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ANALIZA GEOSPAȚIALĂ A SCHIMBĂRILOR BIOMASEI FORESTIERE DIN ROMÂNIA ÎN ULTIMELE DECENII

PROIECT DE CERCETARE POSTDOCTORALĂ
– RAPORT DE CERCETARE –

Domeniul GEONOMIE

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1. Contextul general al proiectului

Prin serviciile ecosistemice diverse (Brockerhoff et al., 2017), pădurile sunt printre cele mai importante ecosisteme terestre din lume și din România (Prăvălie, 2018). Varietatea serviciilor ecosistemice (beneficii aduse societății umane) ale acestor sisteme biotice depinde însă, în mod fundamental, de biomasă, un atribut ecologic al pădurilor care a fost influențat la nivel mondial de schimbările climatice (încălzirea climatică, intensificarea regimului de evapotranspirație, modificarea cantitaților de precipitații etc) (IPCC, 2021) și activitățile antropice directe (în special defrișările și tăierile forestiere necontrolate) (Curtis et al., 2018). În această direcție, deși biomasa pădurilor tropicale a scăzut în ultimele decenii pe fondul defrișărilor masive, se pare că în zonele temperată și boreală pădurile au înregistrat o ușoară creștere a biomasei (Liu et al., 2015). Această tendință ecologică pozitivă a pădurilor și a vegetației generale a fost asociată cu o serie de factori favorabili, cum ar fi efectul benefic al fertilizării ecosistemelor forestire cu emisiile atmosferice în creștere ale CO_2 (Zhu et al., 2016), creșterea temperaturilor cu efecte benefice în intensificarea activității fotosintetice a vegetației (Mao et al., 2016) sau expansiunea naturală a pădurilor în mediile agricole abandonate din fostele țări comuniste (Liu et al., 2015).

Așadar, studiile de specialitate au arătat că în zona temperată europeană, care include România, pădurile au înregistrat o ușoară creștere a densității și productivității vegetale (Zhu et al., 2016; Ding et al., 2020), cu efecte directe în creșterea biomasei forestiere (Liu et al., 2015). În România există o probabilitate ridicată a schimbărilor biomasei forestiere, care poate fi asociată nu numai cu intervențiile antropice directe (defrișări/tăieri necontrolate), **deja documentate la nivel național sau regional** (Munteanu et al., 2014; Mihai et al., 2017; Andronache et al., 2019; Ciobotaru et al., 2019; Kucsicsa & Dumitrică, 2019), ci și cu schimbările parametrilor de temperatură (Dumitrescu et al., 2015; Micu et al., 2021), precipitații (Cheval et al., 2014; Dumitrescu et al., 2015) sau evapotranspirație (Croitoru et al., 2013; Prăvălie et al., 2019). Deși aceste variabile cu rol cheie în dinamica biomasei au suferit modificări importante la nivel național, până în prezent nu a fost efectuat niciun studiu național al schimbărilor recente ale biomasei forestiere, determinate de schimbările climatice sau de alți factori, **după cum s-a specificat în aplicația proiectului de față.**

Asemenea analize detaliate ale dinamicii pot fi făcute prin intermediul abordărilor satelitare și sunt cruciale pentru înțelegerea aprofundată a dinamicii ecologice a acestor ecosisteme, dar și pentru politicile guvernamentale variate. Aceste politici au legătură cu adaptarea pădurilor din România la schimbările climatice, combaterea schimbărilor climatice prin intermediul acestor sisteme ecologice, protecția biodiversității acestor ecosisteme valoroase, implementarea obiectivelor de dezvoltare durabilă aflate în legătură cu sectorul forestier etc.

2. Obiectivele proiectului

Conform aplicației depuse, **obiectivul general** al acestui studiu a fost investigația aprofundată a schimbărilor recente (1987–2018) ale biomasei pădurilor din România, prin intermediul unor date satelitare complexe analizate la nivelul suprafeței forestiere a țării. În esență, proiectul și-a propus să utilizeze o bază complexă de date satelitare (BCDS), în vederea investigării tendințelor biomasei pe unități spațiale detaliate (geografice, ecologice și administrative) și pe clase/specii forestiere principale. Astfel, obiectivele specifice stabilite în cadrul proiectului au fost:

1) utilizarea BCDS pentru modelarea geospațială a tendințelor biomasei pădurilor la nivelul unităților geografice reprezentative (regiuni majore și unități principale de relief) din România;

2) folosirea BCDS pentru modelarea geospațială a tendințelor biomasei pădurilor la nivelul unităților ecologice reprezentative (ecoregiuni) din România;

3) utilizarea BCDS pentru modelarea geospațială a tendințelor biomasei pădurilor la nivelul unităților administrative reprezentative (regiuni de dezvoltare și județe) din România;

4) folosirea BCDS pentru modelarea geospațială a tendințelor biomasei pădurilor la nivelul claselor (păduri de foioase, păduri de conifere și păduri mixte) și speciilor (de ex. fag, molid, brad, pin, salcâm ş.a) forestiere principale din România;

5) extragerea datelor geostatistice (arii, în ha/km^2 și %, respectiv cuantificări ale dinamicii totale a biomasei, în tone/ha/an, pentru întreaga perioadă 1987–2018) ale diverselor tipuri de tendințe ale biomasei (pozitive, negative, neutre) și cartografierea acestora la nivelul unităților geografice, ecologice, administrative și claselor/speciilor forestiere principale din România.

3. Metodologia aplicată în cadrul proiectului

După cum s-a prezentat în detaliu în aplicația proiectului, **datele folosite** constau în BCDS, compusă din imagini Landsat (5 TM, 7 ETM+ și 8 OLI/TIRS) multitemporale, descărcate (la o rezoluție spațială inițială de 30 m) în perioada 1987–2018, cu ajutorul platformei *Google Earth Engine* (GEE, 2021). Cele trei serii de date Landsat au fost descărcate și preprocesate pentru perioada verii (lunile iunie, iulie și august) a fiecărui an, care constituie anotimpul cu activitate biologică maximă a vegetației din România. Utilizând 22 de scene satelitare multispectrale (existente de-a lungul teritoriului României) (Fig. 1a), rezoluția temporală de 16 zile a datelor Landsat și cei 32 de ani investigați, BCDS folosită în cadrul acestui proiect a fost alcătuită din **peste 4000 de imagini satelitare**, care au fost descărcate și procesate la nivelul întregului teritoriu forestier al României.

Toate datele satelitare descărcate au fost investigate strict la nivelul limitelor forestiere naționale, extrase din baza de date *CORINE Land Cover* (CLC) descărcată pentru România (CLC, 1990-2018). Mai exact, clasele forestiere CLC (311, 312 și 313) au fost extrase pentru teritoriul României (pentru cinci ani disponibili, 1990, 2000, 2006, 2012 și 2018) și ulterior suprapuse/ intersectate în vederea detectării suprafețele comune de pădure, considerate constante, stabile și neafectate/foarte puțin afectate de activitățile antropice directe (defrișări/tăieri de pădure). În acest fel, schimbările biomasei au fost investigate la nivelul ariilor forestiere permanente din ultimele decenii (Fig. 1a), eliminând astfel influența antropică directă și facilitând analizele dinamicii biomasei în relație cu schimbările climatice (conform mențiunilor din aplicația acestui proiect).

Metodele utilizate până în stadiul actual au rezultat din parcurgerea mai multor etape metodologice succesive, care au fost aplicate prin intermediul Sistemelor Informaționale Geografice (SIG) și care au urmărit I) estimarea anuală indirectă a biomasei pădurilor prin intermediul indicelui *Normalized Difference Vegetation Index* (NDVI), II) procesarea tendințelor seriilor anuale ale NDVI și III) analiza geospațială detaliată a tendințelor NDVI la nivel național. În prima etapa (I), indicele NDVI a fost calculat (în fiecare an, în perioada verii) ca diferență între benzile spectrale *near infra-red* (NIR) și *red*, pe baza următoarei formule: NDVI = (NIR - Red) / (NIR + Red) (Rouse et al., 1974). Valorile acestui indice sunt încadrate în intervalul -1...+1, valorile negative sau apropiate de 0 fiind asociate cu suprafete acvatice, dezgolite (roci, nisip), lipsite de vegetație sau acoperite cu zăpadă, în timp ce valorile pozitive indică vegetație slab/mediu dezvoltată (în intervalul aproximativ 0.2...0.5, în care se pot detecta, de exemplu, pășuni sau arbuști) sau densă (>0.6, valori în general specifice pădurilor, **deci biomasei vegetale ridicate**) (Weier and Herring, 2000; NCAR, 2018; USGS, 2021).

Astfel, deși acest indice evidențiază în mod direct densitatea și productivitatea vegetației, **în mod indirect NDVI reflectă inclusiv biomasa pădurilor**, la valori ridicate (>0.6, după cum s-a menționat anterior). Așadar, NDVI este unul dintre principalele variabile predictor folosite în estimarea biomasei (Gasparri et al., 2010; Zhu & Liu, 2015; Macedo et al., 2018; Pandey et al., 2019; Zhu et al., 2020) și un instrument ecologic larg utilizat la nivel internațional pentru evaluarea de ansamblu a vegetației, forestiere și non-forestiere (Huang et al., 2021; Soubry et al., 2021). Considerând aceste aspecte, **rezultatele acestui raport de cercetare se bazează pe analiza indirectă a schimbărilor biomasei forestiere din România**, care a fost făcută prin intermediul acestui indice ecologic calculat și investigat, în detaliu, la nivel național (Fig. 1a).

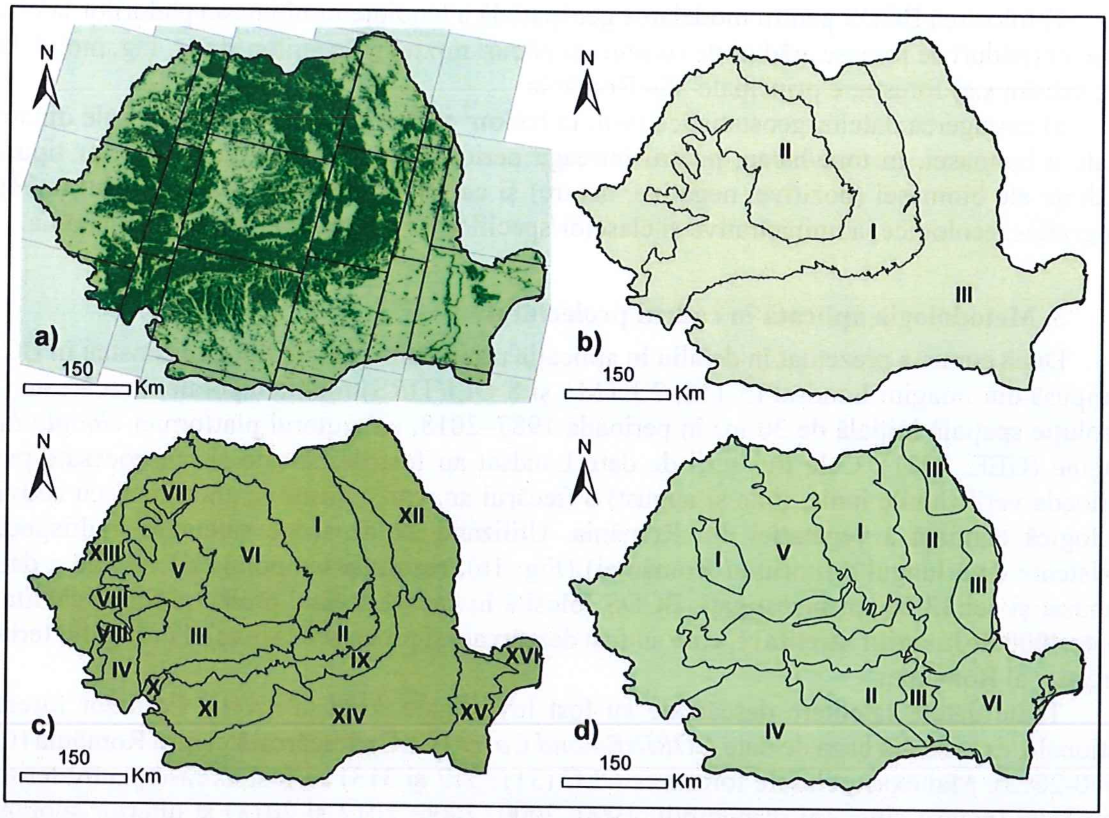

Fig. 1. Reprezentarea spațială a scenelor satelitare/pădurilor permanente (a), regiunilor geografice majore (b), unităților principale de relief (c) și ecoregiunilor majore (Fig. 1d) din România. Note: toate datelele satelitare Landsat au fost descărcate din cadrul scenelor satelitare (a), care sunt suprafețe terestre scanate (cu forma unor dreptunghiuri) de către senzorii satelitari; arealele cu verde închis din interiorul României (a) reprezintă pădurile permanente/stabile după 1990, rezultate din suprapunerea/intersectarea claselor forestiere 311 (păduri de foioase), 312 (păduri de conifere) și 313 (păduri mixte), extrase din cele cinci baze de date CLC; toate analizele NDVI au fost procesate strict la nivelul acestor suprafețe forestiere; arealele cu verde deschis din interiorul țării (a) reprezintă alte clase de acoperire/utilizare a terenurilor (în afara pădurilor) din România; regiuni geografice majore (b): I – regiunea carpatică, II – regiunea intracarpatică, III – regiunea extracarpatică; unități principale de relief (c): I – Carpații Orientali, II – Carpații de Curbură, III – Carpații Meridionali, IV – Carpații Banatului, V – Carpații Occidentali, VI – Depresiunea Transilvaniei, VII – Dealurile Crișanei, VIII – Dealurile Banatului, IX – Subcarpații, X – Podișul Mehedinți, XI – Podișul Getic, XII – Podișul Moldovei, XIII – Câmpia de Vest, XIV – Câmpia Română, XV – Podișul Dobrogei, XVI – Delta Dunării; ecoregiuni majore (d): I – păduri de conifere montane carpatice, II – păduri mixte central-europene, III – silvostepă est-europeană, IV – păduri mixte balcanice, V – păduri mixte panonice, VI – stepă pontică.

După calcularea și obținerea seriilor anuale (de tip raster) ale densității forestiere, care evidențiază indirect biomasa pădurilor, ulterior au fost estimate (la nivel de pixel) schimbările forestiere sub forma unor tendințe pozitive și negative ale densității/consistenței vegetației (II). Procesarea tendințelor a fost făcută prin utilizarea testului neparametric *Mann-Kendall* și a procedurii *Sen's slope* (Salmi et al., 2002), două instrumente geostatistice larg utilizate în detectarea direcției (pozitive sau negative), magnitudinii (intensității) și semnificativității (credibilității) statistice a tendințelor (la pragul α de 0.1 sau 90%) unor variabile diverse de mediu (Chattopadhyay et al., 2012; Zhang et al., 2016; Do et al., 2017; Young and Ribal, 2019; Sobrino et al., 2020). Modelarea tendințelor a fost făcută la o rezoluție finală de 1 km, pentru procesarea mai eficientă a datelor, eliminarea variațiilor punctuale/locale și, astfel, pentru detectarea unui tipar mai clar/generalizat al tendințelor NDVI în România.

În ultima etapă au fost explorate tendințele detaliate ale densității forestiere la nivel teritorial (III), prin analiza statistică și cartografică a datelor NDVI la nivelul unor unități spațiale relevante, și anume regiuni geografice majore (Fig. 1b), unități principale de relief (Fig. 1c) și ecoregiuni majore (Fig. 1d). Toate cele trei etape metodologice, prezentate succint în acest raport de cercetare, au fost aplicate prin utilizarea unor tehnici SIG variate şi a unor softuri specifice de modelare geospaţială, precum ArcGIS (ESRI, 2020) sau pachetul R (Evans, 2020).

4. Rezultatele proiectului obţinute până în stadiul actual

Aplicarea procedurilor *Mann-Kendall* şi *Sen's slope* la nivelul seriilor anuale de date NDVI a evidenţiat, pentru prima dată în întreaga ţară, o înverzire generalizată a pădurilor României (Fig. 2), după 1987. Această dinamică generală, care indică o amplificare a densităţii/productivităţii vegetaţiei forestiere şi, implicit/indirect, o creştere de ansamblu a biomasei pădurilor, poate fi detectată în cadrul tendinţelor neclasificate (Fig. 2) şi clasificate (Fig. 3).

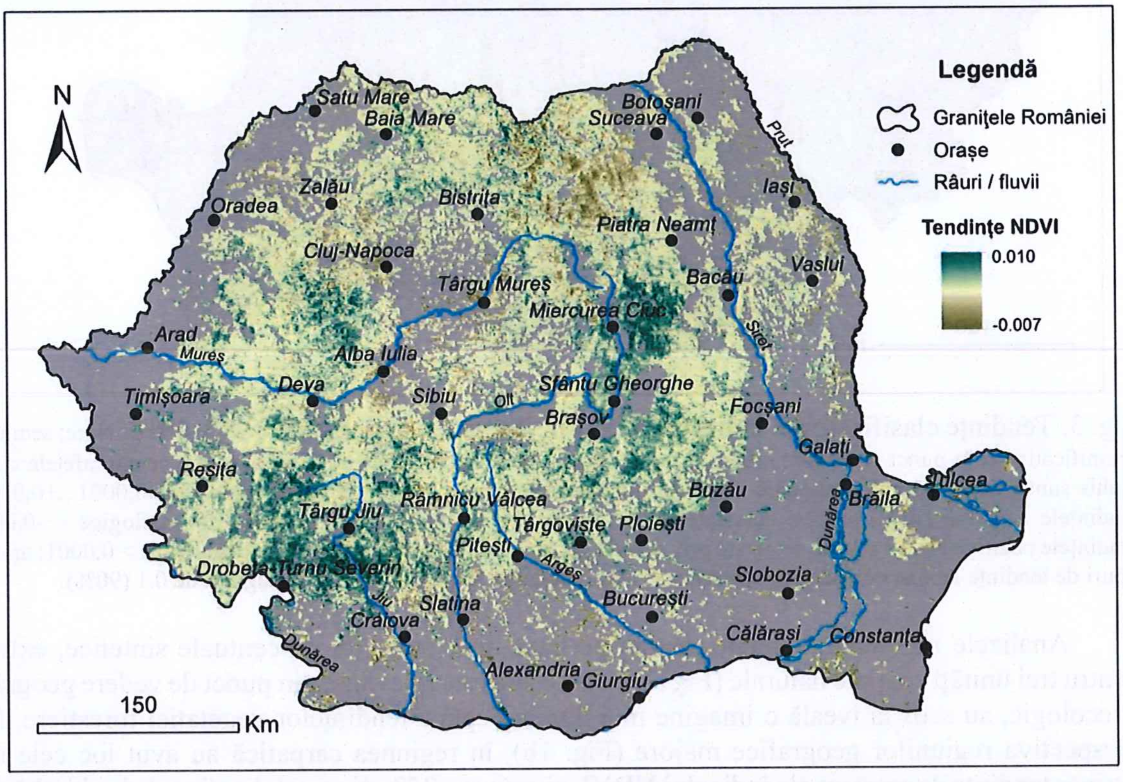

Fig. 2. Dinamica generală a indicelui NDVI în România, în perioada 1987–2018. **Notă: tendinţele NDVI exprimă rata anuală de schimbare a valorilor acestui indice de-a lungul teritoriului forestier al ţării.**

Clasificarea valorilor pantei (*Sen's slope*) schimbărilor NDVI în tendinţe negative, pozitive şi staţionare (nule) a arătat că circa jumătate din pădurile României au fost afectate de schimbări negative şi pozitive în densitatea vegetatiei, în timp ce cealaltă jumătate a rămas stabilă/relativ stabilă, conform tendinţelor nule care pot fi observate prin tonul de gri foarte închis (Fig. 3). Statistic, din totalul ariei schimbărilor negative şi pozitive ale indicelui NDVI (care însumează mai mult de 30000 km^2 în întreaga ţară), ~65% se încadrează în clasa tendinţelor pozitive, în timp ce procentul rămas de ~35% este reprezentat de tendinţe negative, care reflectă scăderi în densitatea şi, implicit, în biomasa vegetaţiei forestiere. Trebuie avut în vedere că cele două tipuri generale de tendinţe au o semnificativitate statistică limitată de-a lungul fondului forestier al României (Fig. 3), însă acest lucru nu înseamnă că toate tendinţele detectate nu merită explorate în detaliu, chiar dacă deocamdată au o credibilitate statistică redusă la nivel naţional. De fapt, aceste tendinţe incipiente indică schimbările ecologice din România care deja au fost declanşate şi care, cel mai probabil, vor fi din ce în ce mai evidente în următoarele decenii, fiind posibil să devină semnificative statistic la scară largă, dacă magnitudinea schimbărilor (rata anuală evidenţiată de metoda *Sen's slope*) se va accentua în viitorul apropiat.

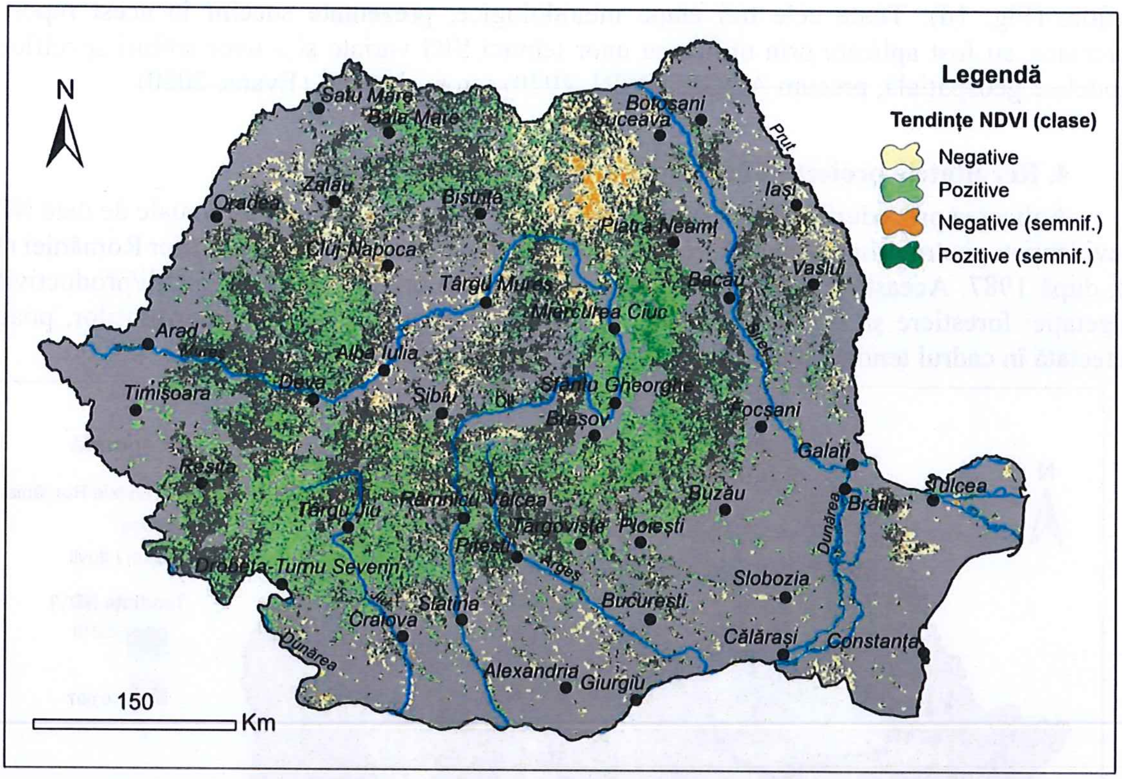

Fig. 3. Tendinţe clasificate ale indicelui NDVI în România, în perioada 1987–2018. Note: semnif. – semnificative (din punct de vedere statistic); ariile cu gri deschis sunt non-forestiere, în timp ce suprafeţele cu gri închis sunt modificări nule/staţionare ale pădurilor (valorile pantei NDVI situate în intervalul -0,0001...+0,0001); tendinţele negative NDVI au fost detectate prin considerarea valorilor pantei schimbărilor ecologice < -0,0001; tendinţele pozitive NDVI au fost detectate prin considerarea valorilor pantei schimbărilor ecologice > 0,0001; ambele tipuri de tendinţe au fost considerate semnificative (din punct de vedere statistic) la pragul α de 0.1 (90%).

Analizele regionale detaliate, făcute pe baza unor statistici procentuale sintetice, extrase pentru trei unităţi spaţiale naturale (Fig. 1b–d) considerate relevante din punct de vedere geografic şi ecologic, au scos la iveală o imagine mai diversificată a tendinţelor vegetaţiei forestiere. Din perspectiva regiunilor geografice majore (Fig. 1b), în regiunea carpatică au avut loc cele mai extinse tendinţe de creştere ale indicelui NDVI, şi anume ~35% din totalul naţional al schimbărilor acestui indice ecologic (Fig. 4). Tendinţe importante de creştere în densitatea vegetaţiei forestiere pot fi observate şi în regiunea extracarpatică (21%), dar care sunt contrabalansate de tendinţe însemnate de scădere (degradare) în consistenţa vegetaţiei (13%) (Fig. 4). În regiunea intracarpatică predomină tendinţe mixte într-o măsură aproximativ echilibrată (Fig. 4).

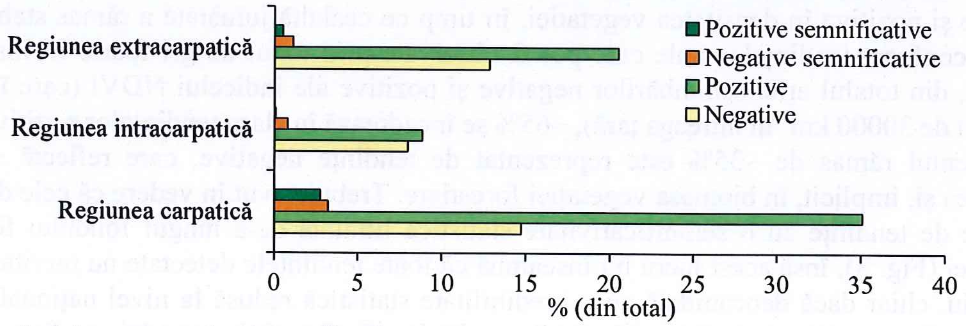

Fig. 4. Statistici procentuale ale tendinţelor NDVI detectate la nivelul regiunilor geografice majore din România. Note: tendinţe negative – aria procentuală a tendinţelor negative NDVI (valorile pantei < -0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe pozitive – aria procentuală a tendinţelor pozitive NDVI (valorile pantei > 0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe negative semnificative – aria procentuală a tendinţelor negative

NDVI, semnificative din punct de vedere statistic (valorile pantei < -0,0001, detectate **la pragul α de 0.1**), **raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe pozitive – aria procentuală a tendinţelor pozitive NDVI**, semnificative din punct de vedere statistic (valorile pantei > 0,0001, **detectate la pragul α** de 0.1), **raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România.**

În ceea ce priveşte unităţile principale de relief (Fig. 1c), este evidentă înverzirea generalizată a ecosistemelor forestiere situate cu precădere în regiunea carpatică (Fig. 5). În esenţă, toate unităţile de relief suprapuse regiunii carpatice (Fig. 1b,c) sunt marcate de un bilanţ net pozitiv al tendinţelor NDVI, în care tendinţele pozitive sunt mai mult (de exemplu Carpaţii Meridionali, cu cea mai mare diferenţă între tendinţele pozitive, care deţin peste 8% din totalul schimbărilor naţionale, şi cele negative, 2%) sau mai puţin (Carpaţii Orientali, cu >12% tendinţe de creştere vs ~10% tendinţe de scădere) pronunţate faţă de cele negative (Fig. 5).

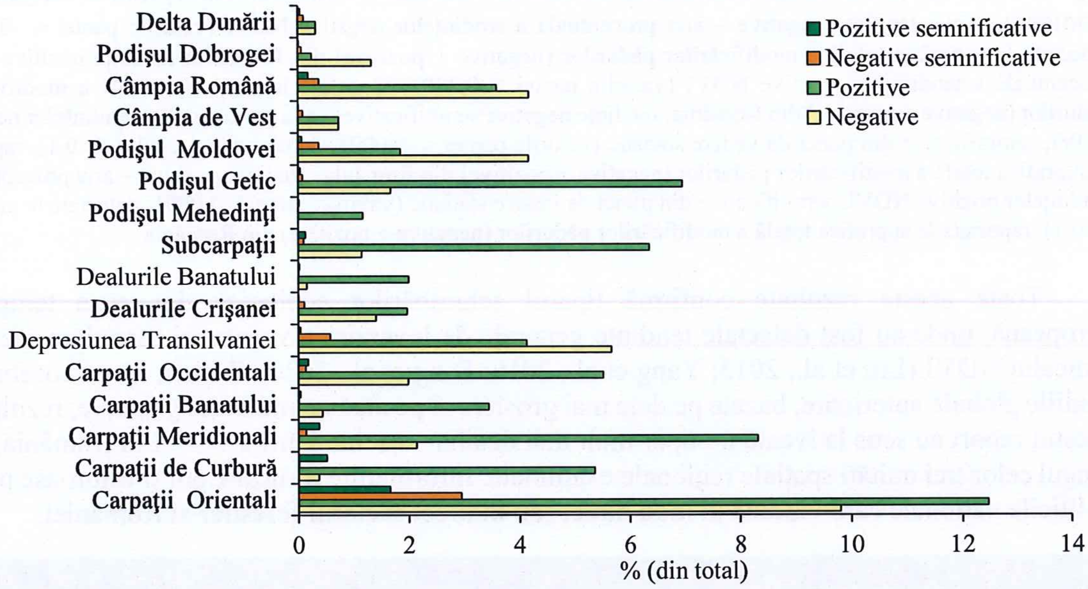

Fig. 5. Statistici procentuale ale tendinţelor NDVI detectate la nivelul unităţilor principale de relief din România. Note: **tendinţe negative – aria procentuală a tendinţelor negative NDVI (valorile pantei < -0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe** pozitive – aria procentuală a tendinţelor pozitive NDVI (valorile **pantei > 0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe negative** semnificative – **aria procentuală a tendinţelor negative** NDVI, semnificative din punct de vedere statistic (valorile pantei < -0,0001, detectate **la pragul α de 0.1**), **raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe pozitive – aria procentuală a tendinţelor pozitive NDVI**, semnificative din punct de vedere statistic (valorile pantei > 0,0001, **detectate la pragul α** de 0.1), **raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România.**

La polul opus, unităţile extinse de relief din regiunea extracarpatică se remarcă printr-un bilanţ net negativ în dinamica NDVI, ca urmare a schimbărilor ecologice de degradare (tendinţe negative) prezente la scară largă în Podişul Moldovei (~4%), Câmpia Română ~(4%) şi Podişul Dobrogei (>1%) (Fig. 5). Tendinţe ecologice negative, care reflectă inclusiv o posibilă degradare a biomasei pădurilor, pot fi observate şi în Depresiunea Transilvaniei (aproape 6%), însă în regiunea intracapatică există şi unităţi de relief (Dealurile Banatului şi Crişanei) cu schimbări pozitive predominante în densitatea şi productivitatea ecologică a pădurilor (Fig. 5).

Investigaţia datelor procentuale la nivel ecoregiunilor majore (Fig. 1d) a evidenţiat pădurile de conifere montane carpatice ca principal *hotspot* al schimbărilor NDVI, cu >28% tendinţe pozitive, respectiv ~14% tendinţe negative, sau circa 42% din toate schimbările forestiere naţionale (Fig. 6). Alte schimbări importante, de îmbunătăţire a stării ecosistemelor forestiere, pot fi observate şi în pădurile mixte panonice, pădurile mixte balcanice sau în pădurile mixte central-europene, în timp ce tendinţe contrare generale, de degradare a vegetaţiei forestiere, pot fi remarcate doar în silvostepa est-europeană şi în stepa pontică din România (Fig. 6).

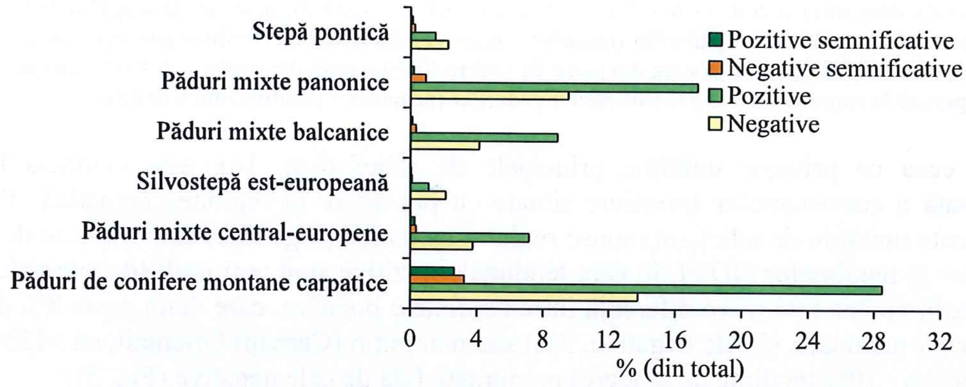

Fig. 6. Statistici procentuale ale tendinţelor NDVI detectate la nivelul ecoregiunilor majore din România. Note: tendinţe negative – aria procentuală a tendinţelor negative NDVI (valorile pantei < -0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe pozitive – aria procentuală a tendinţelor pozitive NDVI (valorile pantei > 0,0001) raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe negative semnificative – aria procentuală a tendinţelor negative NDVI, semnificative din punct de vedere statistic (valorile pantei < -0,0001, detectate la pragul α de 0.1), raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România; tendinţe pozitive – aria procentuală a tendinţelor pozitive NDVI, semnificative din punct de vedere statistic (valorile pantei > 0,0001, detectate la pragul α de 0.1), raportată la suprafaţa totală a modificărilor pădurilor (negative + pozitive) din România.

Toate aceste rezultate confirmă tiparul schimbărilor ecologice din zona temperată europeană, unde au fost detectate tendinţe generale de înverzire a vegetaţiei forestiere, pe baza indicelui NDVI (Liu et al., 2015; Yang et al., 2019; Ding et al., 2020). Totuşi, spre deosebire de studiile globale anterioare, bazate pe date mai grosiere şi pe analize mult mai generale, rezultatele acestui raport au scos la iveală un tipar mult mai detaliat al schimbărilor NDVI în România, de-a lungul celor trei unităţi spaţiale regionale examinate. Informaţiile furnizate pot fi valoroase pentru politicile naţionale care vizează în mod direct sau indirect sectorul forestier al României.

Mult mai multe informaţii privind dinamica NDVI, instrument prin care poate fi examinată indirect biomasa forestieră, pot fi consultate în lucrarea **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. (în curs de publicare).** Rezultatele acestui studiu, în care sunt explorate inclusiv **tendinţele NDVI în relaţie cu schimbările climatice** (responsabile în mare parte de tendinţele ecologice identificate), pot fi consultate în articolul recent revizuit pentru **jurnalul prestigios *Ecological Indicators* (Factor de impact 5**, Scor relativ de influenţă 1.7, Scor AIS 1), unde există **afilierea personală la Academia Oamenilor de Ştiinţă din România,** conform dovezilor prezentate (lucrare revizuită pdf şi confirmare editorială pe e-mail).

5. Rezultatele proiectului preconizate în perioada imediat următoare

În următoarele săptămâni va fi realizată o **modelare directă** a biomasei forestiere din România, prin calcularea indicelui *Above-ground Biomass* (AGB), cunoscut ca fiind un instrument cantitativ al biomasei forestiere (Gasparri et al., 2010; Zhu & Liu, 2015; Matasci et al., 2018; Puliti et al., 2021). Modelarea AGB se va face în aceeaşi perioadă (1987–2018) şi în acelaşi anotimp (vara) cu activitate biologică relevantă, iar datele folosite pentru obţinerea acestui indice (cu valori în tone/ha) vor include un al 3-lea set de date crucial, pe lângă BCDS şi CLC.

Mai exact, vor fi folosite aproape 500 de sondaje forestiere distribuite relativ uniform de-a lungul pădurilor României (Fig. 7a), care conţin date măsurate (în cadrul unor parcele forestiere standardizate) ale biomasei forestiere (tone/ha) pentru anii 2010 şi 2015 (IFN, 2012, 2018). **Aceste date au fost deja achiziţionate din cadrul Inventarului Forestier Naţional** (IFN) (Fig. 7a) **şi preprocesate pentru modelarea viitoare a AGB**, care se va baza pe cele două seturi de date IFN, utilizând tehnici avansate de tip *machine learning*.

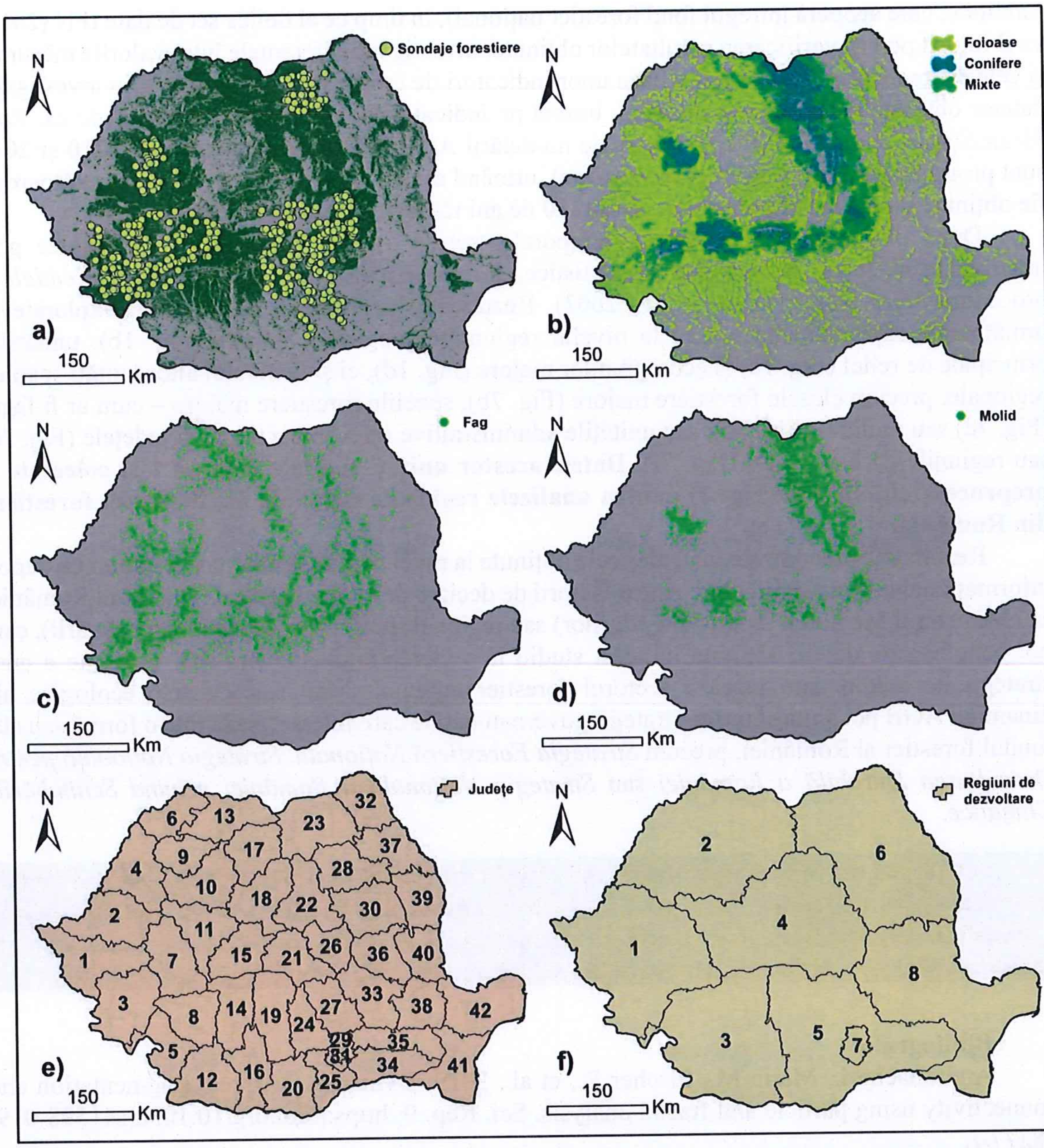

Fig. 7. Distribuția spațială a sondajelor forestiere (a), claselor forestiere (b), fagului (c), molidului (d), județelor (e) și regiunilor de dezvoltare (f) din România. Note: cele aproape 500 de sondaje forestiere, ale căror date (2010 și 2015) au fost achiziționate din cadrul IFN și preprocesate până în prezent, au fost suprapuse limitelor forestiere naționale (cu verde închis) (a), la nivelul cărora se va face întreaga modelare a biomasei pădurilor; clasele forestiere majore (b) au fost extrase din bazele de date CLC (1990–2018); speciile de fag (c) și de molid (d) au fost extrase din bazele de date IFN, ca exemple de specii forestiere predominante din România la nivelul cărora vor fi investigate, în detaliu, tendințele AGB (tendințele forestiere vor fi explorate și la nivelul altor specii forestiere importante din România); județe (e): 1 – Timiș, 2 – Arad, 3 – Caraș-Severin, 4 – Bihor, 5 – Mehedinți, 6 – Satu-Mare, 7 – Hunedoara, 8 – Gorj, 9 – Sălaj, 10 – Cluj, 11 – Alba, 12 – Dolj, 13 – Maramureș, 14 – Vâlcea, 15 – Sibiu, 16 – Olt, 17 – Bistrița-Năsăud, 18 – Mureș, 19 – Argeș, 20 – Teleorman, 21 – Brașov, 22 – Harghita, 23 – Suceava, 24 – Dâmbovița, 25 – Giurgiu, 26 – Covasna, 27 – Prahova, 28 – Neamț, 29 – Ilfov, 30 – Bacău, 31 – București, 32 – Botoșani, 33 – Buzău, 34 – Călărași, 35 – Ialomița, 36 – Vrancea, 37 – Iași, 38 – Brăila, 39 – Vaslui, 40 – Galați, 41 – Constanța, 42 – Tulcea; regiuni de dezvoltare (f): 1 – Vest, 2 – Nord-Vest; 3 – Sud-Vest, 4 – Centru, 5 – Sud, 6 – Nord-Est, 7 – București-Ilfov, 8 – Sud-Est.

Pe scurt, modelarea cantitativă a biomasei se va face utilizând un set de date (2010) pentru estimarea AGB (pe baza unor modele de regresie între datele IFN și informațiile spectrale satelitare, care acoperă întregul fond forestier național), în timp ce al doilea set de date IFN (2015) va fi folosit pentru verificarea rezultatelor obținute, investigând diferențele între valorile măsurate și cele estimate prin modelare (pe baza unor indicatori de eroare larg cunoscuți). Din investigația datelor obținute până în acest moment, bazată pe indicatori de eroare standardizați (de ex. *Root Mean Square Error* – RMSE), rezultatele modelării AGB în România pentru anii 2010 și 2015 sunt promițătoare (valori RMSE acceptabile), urmând așadar ca în perioada imediat următoare să fie obținute datele raster pentru toți ceilalți 30 de ani rămași, în intervalul 1987–2018.

După obținerea tuturor datelor temporale, seriile anuale AGB vor fi investigate prin intermediul acelorași instrumente geostatistice, și anume testul neparametric *Mann-Kendall* și procedura *Sen's slope* (Salmi et al., 2002). Rezultatele tendințelor AGB vor fi explorate în următoarele săptămâni nu numai la nivelul regiunilor geografice majore (Fig. 1b), unităților principale de relief (Fig. 1c) și ecoregiunilor majore (Fig. 1d), ci și la nivelul altor unități spațiale regionale, precum clasele forestiere majore (Fig. 7b), speciile forestiere majore – cum ar fi fagul (Fig. 7c) sau molidul (Fig. 7d), sau unitățile administrative relevante, cum ar fi județele (Fig. 7e) sau regiunile de dezvoltare (Fig. 7f). **Datele acestor unități spațiale deja au fost colectate și preprocesate/pregătite (Fig. 7) pentru analizele regionale detaliate ale biomasei forestiere din România.**

Rezultatele preconizate, mai ales cele obținute la nivel administrativ, vor constitui un suport informațional util în primul rând pentru factorii de decizie de la nivel central (Gurvenul României sau Ministerul Mediului, Apelor și Pădurilor) sau regional (prefecturi județene sau primării), care pot beneficia de datele obținute în acest studiu în vederea implementării mai eficiente a unor strategii de mediu care vizează sectorul forestier național. Mai exact, datele ecologice ale dinamicii AGB pot ajuta anumite strategii guvernamentale care intersectează într-o formă sau alta fondul forestier al României, precum *Strategia Forestieră Națională*, *Strategia Națională pentru Dezvoltarea Durabilă a României* sau *Strategia Națională a României privind Schimbările Climatice.*

O ultimă mențiune importantă este legată de faptul că toate rezultatele analizelor preconizate vor fi **trimise spre publicare (la începutul anului 2022) către o nouă revistă științifică** de specialitate (cu indicatori scientometrici ridicați), într-o lucrare în care va fi precizată, din nou, **afilierea personală la Academia Oamenilor de Știință din România.**

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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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Ecological Indicators

Investigating the ecological dynamics of forest vegetation and its relationship to climate changes in Romania. A countrywide analysis based on 1987–2018 Landsat NDVI and climate data

--Manuscript Draft--

Manuscript Number:	ECOLIND-20704R1
Article Type:	Research paper
Keywords:	forest vegetation; NDVI; trends; vegetation enhancement; vegetation degradation; Climate change; Romania
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Abstract:	Forests are crucial for humanity and biodiversity, through the various ecosystem services and functions they provide all over the world. These ecological systems have however become increasingly stressed in a world dominated by environmental transformations, such as climate change, which has also affected Romania over recent decades, but the impact of which has not yet been analysed in relation to the possible ecological changes of forests from 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 downloaded and processed for forest boundaries over the 32 years, in order to compute annual NDVI (Normalized Difference Vegetation Index, a highly useful tool in the assessment of the density, health and productivity of forests) datasets, which were subsequently investigated as trends using the well-known Mann-Kendall and Sen's slope procedures. Simultaneously, various climatic data (temperature, precipitation and reference evapotranspiration) were processed and used for exploring climate change (through the same two geostatistical procedures) that affected Romanian forestlands after 1987, but also in order to identify statistical correlations between eco-climatic data. The results highlighted general greening (NDVI increasing) trends of forests nationally (65% of all NDVI changes across Romania), which were dominated by widespread NDVI positive trends detected in the Carpathians region of Romania. This general ecological dynamic suggests a possible enhancement in vegetation growth, health and productivity in the country's high-altitude areas. Regionally, contrasting browning (NDVI decreasing) trends were found in numerous forest areas especially in the Extra-Carpathians (lowland) region, which indicates that in these cases forests were degraded (e.g. via withering) or at least slightly disturbed (e.g. via devitalization). The analysis of climatic trends and of correlations between annual NDVI and climate data indicated that recent warming

	throughout Carpathians is an important driving force of forest greening in temperature-limited mountainous regions. 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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Dear Editor,

We are sending you the revised version of the paper titled "Investigating the ecological dynamics of forest vegetation and its relationship to climate changes in Romania. A countrywide analysis based on 1987–2018 Landsat NDVI and climate data" (the title of this revised article was changed to "NDVI-based ecological dynamics of forest vegetation and its relationship to climate change in Romania during 1987–2018"). We did our best to address all 153 comments of the three reviewers, to whom we sent 25 pages of detailed answers that covered all comments. At the same time, changes made to the manuscript text were significant. We hope there will be no issues with Reviewer #2, who, in our opinion, exaggerated with 116 comments, which were made to almost every phrase in the paper. Although we showed diplomacy and made great efforts to answer / address all 116 comments of Reviewer #2, we confess to you that, in fact, many comments were quite pointless and repetitive. However, we hope that this carefully revised version will be to the liking of the three reviewers.

Best regards,
Remus Pravalie

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

Abstract. Forests have become increasingly stressed in a world dominated by climate change, which has also affected Romania over recent decades, but the impact of which has not yet been analysed in relation to the possible ecological changes of forests 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) NDVI (Normalized Difference Vegetation Index) datasets, which were subsequently investigated as trends using the Mann-Kendall and *Sen's slope* procedures. Simultaneously, various climatic data (temperature, precipitation and reference evapotranspiration) were processed through interpolation techniques and via the same two geostatistical procedures, and were subsequently used for exploring the impact of climate change on Romanian forestlands after 1987. The results highlighted general greening (NDVI increasing) trends of forests nationally (65% of all NDVI changes across Romania), which were dominated by widespread NDVI positive 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. Regionally, contrasting browning (NDVI decreasing) trends were found especially 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. 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.

Keywords: forest vegetation, NDVI, trends, vegetation enhancement, vegetation degradation, climate change, Romania.

1. Introduction

With a vast presence worldwide (~40 million km^2 or ~30% of the global land area) (Keenan et al., 2015) and a multidimensional ecological role (Masiero et al., 2019), 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 (Lewis et al., 2015) or by regulating the climate system, through carbon sequestration (Pan et al., 2011) and evaporative cooling (Ellison et al., 2017) processes.

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, precipitation (IPCC, 2014) or evapotranspiration (Zhang et al., 2016), 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 the 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; Han et al., 2019; Ols et al., 2019; Zhao et al., 2020; Islam et al., 2021; Jiang et al., 2021; Li et al., 2021; Liu et al., 2021a; Liu et al., 2021b; Zhe and 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. The hypothesis of national forest changes caused by climate is viable considering the fact that Romania has recently experienced various forms of climate change, like some important 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 of the country, 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 indicates considerable changes of climate conditions over the past decades, it is reasonable to hypothesize a climatic impact onto the ecological state of the country's forests.

This hypothesis 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 complex index for climate change analysis), showed that Romania's territory has become drier overall 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; Sfîca et al., 2017; Cheval et al., 2020; Nita et al., 2020; Micu et al., 2021), indirectly suggest a possibly high vulnerability of forests (and of other ecosystems) to climate change, although the concrete relationship between climate change and 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 affected Romania in recent times. In line with this goal, the paper is based on the analysis of the 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. 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^2) (Fig. 1). According to the official definition, Romanian forests comprise all lands that exceed 0.5 hectares covered by trees with a minimal height of 5 meters upon reaching maturity, and with a canopy cover of over 10% (NFI, 2020). At the end of 2017, these ecological systems covered extensive areas in Romania, of ~6.5 million ha (or ~65,000 km^2) or equivalent to ~27.5% of the national territory (MEWF, 2017a). 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, 2017a).

In terms of composition, there is a high diversity of forest species. According to the available official data, beech (*Fagus sylvatica*) is the country's main forest species (32% of national forest areas), followed by softwood species (26%), which are mainly represented by spruce (*Picea abies*, 20%) and fir (*Abies alba*, 4%) (MEWF, 2017a). In addition to beech, Romanian forests also feature many other hardwood species (19%, with various acacia, hornbeam, ash species etc.), oak species (17%, sessile oak, pedunculate oak etc.) and various deciduous softwood species (6%, linden, poplar, willow etc.) (MEWF, 2017a).

Romanian forests span across various climatic and ecological conditions nationally (Geacu et al., 2018; Dumitraşcu 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; Prăvălie et al., 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; Prăvălie et al., 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 (group I, 53% of the total) and forests with production and protection functions (group II, 47%) (MEWF, 2017b). In the first group, the main functions of forests are the 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, 2017b).

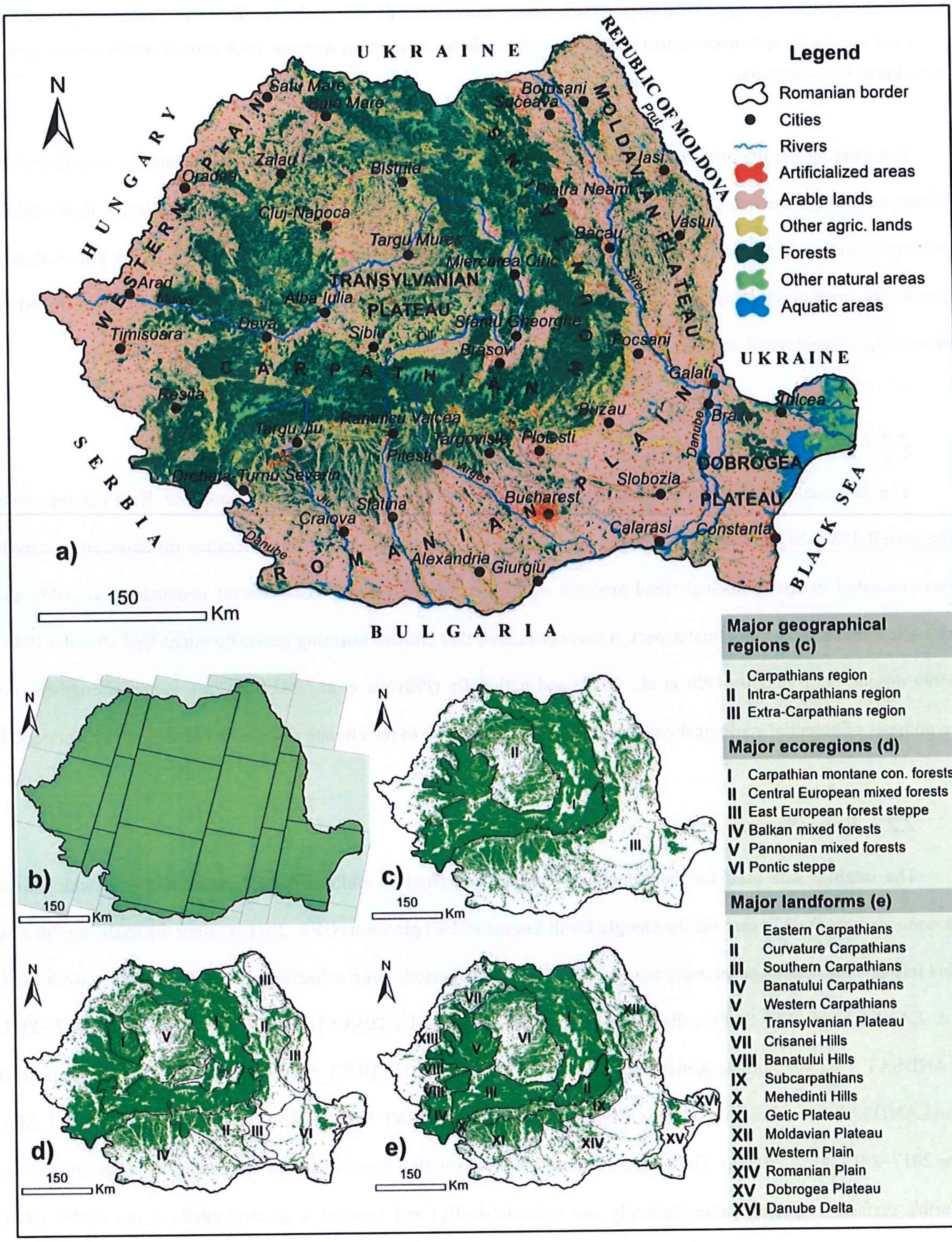

Fig. 1. The main geographical characteristics of Romania (a), the satellite scenes across Romania (at which the remote sensing data was downloaded) (b) and the major natural spatial units where various geostatistics were extracted in this

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.

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), which strengthens the hypothesis of potential ecological changes of forests, in response to the climate change recorded in the recent period.

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 this 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 technical issues of the sensor 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.

Table 1. Number or satellite images processed every year across Romania, based on remote sensing data quality downloaded in the 1987–2018 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.

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 × 1 km spatial resolution, using observational data collected from all weather stations of Meteo Romania (NMA, 2021). The three 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. While T and P were collected directly from Meteo Romania's observational measurements, ETo values were estimated based on a series of detailed climate data (air temperature, relative humidity, sunshine duration, and wind speed data, also collected from Meteo Romania) using the FAO-56 Penman-Monteith method (Allen et al., 1998), which is the best in ETo computation (Djaman et al., 2016; 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., 2017; 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 mosaiced 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 quite 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 some 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. 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 the immense use (historical and current) of this index in the forestry or non-forestry fields (Huang et al., 2021; Soubry et al., 2021). Even in the last years of increasing use of unmanned aerial systems with the data products of several cm spatial resolution, 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. For the interpolation of T, P and ETo summer values recorded every year, the Regression-Kriging (RK) spatial interpolation method was applied, using the R geostatistical software (Evans, 2020). 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 the 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 the regression residuals, by means of the Kriging method (Dumitrescu et al., 2016, 2017, 2020).

With this method, the first step consists in statistically validating the deterministic model, in the sense of verifying the intensity of the relationships between predictors and the dependent variables (T, P and ETo). The best regression model could be determined by applying stepwise regression. 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 the 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 the predictors through PCA was performed using the same (R) software (Evans, 2020), by transforming the initial variables into a new set of variables, uncorrelated and of a smaller size. Hence, the new obtained dataset contains most of the original dataset variability.

Once the T, P and ETo data were interpolated, 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 index was used in this study as a synthetic picture of climatic changes with potential recent effects in the Romanian forests' ecological state. The CWB index is therefore relevant in climate or interdisciplinary approaches, and was already used in Romania in several studies that analyzed the importance and recent dynamics of this index across the country (Prăvălie and Bandoc, 2015; Mihăilă et al., 2017; Prăvălie et al., 2016, 2019, 2020c).

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 ≤ 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* procedures, 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 eco-climatic 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).

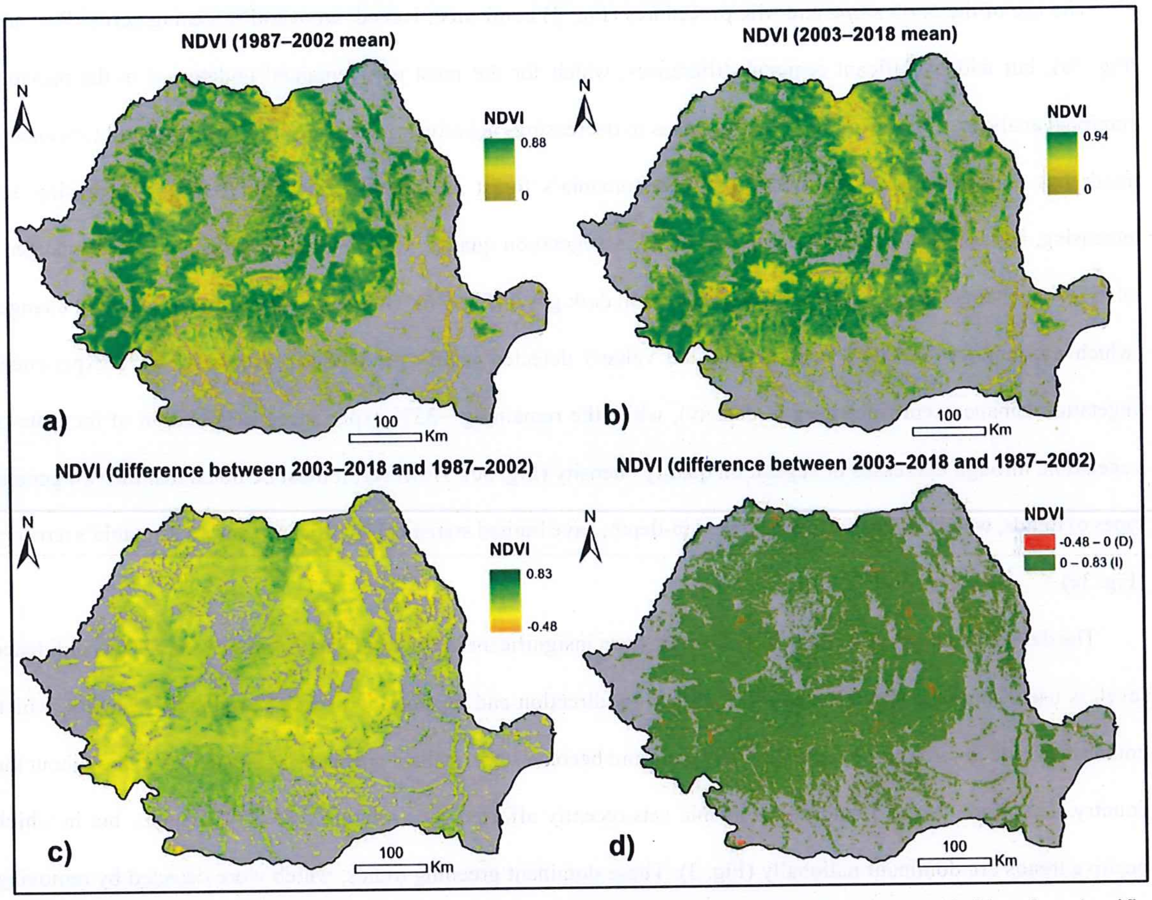

Fig. 2. Mean NDVI values (summer season data) in Romania during 1987–2002 (a), 2003–2018 (b) and unclassified (c) and classified (d) differences of mean NDVI values between the two periods. Note: D – Decreases; I – Increases; light gray areas are non-forestlands; positive values in bottom left map are 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 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.

Upon a visual comparative analysis of the two NDVI mean values (Fig. 2a,b), a greening of Romanian forestlands can be noticed, 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 procedures (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 has 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^2 in absolute values) detected across the country's forests, ~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).

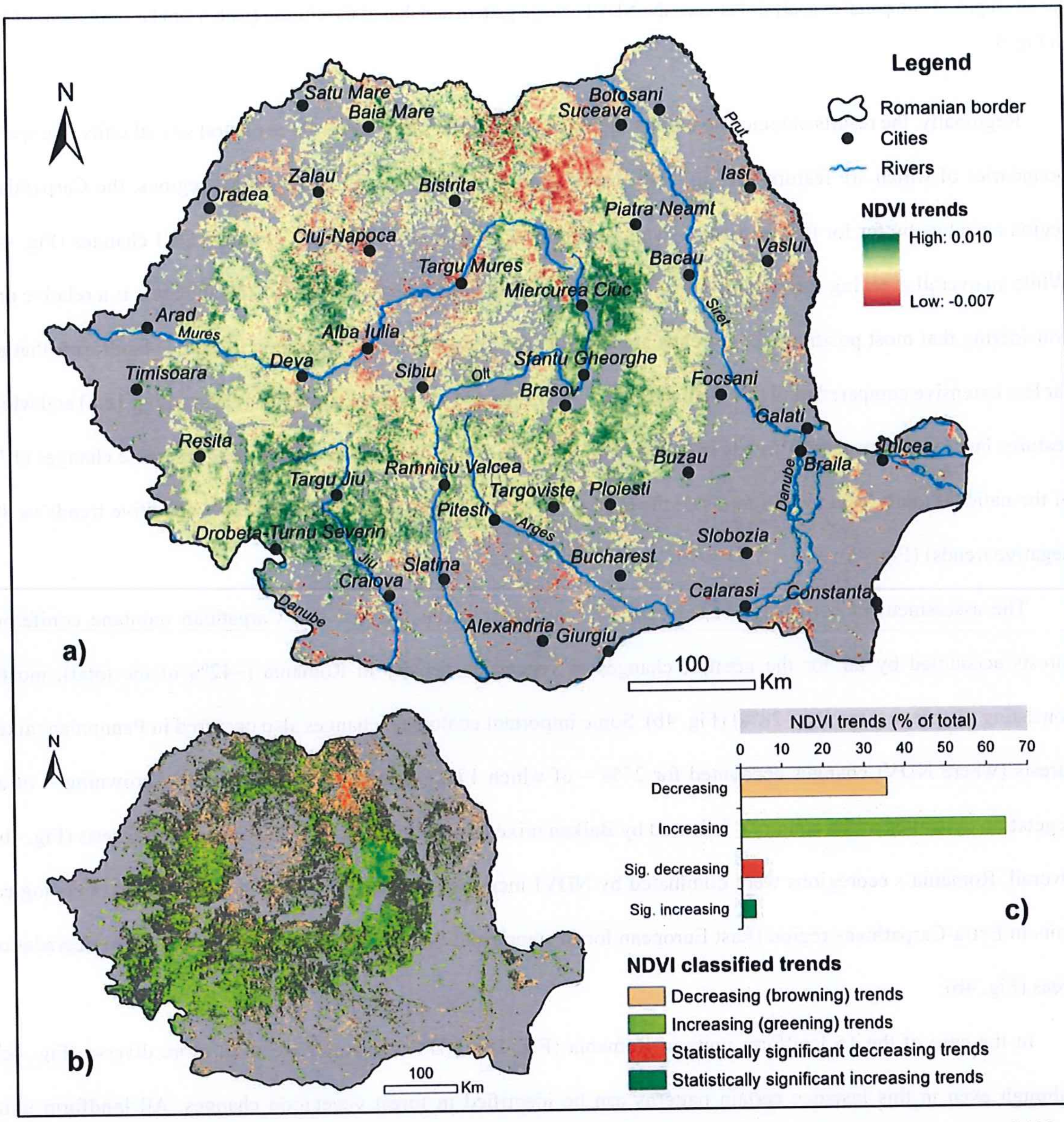

Fig. 3. General (a) and classified (b) NDVI annual trends (in the summer season) in Romania during 1987–2018 and extracted percentage-based statistics (c) of the two types of trends resulting from the NDVI trend classification. Note: light gray areas (a, b) are non-forestlands, while dark gray areas (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), detected by applying *Sen's slope* estimator to temporal satellite data (32 years); Sig. Decreasing – statistically significant decreasing trends (NDVI slope values < -0.0001 and with p-values ≤ 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 ≤ 0.1), detected by applying *Sen's slope* estimator and MK test to temporal satellite data (32 years); Romania's forest area is visually exaggerated, as a result of the NDVI pixel size of ~1 km, set

for an empirical comparative analysis between the NDVI change pattern and that of the climate (with a similar resolution, ~1 km) in Fig. 5.

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 a relative one, considering that most positive NDVI trends are found in the Subcarpathians and Getic Plateau – landforms that are far less extensive compared to the 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 (~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 less than 10% browning – of all vegetation dynamics of the country), followed by Balkan mixed forests and Central European mixed forests (Fig. 4b). Overall, Romania's ecoregions were dominated by NDVI increasing trends, except for forests located in ecological units in Extra-Carpathians region (East European forest steppe and Pontic steppe), with more vegetation degradation areas (Fig. 4b).

In the case of the 16 landform units in Romania (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 Carpathians territories (Eastern, Curvature, Southern, Banatului and Western Carpathians) are characterized by a positive net balance of NDVI greening trends (increasing trends more widespread than decreasing trends), which is most pronounced in 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 ~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). It seems that forests in landforms located in the Intra-Carpathians region (Crisanei and Banatului Hills, and Western Plain) experienced a slight ecological improvement, except for the Transylvanian Plateau, which exhibited a general decline in vegetation density (Fig. 4c).

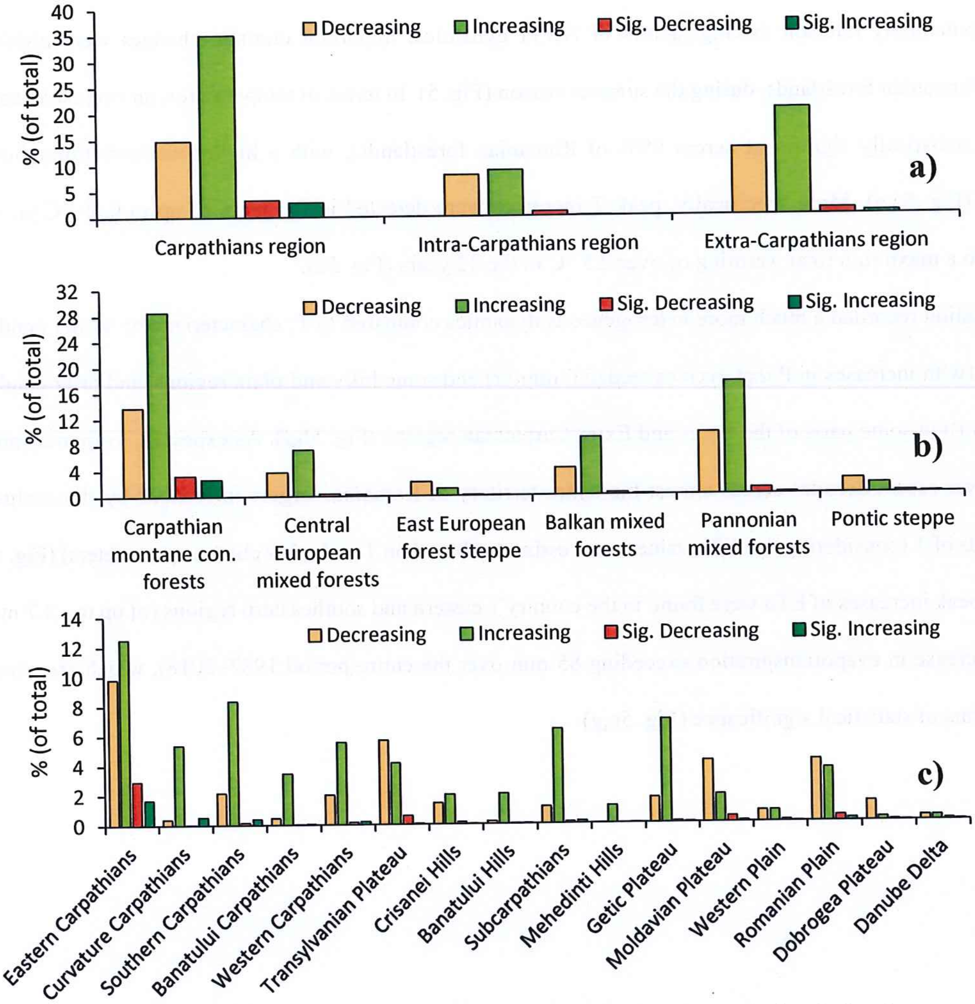

Fig. 4. Percentage-based areas of NDVI changes (trends) during 1987–2018, at the level of major geographical regions (a), major ecoregions (b) and major landforms (c) of Romania. Note: con – coniferous; the three spatial units are shown in Fig. 1; the statistics of the four types of trends (Decreasing,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

3.2. Climatic changes during 1987–2018

By using the same geostatistical tools (*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 were detected in Romania of up to 0.08 °C/yr, which correspond to a maximum total warming of over 2.5 °C in the 32 years (Fig. 5a).

Precipitation recorded a much more heterogeneous dynamics compared to T, characterized by wetter conditions in mountain (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 territory of Romania, 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 ~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).

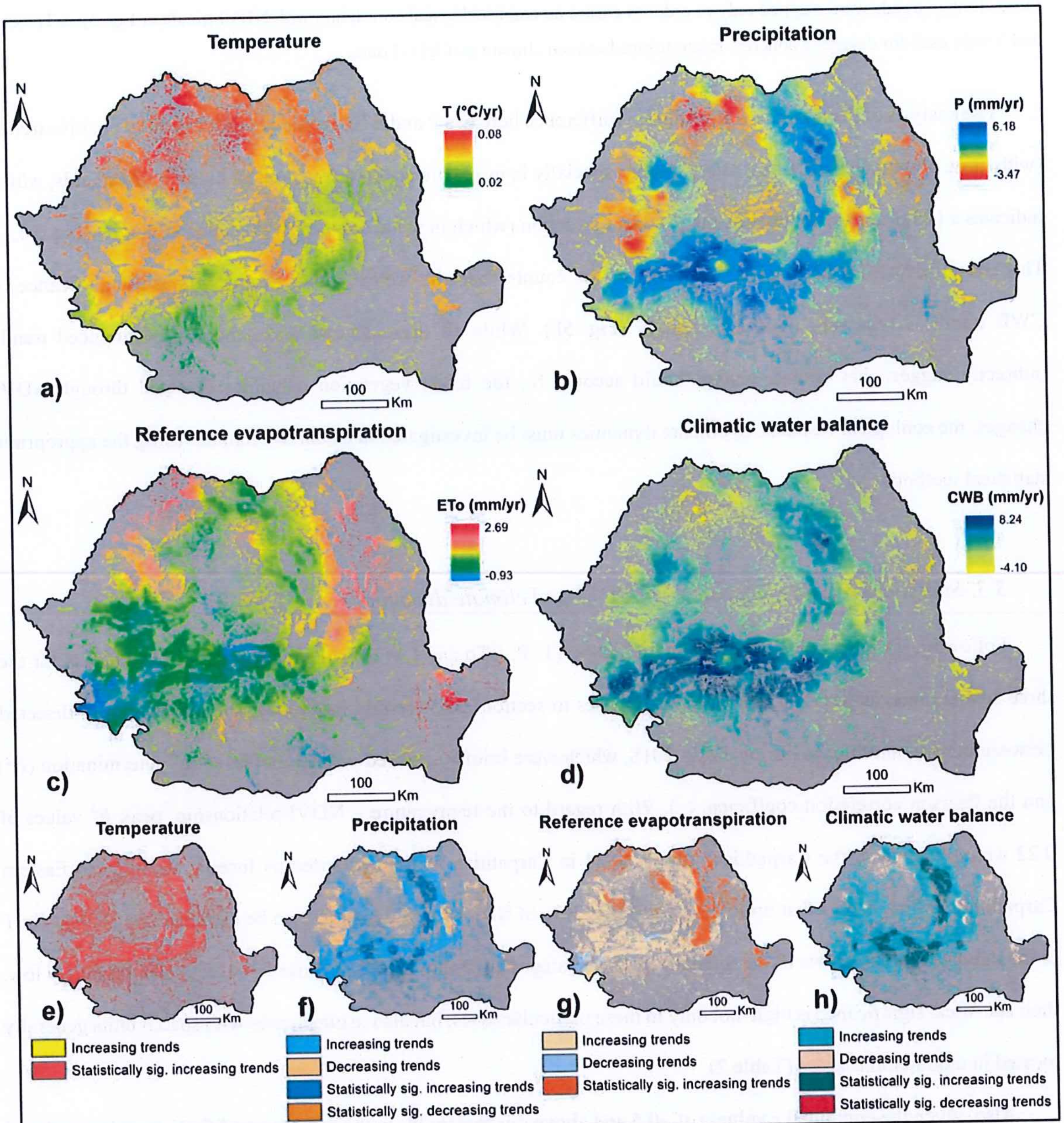

Fig. 5. General (a–d) and classified (e–h) annual trends (in the summer season) for temperature, precipitation, reference evapotranspiration and climatic water balance (precipitation minus reference evapotranspiration) in Romania during 1987–2018. Note: light gray areas are non-forestlands, while colored 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* procedure; Increasing – positive trends of climatic data (slope values > 0.0001), detected by applying the *Sen's slope* procedure; Sig. Decreasing – statistically significant decreasing trends of climatic data (slope values < -0.0001 and with p-values ≤ 0.1), detected by applying the *Sen's slope* and MK procedures; Sig. Increasing – statistically significant increasing trends of climatic data (slope values > 0.0001 and with p-values ≤ 0.1), detected by applying the *Sen's slope* and MK procedures; null changes (slope values framed in the -0.0001...+0.0001 range) were not displayed on classified maps, as they are almost nonexistent; all

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.

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 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, it was found an at least moderate intensity (of ~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 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.

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^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 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.

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.

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^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 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.

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, where Romania is located. Similar widespread 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.

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 in Romania were affected negatively 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 can be, at least indirectly, consistent with certain studies, which confirmed temperature's important role in vegetation productivity in the temperate European region, for instance through the lengthening of the vegetation growing season and by increasing phenological activity (Jeong et al., 2011; Fitchett et al., 2015; 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. 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 increasing) 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 the NDVI trends. Moreover, observations on certain decreases in NDVI in the Intra-Carpathians region (Transylvanian Plateau) (Fig. 3b) reenforce, 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 known both in the aforementioned national sources (MEWF, 2012, 2014, 2017a; Sidor et al., 2019), and in international literature (Allen et al., 2010, 2015; 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) 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 very methodology used in this study 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 non-climatic) 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_2 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.

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, it was found an overall greening of Romania's forests, due to large scale NDVI increasing 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 NDVI decreasing trends, which suggests that in many cases forest vegetation was degraded or, at least, devitalized. Nevertheless, as clearly signaled 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 Extra- and Intra-Carpathian areas. Also, it seems that the intensification of the evapotranspiration regime over recent decades accounts at least in part for NDVI decreasing (browning) 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.

While a moderate relationship between climate and forests was detected after 1987, in the coming decades the impact of climate change on forests is expected to intensify in Romania, considering several global studies that confirm that, under future warming, temperate forests will face some important disturbances, linked to certain phenological changes (which will slow down the photosynthetic activity of forests) (Fu et al., 2015) or to intensification in drier conditions (with consequences in the increasing of fires and insect activity) (Seidl et al., 2017). In Romania, in the lowland and hilly areas (Extra- and Intra-Carpathian regions) it is possible that after 2040 the decrease in forest density, productivity and diversity will accelerate, 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 will intensify 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 associated causes such as insect infestations and fires (Falup et al., 2017), 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.

This paper's 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 forestry good practice guides to promote forest resilience to the effects of climate change. All 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, 2017b), 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, 2017b).

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