and were already used in Romania in several studies that analyzed the importance and recent dynamics of the CWB across the country (Prăvălie and Bandoc, 2015; Mihăilă et al., 2017; Prăvălie et al., 2016b; 2020c; 2019).

# 2.3.3. Forest boundaries delimitation

While NDVI and climatic data were initially obtained for Romania's entire territory, they were subsequently cropped based on national forest boundaries, in order to detect statistical eco-climatic trends and relationships strictly across Romanian forests. Forest boundary delimitation was performed using CLC classes 311, 312 and 313 (broad-leaved, coniferous and mixed forests), which were extracted from five CLC databases (1990, 2000, 2006, 2012 and 2018) and intersected in Romania, in order to detect common forest areas that can be considered constant, stable and unaffected/slightly affected by anthropogenic activities (e.g. via historic deforestation). The entire procedure for extracting and intersecting CLC data, available as vector layers for the five reference years, was conducted using the ArcGIS software (ESRI, 2020). Thus, the possible changes in forest productivity can be mainly attributed to climate change instead of direct anthropogenic interferences, which were eliminated, in principle, by considering permanent forest areas over the past three decades.

#### 2.3.4. NDVI and climate trends assessment

Once the annual (summer season) raster series of NDVI and climate (T, P, ETo and CWB) data were obtained, the non-parametric Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) and *Sen's slope* estimator (Sen, 1968; Gilbert, 1987) were used to investigate the eco-climatic trends within the forest boundaries of Romania, set based on the aforementioned CLC data. The eco-climatic trends were explored at pixel level in terms of their direction (positive or negative), magnitude (the change per year) and statistical significance (according to the two-

tailed test) (Salmi et al., 2002). In the final case, the significance level  $\alpha = 0.1$  or 90% was considered (the p-value threshold  $\leq 0.1$ , which includes strong significant trends, with p-values < 0.05, and trends with a lower statistical significance, with p-values that range from 0.05 to 0.1), similarly to many other studies that analysed eco-climatic trends using the same significance level (Huang et al., 2013; Mamara et al., 2016; Prăvălie et al., 2019; Chen et al., 2019; Berner et al., 2020). The MK and *Sen's slope* methods, which were applied using the R geostatistical software (Evans, 2020), were used in order to identify the overall eco-climatic dynamics over the past decades, as well as possible spatial and temporal relationships between ecological and climatic data, by empirically assessing the actual trends that were detected (e.g. by identifying spatial patterns with NDVI decreases and P negative trends, or with NDVI decreases and ETo positive trends).

#### 2.3.5. Eco-climatic statistical analysis

In addition to empirically assessing eco-climatic relationships, based on the analysis of the aforementioned trends, this study investigated concrete relationships between NDVI and climate (T, P, ETo and CWB) data, by statistically correlating the two datasets. In this respect, average values of NDVI and climate raster data were computed for the three spatial units (major geographical regions, major ecoregions and major landforms, which were considered natural homogeneous/relatively homogeneous units where the climate impact on NDVI can be detected) and for each year from 1987 to 2018, using the "zonal statistics as table" module from ArcGIS software and model builder capabilities (ESRI, 2020). The averaged values were exported in Excel (MOE, 2020) and the temporal relationships between NDVI and climatic data were subsequently investigated by means of basic statistical correlation indices, such as the adjusted coefficient of determination ( $R^2$ ) and the Pearson linear correlation coefficient (r). The statistical significance of ecoclimatic correlations was assessed by p-value thresholds – high significance was assigned to p-values < 0.05, low significance to correlations with p-values between 0.05 and 0.1, while p-values higher than 0.1 were considered not significant. P-values were computed with the F test tool of the Excel software (F,DIST.RT tool).

# 3. Results

#### 3.1. NDVI changes during 1987-2018

Based on annual NDVI raster data, computed according to the aforementioned methodology, the spatial and temporal dynamics of NDVI changes in Romania were investigated, after 1987. A quick (empirical) analysis of these changes, based on the arithmetic mean of NDVI values in two equal periods (16 years each) of the analysed interval (1987–2002 and 2003–2018), highlighted a first simple proof of changes in vegetation density in Romania over recent decades (Fig. 2).

Upon a visual comparative analysis of the two NDVI mean values (Fig. 2a & b), a greening of Romanian forestlands can be noticed,



**Fig. 2.** Mean NDVI values (summer season data) in Romania during 1987–2002 (a), 2003–2018 (b) and unclassified (c) and classified (d) differences of mean NDVI values between the two periods. Note: D - Decreases; I - Increases; light gray areas are non-forestlands; positive values in bottom left map (c) are higher NDVI values in the 2003–2018 period, compared to 1987–2002, and the opposite applies to negative values; the green class in bottom right map (d) features higher NDVI values in the 2003–2018 period, compared to 1987–2002 period, and the opposite applies to the red class; Romania's forest area (colored areas) is visually exaggerated in these maps, as a result of the NDVI pixel size of ~ 1 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

highlighted by predominantly slightly higher NDVI values in 2003–2018, compared to the previous interval. This overall positive change of NDVI can be noticed especially by computing the mathematical difference between pixels, which showed punctual increases in vegetation density of up to over 0.8 units, in the country's mountainous area (Fig. 2c). Grouping NDVI differences into two general classes, one for decreases (negative differences, with pixel values < 0) and the other for increases (positive differences, > 0), indicated an overall increase in vegetation density in Romania, in the recent period (Fig. 2d).

The use of the Sen's slope and MK statistical tools (Fig. 3) confirmed,

indeed, an overall greening across Romania (Fig. 3a), but with significant regional differences, which for the most part remained undetected in the previous empirical analysis. Classifying *Sen's slope* values in decreasing (negative), increasing (positive) and null (stationary) trends revealed that approximately half of Romania's forest area was affected by changes (decreasing and increasing, including statistically significant ones) in vegetation quality, while the other half remained unchanged / relatively unchanged (uncertain trends highlighted in dark gray) (Fig. 3b). Quantitatively, of the total NDVI changes (which account for > 30.000 km<sup>2</sup> in absolute values) detected across the country's forests,



**Fig. 3.** General (a) and classified (b) annual NDVI 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: light gray areas (a, b) are non-forestlands, while dark gray areas (b) are forests with null changes (NDVI slope values framed in the -0.0001... + 0.0001 range); general and classified trends (colored areas) are expressed as changes in NDVI per year; Decreasing – negative NDVI trends (slope values < -0.0001), detected by applying *Sen's slope* estimator to temporal satellite data (32 years); Increasing – positive NDVI trends (slope values < -0.0001 and with p-values  $\leq 0.1$ ), detected by applying *Sen's slope* estimator and MK test to temporal satellite data (32 years); Sig. Increasing – statistically significant increasing trends (NDVI slope values > 0.0001 and with p-values  $\leq 0.1$ ), detected by applying *Sen's slope* estimator and MK test to temporal satellite data (32 years); Sig. Increasing – statistically significant increasing trends (NDVI slope values > 0.0001 and with p-values  $\geq 0.0001$  and with p-values  $\geq 0.0001$  and with p-values  $\leq 0.1$ ), detected by applying *Sen's slope* estimator and MK test to temporal satellite data (32 years); Sig. Increasing – statistically significant increasing trends (NDVI slope values > 0.0001 and with p-values  $\leq 0.1$ ), detected by applying *Sen's slope* estimator and MK test to temporal satellite data (32 years); all statistically significant trends include strong significant trends (p-values < 0.05) and trends with a lower statistical significance (p-values between 0.05 and 0.1); Romania's forest area is visually exaggerated, as a result of the NDVI pixel size of  $\sim 1$  km, set for an empirical comparative analysis between the NDVI change pattern and that of the climate (with a similar resolution,  $\sim 1$  km) in Fig. 5.

~65% experienced vegetation enhancement (increases in density), while the remaining ~35% experienced degradation of the state of vegetation, through decreases in vegetation quality / density (Fig. 3c). However, it must be noted that the two general types of trends, which will be further analyzed in-depth, have limited statistical significance across Romania's territory (Fig. 3c).

The detailed analysis of current NDVI trends, even insignificant in most parts of the country at a 90% confidence level, is useful because it can indicate the triggering, direction and persistence of forest ecological changes, which could accelerate in the coming years and may therefore become statistically significant on a large scale throughout the country. Therefore, it was found that Romania was recently affected by a mixture of NDVI changes, but in which positive trends are dominant nationally (Fig. 3). These dominant greening trends, which were detected by removing pixels with very low change magnitude (null class, with stationary trends or trends very close to stationarity), suggest a possible overall enhancement in vegetation growth and productivity in Romania, even though the trends' statistical significance is low nationally. However, regional observations on NDVI trends indicate a heterogeneous picture, marked by widespread vegetation greening and browning that occurred across the country (Figs. 3 & 4).

Regionally, the results obtained by extracting percentage-based statistics for three natural spatial units (the spatial boundaries of which are featured in Fig. 1c-e) reveal that, in terms of major geographical regions, the Carpathians region accounts by far for the most extensive greening trends (~35%) of the total national NDVI changes (Fig. 4a). While an overall greening can also be noticed in the Extra-Carpathians region (Fig. 4a), this dynamic is relative, considering that most positive NDVI trends are found in the Subcarpathians and Getic Plateau – landforms that are far less extensive compared to the



**Fig. 4.** Percentage-based areas of NDVI changes (trends) during 1987–2018, at the level of major geographical regions (a), major ecoregions (b) and major landforms (c) of Romania. Note: con – coniferous; the three spatial units are shown in Fig. 1; the statistics of the four types of trends (Decreasing, Increasing, Sig. Decreasing, Sig. increasing) were extracted from Fig. 3b; Decreasing – percentage-based area of negative NDVI trends (slope values < -0.0001), obtained by relating the absolute area of decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends to the total area of forest changes (Decreasing trends (NDVI slope values < -0.0001), obtained by relating the absolute area of sig. decreasing trends to the total area of decreasing trends in Romania; Sig. increasing – percentage-based area of statistically significant positive trends (NDVI slope values > 0.0001 and with p-values  $\leq$  0.1), obtained by relating the absolute area of sig. increasing trends to the total area of increasing trends in Romania; Sig. increasing trends to the total area of increasing trends in Romania; all statistically significant trends include strong significant trends (p-values < 0.05) and trends with a lower statistical significance (p-values between 0.05 and 0.1).

Romanian Plain, which is part of the Extra-Carpathians region (Fig. 1c & e) and which features large scale decreasing trends in NDVI (Fig. 3b). The Intra-Carpathians region recorded some changes (17% of the national total), balanced in terms of the spatial footprint of the two types of trends (9% positive trends vs 8% negative trends) (Fig. 4a).

The assessment of percentage-based data for major ecoregions showed that Carpathian montane coniferous forests accounted by far for the greatest changes in vegetation density in Romania ( $\sim$ 42% of the

total), mostly consisting of greening trends (~28%) (Fig. 4b). Some important ecological changes also occurred in Pannonian mixed forests (where NDVI changes accounted for 27% – of which 17% greening and <10% browning – of all national vegetation dynamics), followed by Balkan mixed forests and Central European mixed forests (Fig. 4b). Overall, Romania's ecoregions were dominated by increasing NDVI trends, except for forests located in ecological units in the Extra-Carpathians region (East European forest steppe and Pontic steppe),



**Fig. 5.** General (a–d) and classified (e–h) annual trends (in the summer season) for temperature, precipitation, reference evapotranspiration and climatic water balance (precipitation minus reference evapotranspiration) in Romania during 1987–2018. Note: light gray areas are non-forestlands, while colored areas are climatic trends processed at the level of Romania's forest boundaries; Decreasing – negative trends of climatic data (slope values < -0.0001), detected by applying the *Sen's slope* estimator; Increasing – positive trends of climatic data (slope values > 0.0001), detected by applying the *Sen's slope* estimator; Sig. Decreasing – statistically significant decreasing trends of climatic data (slope values < -0.0001 and with p-values  $\leq$  0.1), detected by applying the *Sen's slope* and MK statistical tools; Sig. Increasing – statistically significant increasing trends of climatic data (slope values > 0.0001 and with p-values  $\leq$  0.1), detected by applying the *Sen's slope* and MK statistical tools; null changes (slope values framed in the -0.0001... + 0.0001 range) were not displayed on classified maps, as they are almost nonexistent; all statistically significant trends include strong significant trends (p-values < 0.05) and trends with a lower statistical significance (p-values between 0.05 and 0.1); these climatic trends were mapped only in order to ensure an empirical visual correlation with NDVI trends in Fig. 3, as Tables 2 and 3 were used for detecting concrete relationships between climate and NDVI data.

with more vegetation degradation areas (Fig. 4b).

In the case of Romania's 16 landform units (Fig. 1e), NDVI dynamics are even more diverse (Fig. 4c), although even in this instance certain patterns can be identified in forest vegetation changes. All landform units overlapping Carpathian territories (Eastern, Curvature, Southern, Banatului and Western Carpathians) are characterized by a positive net balance of greening NDVI trends (increasing trends more widespread than decreasing trends), which is most pronounced in the Southern Carpathians (largest difference between enhancement and degradation NDVI trends), and lowest in the Eastern Carpathians (large scale increasing trends of NDVI, alongside widespread decreasing changes) (Fig. 4c). In contrast, large relief units in the Extra-Carpathians area (Moldavian Plateau, Romanian Plain, Dobrogea Plateau) were exposed to certain dominant degradation (maximal as spatial footprint in the Romanian Plain and Moldavian Plateau, with  $\sim 4\%$  of the total NDVI changes each) or balanced mixed (Danube Delta) trends, except for the Getic Plateau, Subcarpathians and Mehedinti Hills, with generally greening changes (Fig. 4c). Forests in landforms located in the Intra-Carpathians region experienced a slight ecological improvement (Crisanei and Banatului Hills, with dominant NDVI increases, of up to 2% of the total), balanced changes (Western Plain, with equal opposing trends) or a general decline in vegetation density (Transylvanian Plateau, almost 6% browning trends vs  $\sim$  4% greening trends) (Fig. 4c).

#### 3.2. Climatic changes during 1987-2018

By using the same geostatistical methods (*Sen's slope* estimator and MK test) for analysing climatic variable trends, considered potentially relevant driving factors of NDVI dynamics, important climatic changes were highlighted throughout Romanian forestlands, during the summer season (Fig. 5). In terms of temperatures, an exclusive warming was found (statistically significant across 99% of Romanian forestlands), with a higher intensity throughout the Carpathians (Fig. 5a & e). More specifically, peak T increases of up to 0.08 °C/yr were detected, which correspond to a maximum total warming of over 2.5 °C in the 32 years (Fig. 5a).

Precipitation dynamics were far more heterogeneous compared to T, characterized by wetter conditions in mountainous (with increases in P that even exceeded 6 mm/yr) and some hilly and plain regions, and drier conditions (decreases in P) in some parts of the Intra- and Extra-Carpathian regions (Fig. 5b & f). As expected, evapotranspiration intensified over recent decades across almost the entire Romanian territory, largely influenced by the exclusively positive trends of T (considering that ETo values were estimated based on T and other climatic parameters) (Fig. 5c & g). In this case, peak increases of ETo were found in the country's eastern and southeastern regions (of up to  $\sim 2.7$  mm/yr, i.e. a total increase in evapotranspiration exceeding 85 mm over the entire period 1987–2018), which are generally reliable in terms of statistical significance (Fig. 5c & g).

The analysis of the climatic water balance (difference between P and ETo) revealed predominantly positive trends (with more pronounced statistical significance especially in mountain areas) throughout Romanian forestlands, which indicates a CWB dynamics towards the excedent direction (which in some cases even exceeded 8 mm/yr) (Fig. 5d & h). This overall dynamics highlighted that most of the country became wetter, although the statistical significance of CWB trends is relatively limited nationally (Fig. 5h). While all these diverse and generally pronounced trends indirectly suggest that climate change could account for the forest vegetation dynamics detected through NDVI changes, the ecological response to climate dynamics must be investigated in a concrete manner using the appropriate statistical methods.

# 3.3. Statistical relationships between NDVI and climate dynamics

Following the correlation of the annual climatic (T, P, ETo and CWB) and ecological (NDVI) datasets for the three spatial units, as per the

methodological phases featured in section 2.3.5, certain interesting relationships were detected between climate and forests during 1987–2018, which were briefly assessed via the coefficient of determination ( $R^2$ ) and the Pearson correlation coefficient (r). With regard to the temperature – NDVI relationship, peak  $R^2$  values of 0.22 were obtained in the Carpathians region, 0.24 in Carpathian montane coniferous forests, and 0.26 in Eastern Carpathians, which means that up to 22%, 24% and 26% of NDVI value dynamics can be explained by changes in T in the three selected hotspots of the three natural unit categories (Table 2). While these  $R^2$  values seem relatively low, their statistical significance is high, not only in these particular cases, but also in other cases with spatial units generally located in mountainous areas (Table 2).

Also, given the computed *r* values (of ~ 0.5 and above this threshold) in the three exemplified cases, an at least moderate intensity (of ~ 50%, expressed as percentage) of eco-climatic relationships was found in high-altitude areas, as was the fact that NDVI is significantly positively correlated with T in the highlighted mountain regions and in the other units found within Carpathian boundaries. 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 correlation between forest vegetation density variability and that of P, due to the very low  $R^2$  and r values and the overall lack of statistical significance of correlations (Table 2). In contrast, evapotranspiration seems to play a more / far more important role in the ecological dynamics of forests, mainly in the spatial units in the Extra-Carpathians region. In this case, the findings pointed out 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), where  $R^2$  values ranged between 0.12 and 0.18, while *r* coefficient values ranged from -0.39 to -0.46 (Table 3). Moreover, the exclusively negative r coefficient values indicate a significant negative correlation between Eto and NDVI (Table 3), which suggests that the intensification of the evapotranspiration regime over recent decades has generated a negative effect on the density and health of forest vegetation, especially in the mentioned lowland and hilly areas.

The analysis of the final relationship, between climatic water balance and NDVI, highlights a largely statistically significant impact of the combined effects of P and Eto on the country's forest ecological changes. According to the results, it appears this indicator's footprint is larger on NDVI dynamics, compared to the individual influence of P and Eto (Tables 2 & 3). Although the statistical information provided by the two coefficients in this particular case indicated a positive impact of the CWB in the greening trends of NDVI, in all analysed cases, there still are many cases with relatively low  $R^2$  and r values and with low statistical significance across the country.

# 4. Discussion

This study's results on the overall changes of NDVI in Romania, dominated by positive trends (Figs. 2–4), confirm the overall pattern of ecological changes of vegetation in southeastern Europe. Similar wide-spread greening trends were reported in various studies conducted globally and continentally, which focused on detecting NDVI trends after 1980 and which highlighted generally increasing trends across the European continent, including in eastern and southeastern Europe (Piao et al., 2011; Liu et al., 2015; Guo et al., 2018; Yang et al., 2019; Ding et al., 2020). However, even though this study is consistent with the general picture of NDVI positive trends, which marked this continental region over recent decades, the results highlight a more detailed pattern of NDVI changes across Romania, considering the much higher spatial resolution of the NDVI data used (compared to most previous studies, which used coarse global data), but also the detailed regional results extracted for the first time in this paper.

#### Table 2

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 <sup>2</sup> adjusted	r	p-value	Significance <sup>a</sup>	R <sup>2</sup> adjusted	r	p-value	Significance <sup>a</sup>
1	Romania	0.179	0.453	0.009	high	0.041	0.268	0.138	not significant
2	Carpathians region	0.220	0.495	0.004	high	0.030	0.248	0.171	not significant
3	Intra-Carpathians region	0.175	0.449	0.010	high	0.002	0.186	0.309	not significant
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 significant
6	Central European mixed forests	0.062	0.304	0.091	low	0.041	0.269	0.137	not significant
7	East European forest steppe	0.000	0.119	0.516	not significant	0.060	0.301	0.095	low
8	Balkan mixed forests	0.015	0.216	0.236	not significant	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 significant
10	Pontic steppe	0.034	0.256	0.157	not significant	0.182	0.457	0.009	high
11	Eastern Carpathians	0.261	0.533	0.002	high	0.023	0.233	0.199	not significant
12	Curvature Carpathians	0.151	0.423	0.016	high	0.004	0.191	0.296	not significant
13	Southern Carpathians	0.195	0.470	0.007	high	0.049	0.282	0.118	not significant
14	Banatului Carpathians	0.098	0.356	0.045	high	0.007	0.160	0.382	not significant
15	Western Carpathians	0.164	0.437	0.012	high	0.003	0.171	0.350	not significant
16	Transylvanian Plateau	0.231	0.506	0.003	high	0.007	0.199	0.276	not significant
17	Crisanei Hills	0.100	0.359	0.044	high	0.002	0.185	0.311	not significant
18	Banatului Hills	0.043	0.271	0.133	not significant	0.016	0.129	0.481	not significant
19	Subcarpathians	0.083	0.336	0.060	low	0.048	0.281	0.120	not significant
20	Mehedinti Hills	0.103	0.363	0.041	high	0.020	0.228	0.210	not significant
21	Getic Plateau	0.022	0.232	0.201	not significant	0.079	0.330	0.065	low
22	Moldavian Plateau	0.018	0.223	0.220	not significant	0.019	0.117	0.524	not significant
23	Western Plain	0.030	0.248	0.171	not significant	0.078	0.328	0.067	low
24	Romanian Plain	0.015	0.215	0.236	not significant	0.151	0.422	0.016	high
25	Dobrogea Plateau	0.002	0.184	0.313	not significant	0.203	0.478	0.006	high
26	Danube Delta	0.115	0.379	0.033	high	0.008	0.200	0.272	not significant

Note: con. – coniferous; a – statistical significance is considered high for p-values < 0.05, and low for p-values between 0.05 and 0.1; the temperature / precipitation and NDVI data used for this regression analysis were extracted each year (during the 1987–2018 period) strictly at the level of the forest limits, framed within the boundaries of the four categories of spatial units: entire Romania (Fig. 1a), major geographical regions (Fig. 1c), major ecoregions (Fig. 1d) and major landforms (Fig. 1e); the extracted annual data were obtained by averaging the pixel values of the climatic (temperature / precipitation) and NDVI data, framed within the boundaries of the four investigated spatial units.

#### Table 3

Statistical correlations between the 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 <sup>2</sup> adjusted	r	p-value	Significance <sup>a</sup>	R <sup>2</sup> adjusted	r	p-value	Significance <sup>a</sup>
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 significant
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 significant	0.038	0.263	0.147	not significant
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 significant	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: con. – coniferous; a – statistical significance is considered high for p-values < 0.05, and low for p-values between 0.05 and 0.1; the reference evapotranspiration / climatic water balance and NDVI data used for this regression analysis were extracted each year (during the 1987–2018 period) strictly at the level of the forest limits, framed within the boundaries of the four categories of spatial units: entire Romania (Fig. 1a), major geographical regions (Fig. 1c), major ecoregions (Fig. 1d) and major landforms (Fig. 1e); the extracted annual data were obtained by averaging the pixel values of the climatic (reference evapotranspiration/climatic water balance) and NDVI data, framed within the boundaries of the four investigated spatial units.

Moreover, the results of this paper indicated certain relationships (generally moderate) between NDVI trends and climate change, the overall impact of which appears to have been beneficial to the health and productivity of forests in Romania. While numerous environmental components were affected negatively countrywide by climate change (at least in the summer season), like agricultural (e.g. maize crops) (Prăvălie et al., 2020c) or hydrological (e.g. streamflow) (Birsan et al., 2014) systems, it is surprising that the overall (countrywide) climate effect on forest ecosystems was positive over recent decades, considering the positive statistical correlations between T, P, CWB and NDVI, which are generally statistically significant (except for P - NDVI, marked by uncertainty) (Tables 2 & 3). Also, the results on climatic trends confirm an overall increase in atmospheric humidity in Romania (predominantly positive trends of P and CWB), which synced with climate warming across Romania's entire territory (positive T trends) (Fig. 5). In this respect, it seems that climate warming played the most important role (out of the analysed climatic variables) in the overall greening of forest vegetation in Romania.

The increase in T across 100% of Romania's territory (Fig. 5a & e) and the more pronounced correlations countrywide between T and NDVI (higher  $R^2$  and r values compared to the other positive correlations P – NDVI and CWB – NDVI, across the entire Romanian territory) (Tables 2 & 3) indicate that the predominantly positive NDVI trends are generally better explained by the dynamics of this climatic parameter. This finding is, at least indirectly, consistent with certain studies that confirmed temperature's important role in vegetation productivity in temperate European regions, for instance through the lengthening of the vegetation growing season and by increasing phenological activity (Jeong et al., 2011; Chen et al., 2018). In Romania, it appears that the intensification of forest vegetation productivity constitutes a response to warmer conditions, especially in mountain regions, which are, ecologically, more limited by temperature than the Extra- and Intra-Carpathian areas (Mihai et al., 2018; 2020; Micu et al., 2021). The most pronounced climate warming in mountain regions (Fig. 5a), corroborated with the strongest positive (statistically significant) correlations T - NDVI in the Carpathians sector (of the major geographical regions category), Carpathian montane coniferous forests (major ecoregions) or Eastern Carpathians (major landforms) (Table 2), indicate that climate warming played a more important role in the increase of forest density in Romania's mountainous area.

In contrast, forests in Romania's lowland and hilly areas (mostly present in the Extra-Carpathians region) were affected rather negatively by climate warming, which indicates a differentiated climatic impact on regional / local scales, according to the detailed results featured in the previous section. The arguments of climatic pressure in the Extra-Carpathian areas (e.g. in the Romanian Plain, Moldavian Plateau or Dobrogea Plateau) are linked to negative NDVI trends (predominant compared to positive trends) (Fig. 3b) and to the notable negative impact of Eto (negative and generally significant correlations between Eto and NDVI) (Table 3), a parameter that is for the most part influenced by thermal conditions. In the latter case, an overall degradation of Extra-Carpathian forests can be brought into discussion, amid the stronger influence of the overall increase in evapotranspiration (Table 3, Fig. 5c, g) and partial decreases in CWB values (which indicates an amplification of the humidity deficit as a result of Eto increases) in certain parts in eastern and southeastern Romania (Fig. 5d,h).

Forest degradation in many areas in the Extra-Carpathians region can be interpreted as a devitalization / withering / mortality of forests. These processes were reported (but not investigated statistically via NDVI and climate trends, or through the relationships between the two types of data) in a more general context in several reports and scientific studies conducted nationally (MEWF, 2012, 2014, 2017a; Sidor et al., 2019; Ciceu et al., 2020). Some concrete studies clearly confirm that oak (*Quercus*) species, distributed most extensively in the Extra-Carpathians region, are the most vulnerable to climate change (Ciceu et al., 2020), which is indirectly confirmed by the regional findings on NDVI trends. Moreover, observations on certain decreases in NDVI in the Intra-Carpathians region (Transylvanian Plateau) (Fig. 3b) reinforce, at least partially, some previous findings regarding the climatic impact on certain forest species in this central region of the country (Sidor et al., 2019).

The symptoms of climate change impact in the Extra-Carpathians lands can consist of several main pathways of forest disturbances, which are noted both in the aforementioned national sources (MEWF, 2012, 2014, 2017a; Sidor et al., 2019), and in international literature (Allen et al., 2010; Anderegg et al., 2013; Bennett et al., 2015; Seidl et al., 2017). They are temperature-driven increase in evapotranspiration and in climatic water deficit, intensifying droughts, partial / total stomatal closure (for reducing tree transpiration under drought and heat conditions), reduction of stomatal conductance, decrease in carbon dioxide and water exchange between forests and atmosphere (due to stomatal closure) and, finally, forest dieback and tree mortality. Moreover, these ecological degradative processes can result in the physiological weakening of trees, which has already generated, in some cases, favourable conditions for the development of insect infestations (especially defoliating insects) and the accentuation of the declining state of forest health and productivity (MEWF, 2012, 2014, 2017a).

It must be mentioned however that detecting browning trends in forest areas marked by NDVI decreases does not necessarily imply that all the ecological disturbances mentioned above occurred simultaneously across Romanian forests. In fact, the negative regional NDVI trends rather indicate the dominance of some particular disturbances, like devitalization (dehydration) or degradation of the forests' photosynthetic activity (due to changes in stomatal conductance), as forest dieback and severe tree mortality are generally limited across the country. For instance, it is estimated that withering and mortality affect certain forest species in Romania generally up to about 10% (of their total presence nationally) during intense drought and heat conditions, and relevant examples in this respect include the fir (Abies alba) (MEWF, 2015, 2017a; Mihai et al., 2021) or the Scots pine (Pinus sylvestris) (Sidor et al., 2019). Additionally, the degradation (or improvement) of forest ecosystems must be interpreted with caution, also considering the limited statistical significance of negative (and positive) NDVI trends around the country.

In addition to the results that indicate changes in the density, health and productivity of vegetation in Romania, as a moderate response to recent climate change, the methodology used in this study itself highlights a climatic impact on the identified changes in forests. Since direct anthropogenic influences (via deforestation / logging activities) were removed for the most part (by delimiting stable forest areas based on CLC 1990-2018 data, according to the methodological information featured in section 2.3.3), any changes in NDVI can be explained, in principle, by the dynamics of climatic variables. However, one must note the importance of other environmental factors (climatic or nonclimatic) that can be responsible for changes detected in forest density, but which were not analysed in this respect in the present study.

In theory, they can be linked, for instance, to changes in pedological conditions or to effects of atmospheric pollution (e.g. acid rain). While pedological conditions may play a secondary role, considering the general static (constant) nature of soil (Prăvălie et al., 2020a), the overall decrease in  $SO_2$  and  $NO_x$  emissions (causes of acid rain) in Romania after 1990 (Năstase et al., 2018), amid the massive deindustrialization process the country underwent after the fall of the communist regime in late 1989, may have notable effects on the improvement of the ecological quality of forests in recent decades. Moreover, another example may be linked to the overall increase of atmospheric CO<sub>2</sub> fertilization, which is likely to drive a considerable growth in vegetation productivity not only in Romania, but in many other parts of the world as well (Zhu et al., 2016). All these aforementioned factors and possibly others essentially explain the moderate intensity of eco-climatic relationships in Romania, which generally do not exceed 50% (r values) across Romanian forestlands.

While moderate eco-climatic relationships were detected in recent decades, the impact of climate change on forests is expected to intensify in Romania in the coming years, considering several global studies that confirm that, under future warming, temperate forests will face important disturbances linked to certain phenological changes (which will slow down the photosynthetic activity of forests) (Fu et al., 2015) or to the intensification of drier conditions (which may amplify fires and insect activity) (Seidl et al., 2017). In Romania, in the lowland and hilly areas (Extra- and Intra-Carpathian regions), the decrease in forest density, productivity and diversity may accelerate after 2040, due to increasing temperatures (and implicitly increasing evapotranspiration) and decreasing (at least in part) precipitation amounts (MECC, 2013). The effects of these climatic trends will be exacerbated by the intensification of land degradation and desertification conditions, which already affect extensive areas in southern, southeastern and eastern Romania (Prăvălie et al., 2020a; b). All these environmental transformations will force forests to migrate altitudinally on phyto-climatic layers, from lowland and hilly areas towards alpine sectors (MECC, 2013).

In Carpathian areas, forests will not be spared by environmental stressors, such as wind disturbances (and associated windthrows) that are expected to increase across Romania and Europe, due to climate change (Forzieri et al., 2020). It is possible that even air temperature will reverse the beneficial role it plays for mountain forests, if climate warming intensifies considerably across the Carpathians by the end of the century. Considering that Romanian forests will not only be affected by the intensification of climate change, but also by other possible associated causes such as insect infestations or fires, the overall climatic impact over the course of this century will most likely not only be more intense nationally, but also negative throughout the entire country.

#### 5. Conclusions

The analyses on the detailed dynamics of NDVI and of its relationship with climatic factors, conducted for the first time on the entire forested area of Romania, highlighted diverse ecological and climatic changes across the country's forestland boundaries, over approximately the past three decades. Essentially, an overall greening of Romania's forests was observed, due to large scale increasing NDVI trends detected in the Carpathians region. Regionally, in contrast with mountain regions, it was found that extensive forest areas in the Intra- and especially the Extra-Carpathians regions were affected by decreasing NDVI trends, which suggests that in many cases forest vegetation was degraded or, at least, devitalized. Nevertheless, as clearly signalled throughout this paper, the findings of this study must be interpreted with caution, considering the limited statistical significance of forest ecological trends in Romania.

Moreover, the analyses conducted on eco-climatic trends and correlations showed that the increasing (greening) NDVI trends, mainly specific to mountain regions, are best explained by warmer conditions in the Carpathians, which are more limited by temperature than the Extraand Intra-Carpathian areas. Also, it seems that the intensification of the evapotranspiration regime over recent decades accounts at least in part for decreasing (browning) NDVI trends, especially in the Extra-Carpathians area. In terms of precipitation, the role of changes in this climatic parameter in NDVI dynamics remains uncertain throughout Romania. Overall, a moderate intensity of the specified eco-climatic changes was detected, which indicates an additional influence of other (non-climatic) factors in the forests' ecological dynamics, which were not considered in this analysis and which should be a priority in future similar studies.

All these findings can have practical (political) implications for Romania's forest management. The mapping, identification and geostatistical analysis of forest areas vulnerable to climate change can be useful for improving the assessment of the national forests' state (and of the quality of their ecosystem services), adapting forest regeneration

practices amid climate change, planting forest species with higher tolerance and adaptability to climate change more efficiently, promoting the diversity of forest species, or for producing good forestry practice guides to promote forest resilience to the effects of climate change. These exemplified forest adaptation measures for current and future climate change can be implemented through governmental policy vectors that directly or indirectly target the national forestry sector, such as the forestry (MEWF, 2017), climate (MECC, 2013) or sustainable development (Celac and Vădineanu, 2018) strategies of Romania. Therefore, the results of this countrywide study can improve the aforementioned forest adaptation measures, which are addressed with high priority in the National Forestry Strategy 2018-2027, within strategic objective 2 ("Sustainable management of the national forest fund"), with component measure 2.4 ("Continuous adaptation of forests to climate change") which aims to implement various actions to ensure forest ecosystem adaptation to climate change (MEWF, 2017).

# CRediT authorship contribution statement

Remus Prăvălie: Conceptualization, Methodology, Investigation, Writing – original draft, Supervision, Project administration, Funding acquisition. Igor Sîrodoev: Methodology, Software, Data curation. Ion-Andrei Nita: Software, Formal analysis. Cristian Patriche: Software, Formal analysis. Monica Dumitraşcu: Writing – review & editing, Data curation. Bogdan Roşca: Software, Validation, Data curation. Adrian Tişcovschi: Investigation, Writing – review & editing. Georgeta Bandoc: Investigation, Writing – review & editing. Ionut Săvulescu: Formal analysis, Data curation. Valentina Mănoiu: Investigation, Writing – review & editing. Software, Formal analysis.

#### **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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