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Exploring the multidimensional land degradation crisis in Europe and Romania

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- ***General objective****: modelling and assessing the convergence / interaction of land degradation processes across the agricultural environments of Europe and Romania.*

- ***Structure:***

  - *lands (soils) and their ecosystem functions/services;*
  - *the methodological framework of the present research;*
  - *the multiple facets of land degradation processes and their multidimensional spatial crisis in Europe and Romania;*
  - *conclusions;*
  - *references.*

❑ *Lands (soils) and their ecosystem functions/services:*

- *land degradation / land multi-degradation – various degradative pathways (processes) that cause a decline in land productivity (UNCCD, 1994; Reynolds et al., 2007; Cherlet et al., 2018; Prăvălie et al., 2021a), with multiple negative environmental effects, like the reduction / collapse of soil functions (Fig. 1);*

- *for example, the disruption of the climate regulation capacity (Fig. 1) – soil is the second carbon pool at the entire planetary scale and the first carbon pool at global terrestrial scale (Figs. 2, 3).*

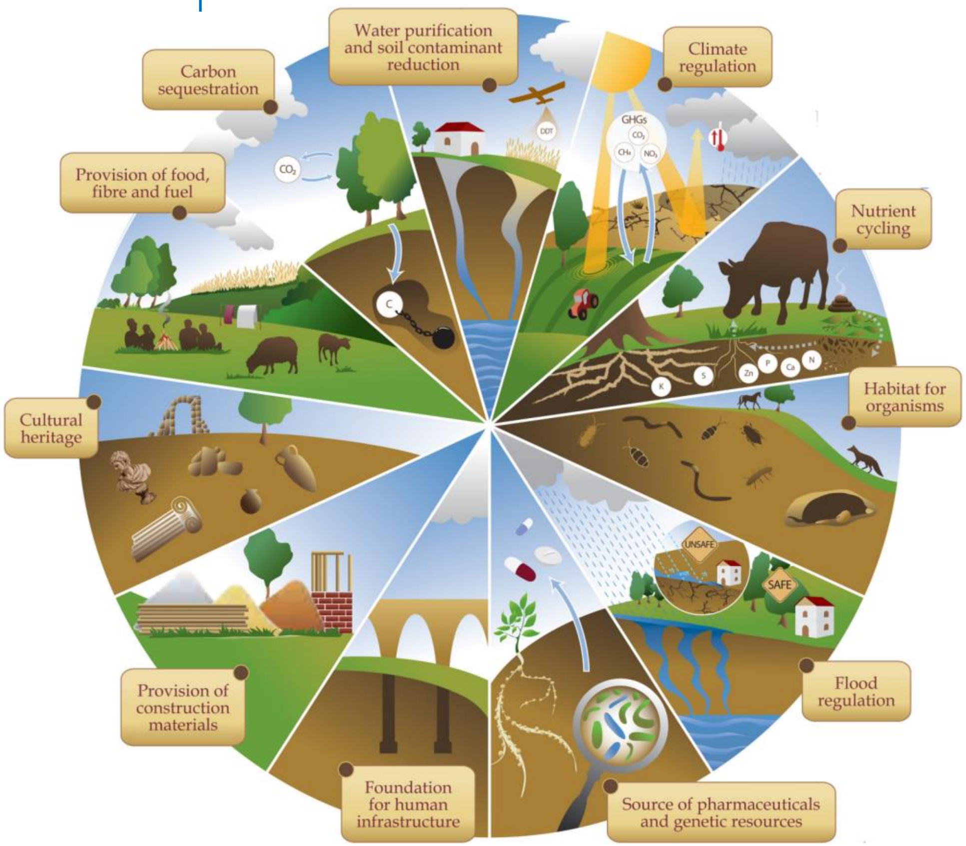

Fig. 1. Schematic approach to various soil functions (after Baveye et al., 2020).

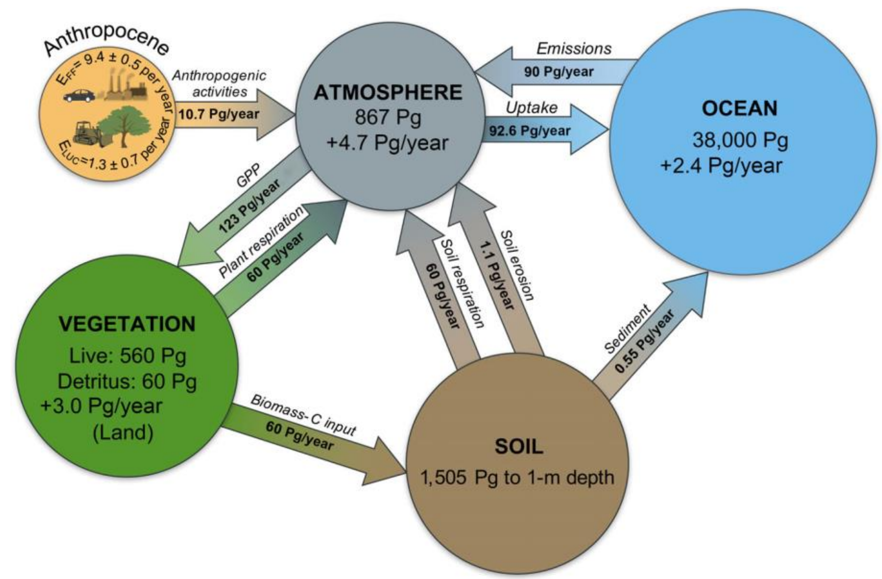

Fig. 2. Carbon cycle at the global scale (after Lal, 2018).

- *land degradation – a major driving force of recent global losses of C from soil to atmosphere (Prăvălie et al., 2021b) (Fig. 3);*

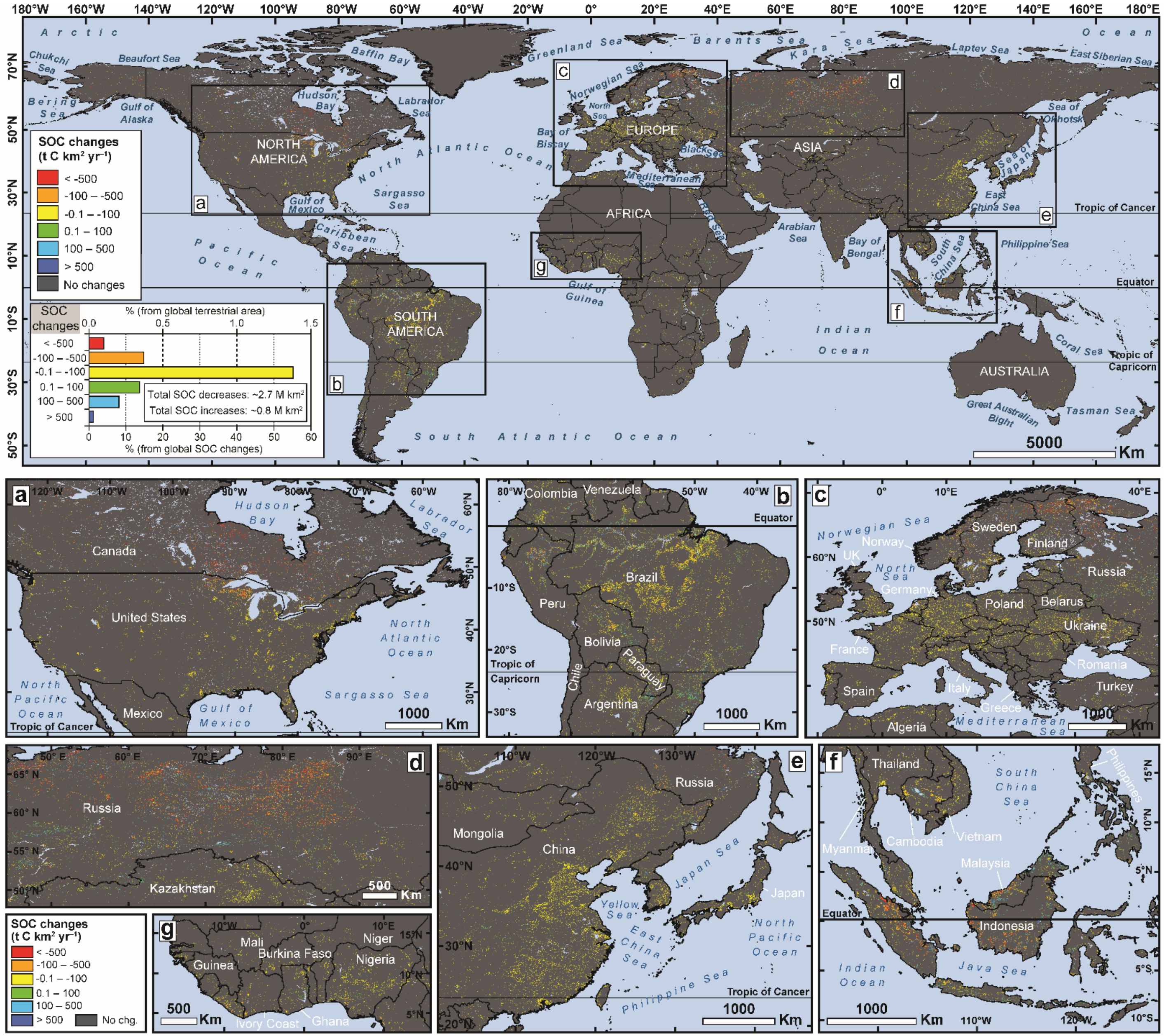

Fig. 3. Recent changes (2001-2015) in soil organic carbon (SOC) across the planet (after Prăvălie et al., 2021b).

❑ *The methodological framework:*

- *most / all land degradation processes – so far* ***analyzed in a singular manner (the "uni-degradation" perspective)*** *across the globe and in Europe (Prăvălie, 2021);*

- *this continental analysis focuses on modelling 12 concurrent processes in Europe –* ***water erosion, wind erosion, soil organic carbon loss, soil salinization, soil acidification, soil compaction, soil nutrient imbalances, soil pollution via pesticides, soil pollution via heavy metals, vegetation degradation, groundwater decline*** *and* ***aridity****) (Table 1);*

- *these land degradation processes are highly relevant for highlighting the agricultural land degradation in Europe and worldwide (Table 1);*

Table 1. *The 12 processes selected for this continental analysis, considering their general negative ecological effects for agricultural land productivity (after Prăvălie et al., 2024).*

No.	Land degradation processes	Examples of negative effects on agricultural land productivity
1	Water erosion	*Degrading soil structure, reducing soil depth or decreasing / losing the soil nutrient content*
2	Wind erosion	*Accelerating dust emission, damaging crops by abrasion or reducing the organic matter content*
3	Soil organic carbon loss	*Disrupting structural stability and water holding capacity of soils or decreasing soil fertility*
4	Soil salinization	*Limiting plant growth due to phytotoxicity, water uptake difficulty or soil organic carbon losses*
5	Soil acidification	*Threatening soil bacterial diversity, increasing toxicity for plants or limiting soil nutrient availability*
6	Soil compaction	*Reducing soil porosity, shrinking oxygen and water supply to plants or restricting root penetration*
7	Soil nutrient imbalances	*Amplifying acidity and micronutrient deficiencies in soils, due to N or P excess, or inhibiting plant growth, due to N or P deficit*
8	Soil pollution via pesticides	*Exerting stress on soil health via toxicity and decline in microbial community or earthworm activity*
9	Soil pollution via heavy metals	*Poisoning the soil, injuring plants via chlorosis and necrosis or hindering root growth and crop yields*
10	Vegetation degradation	*Decreasing soil productivity via soil organic carbon losses or through increased land exposure to water and wind erosion*
11	Groundwater decline	*Depleting groundwater resources, inducing soil water stress or inhibiting plant development*
12	Aridity	*Generating surface low water availability and constant soil water deficit or triggering desertification*

- *6 databases available internationally were directly used – water erosion (Borrelli et al., 2017), soil organic carbon (SOC) loss (Prăvălie et al., 2021), soil salinization (Toth et al., 2008), soil acidification (Ballabio et al., 2019), soil compaction (EC, 2008) and soil pollution via pesticides (Tang et al., 2021) (Fig. 4);*

- *for the other layers (wind erosion, soil nutrient imbalances, soil pollution via heavy metals, vegetation degradation, groundwater decline and aridity), various pre-existent data from other sources were collected, in order to model the geospatial data for the remaining 6 processes (Prăvălie et al., 2024) (Table 2, Fig. 4);*

- *the 12 rasters, with various features (Table 2), were structured into **2 classes – Critical** and Non-critical (Fig. 4);*

- *by intersecting the Critical classes of the 12 datasets, a **Land Multi-degradation Index (LMI)** was obtained (Prăvălie et al., 2024).*

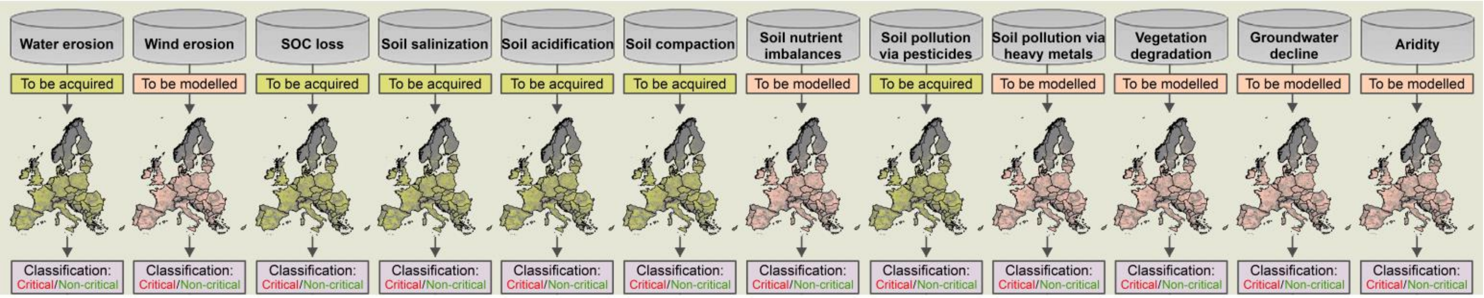

***Fig. 4.** Schematic approach to geospatial database processing in Europe.*

***Table 2.** Characteristics of land degradation data that were used in this continental approach (after Prăvălie et al., 2024).*

No.	LD data	Original resolution ^{a}	Time period	Metric
1	Water erosion	250 × 250 m	2012	t ha^{-1} yr^{-1}
2	Wind erosion	500 × 500 m	2001–2021	t ha^{-1} yr^{-1}
3	SOC loss	1 × 1 km	2001–2015	t C km^2 yr^{-1}
4	Soil salinization	1 × 1 km	2008	%
5	Soil acidification	500 × 500 m	2019	pH units
6	Soil compaction	1 × 1 km	2008	Susceptibility
7	Soil nutrient imbalances	1 × 1 km (N) 100 ×100 m (P)	2010–2019	kg/ha (N) mg/kg (P)
8	Soil pollution via pesticides	10 × 10 km	2015	Risk score
9	Soil pollution via heavy metals	1 × 1 km (As, Cd, Cr, Co, Pb, Sb, Ni) 500 × 500 m (Cu) 250 × 250 m (Hg)	2009	mg/kg
10	Vegetation degradation	500 × 500 m	2000–2015	NDVI units
11	Groundwater decline	1 × 1 km	2004–2013	GTD (m yr^{-1})
12	Aridity	1 × 1 km	1981–2018	AI (mm/mm)

Notes: m – meter, km – kilometer, ha – hectare, t – ton, C – carbon, N – Nitrogen, P – Phosphorous; NDVI – Normalized Difference Vegetation Index; GTD – Groundwater Table Depth; AI – Aridity Index; As – Arsenic; Cd – Cadmium; Cr – Chrome; Co – Cobalt; Pb – Lead; Sb – Antimony; Ni – Nickel; Cu – Copper; Hg – Mercury; a – spatial resolution of the originally collected data, which were processed at an intermediate resolution of 500 × 500 m.

❑ *The multidimensional land degradation pathways in Europe:*

- *different spatial patterns of land (uni-) degradation processes across Europe (Figs. 5, 6);*
- *each driver of degradation – examined according to some specific critical classes (Figs. 5, 6);*

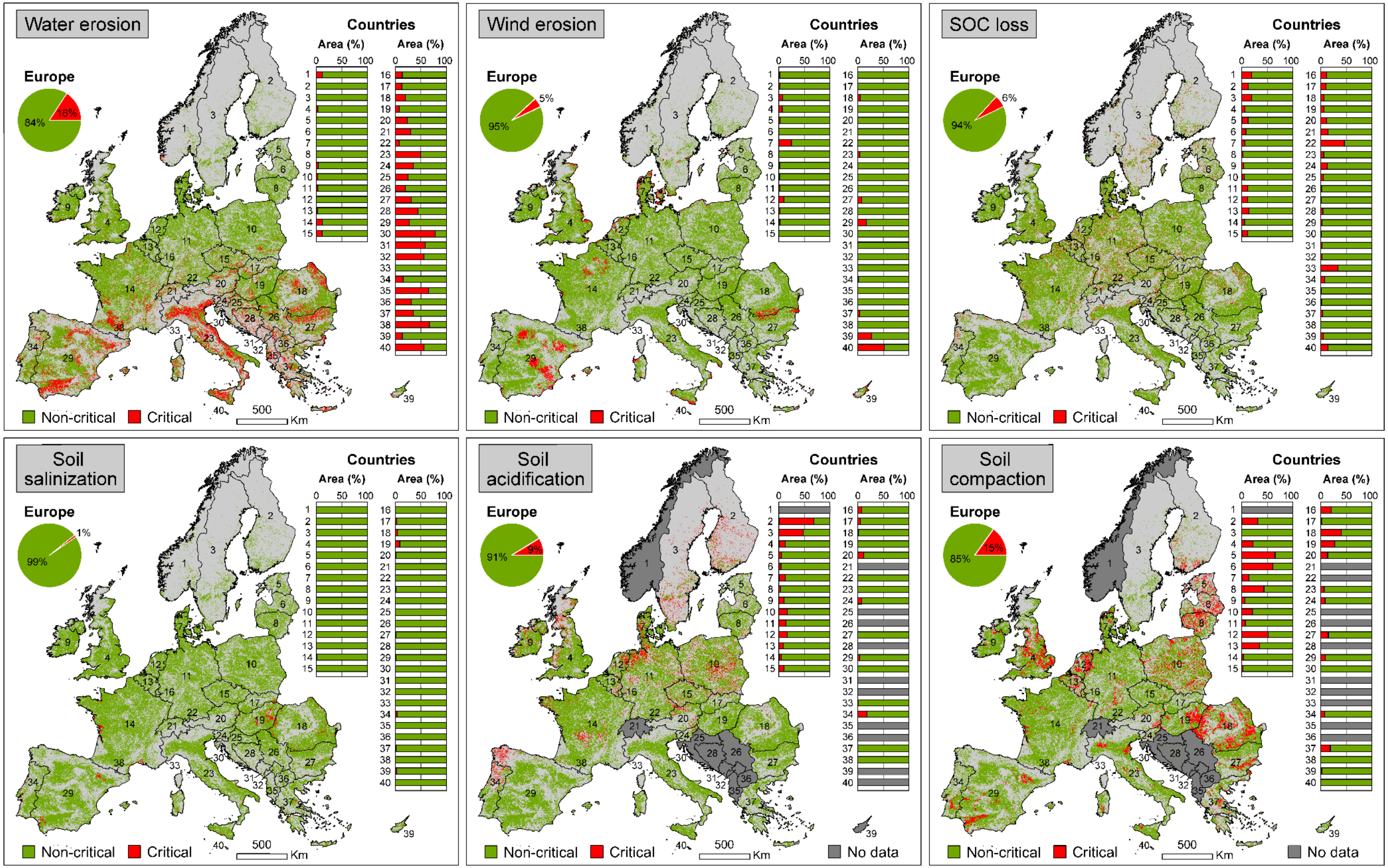

Fig. 5. *Mapping of water erosion, wind erosion, SOC loss, soil salinization, soil acidification and soil compaction in European agricultural areas (after Prăvălie et al., 2024).*

- *soil pollution via pesticides – the largest spatial footprint at continental level (52% of the cumulated agricultural area of 40 investigated countries) (Fig. 6);*
- *followed by soil nutrient imbalances (39%), soil pollution via heavy metals (31%) and aridity (26%) (Fig. 6);*

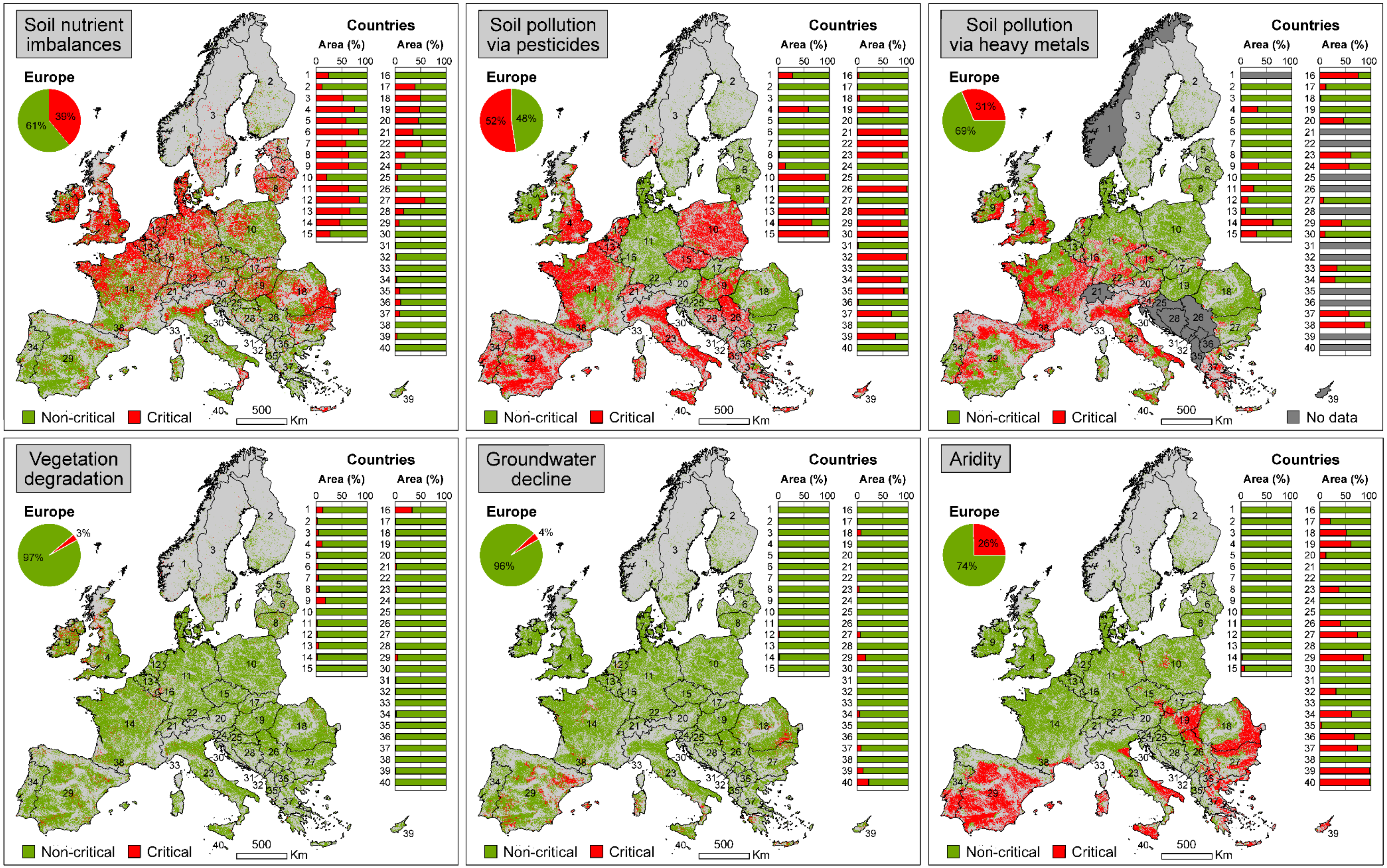

Fig. 6. *Mapping of soil nutrient imbalances, soil pollution via pesticides, soil pollution via heavy metals, vegetation degradation, groundwater decline and aridity in European agricultural areas (after Prăvălie et al., 2024).*

- ***Land Multi-degradation Index (LMI)*** *– obtained by fusing the 12 land degradation (the critical classes) databases (Fig. 7);*
- *LMI results – between one and ten converging (co-occurring) processes in Europe (Fig. 7);*
- *~10% of agricultural/arable lands are cumulatively affected by 4 and ≥ 5 concurrent processes (Table 3).*

Table 3. *Spatial extent (in km² and %) of LMI classes in agricultural/arable environments of Europe (after Prăvălie et al., 2023).*

No.	LMI classes (number of co-occurring processes)	Agricultural lands		Arable lands	
		km²	%	km²	%
1	No degradation (0)	143,626	6.84	71,196	6.23
2	Very low degradation (1)	577,279	27.50	304,105	26.60
3	Low degradation (2)	727,147	34.65	395,940	34.64
4	Medium degradation (3)	451,213	21.50	249,178	21.80
5	High degradation (4)	156,170	7.44	95,169	8.33
6	Very high degradation (≥ 5)	43,473	2.07	27,562	2.40

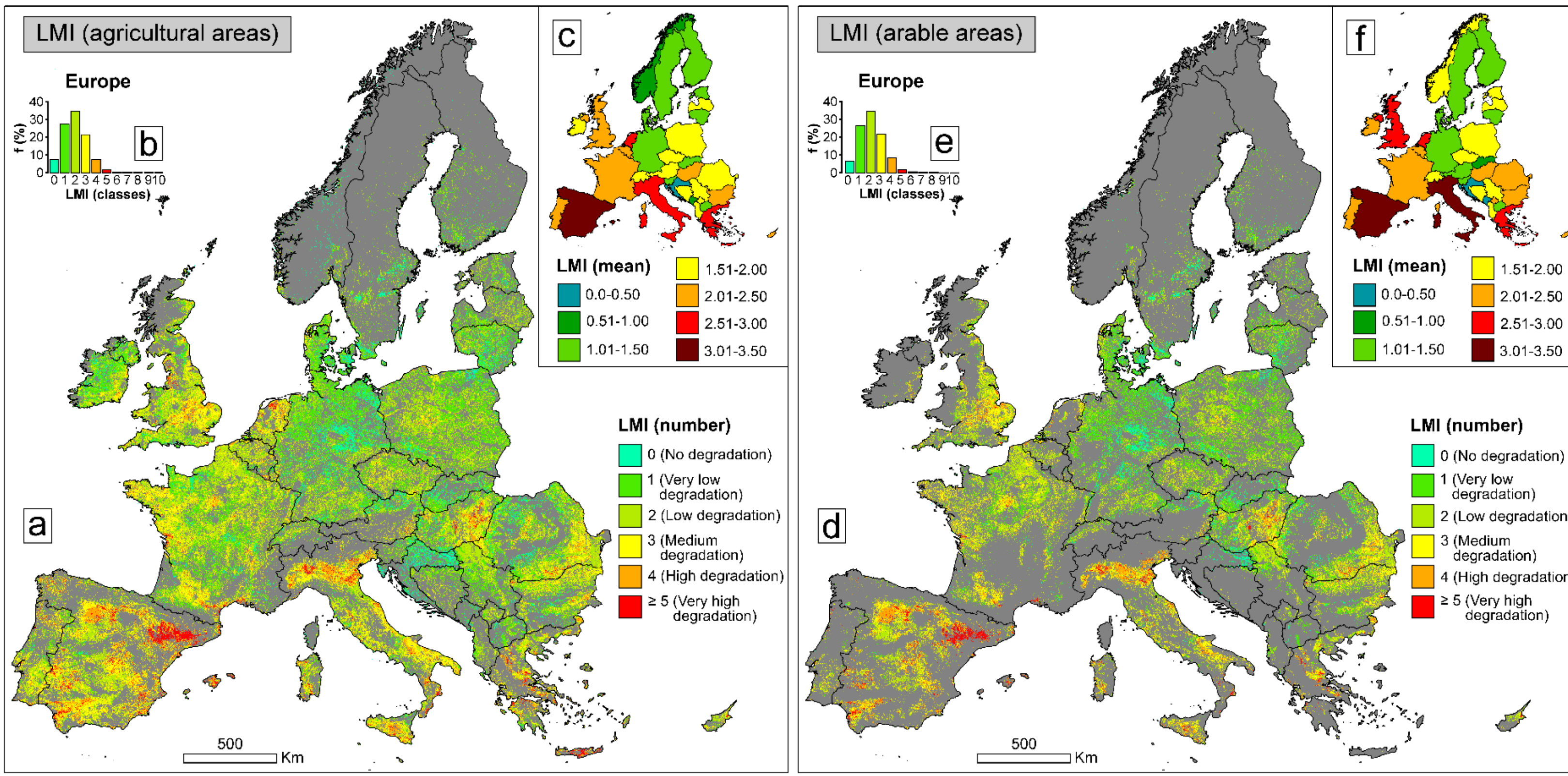

Fig. 7. Land multi-degradation Index (LMI) in Europe. ***a,d*** *Spatial distribution of LMI values in agricultural / arable landscapes.* ***b,e*** *Histogram of LMI values for European agricultural /arable lands.* ***c,f*** *Average number of co-occurring processes in agricultural / arable environments of Europe.*

- *besides the number (LMI), a complex pattern of interacting land degradation pathways was detected in Europe (Figs. 8, 9).*

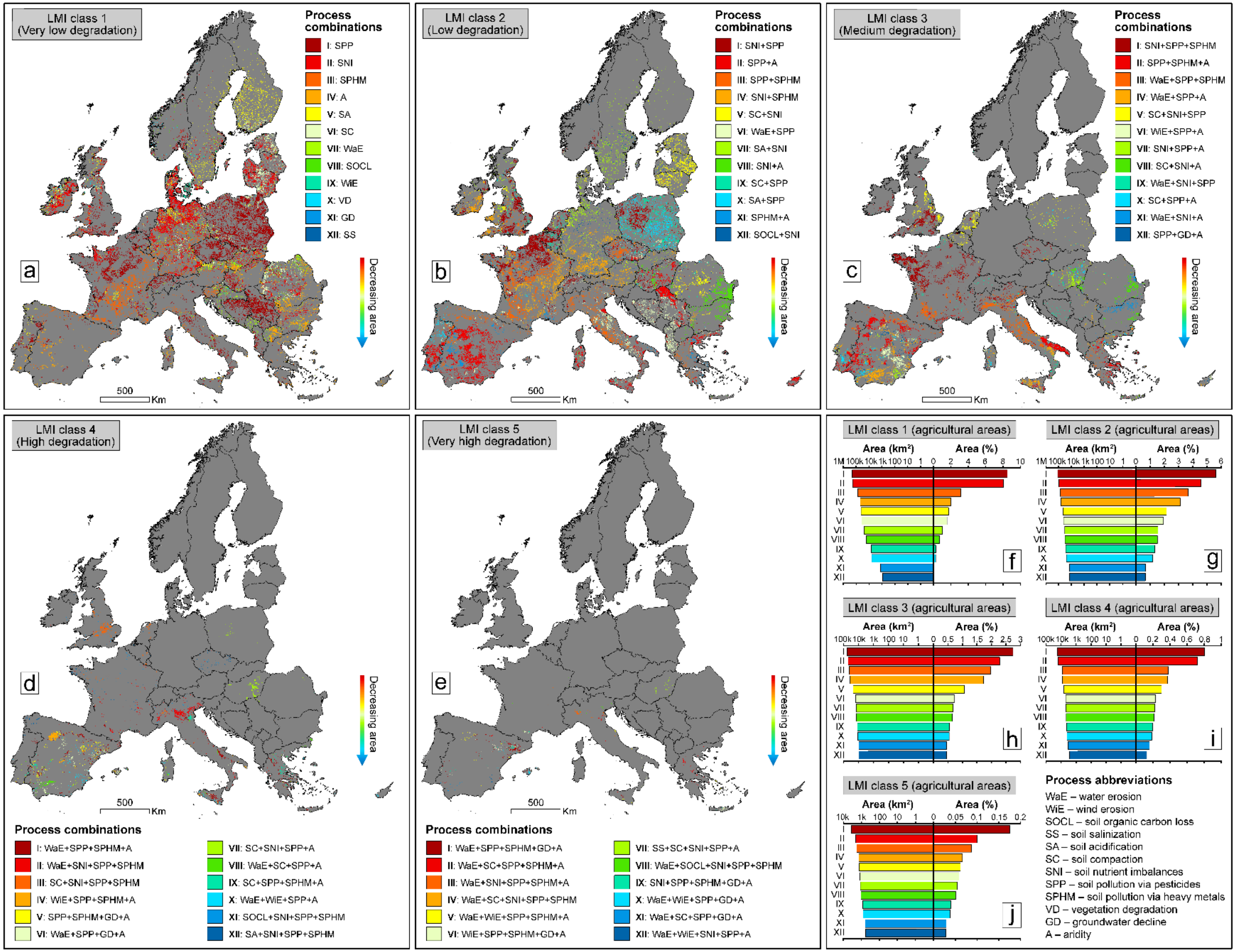

Fig. 8. *Spatial pattern of interacting convergent processes in agricultural environments of Europe.* ***a–e****, Spatial distribution of the dominant (most frequent) co-occurring process types (combinations) in LMI agricultural classes 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e).* ***f–j****, Absolute and percentage-based (% of the total continental agricultural lands) spatial footprint of the dominant co-occurring process types in LMI agricultural classes 1 (f), 2 (g), 3 (h), 4 (i) and 5 (j) (after Prăvălie et al., 2024).*

- *the main combinations of 4 and 5 concurrent processes – the major hotspots of land degradation in Europe (Figs. 8, 9).*

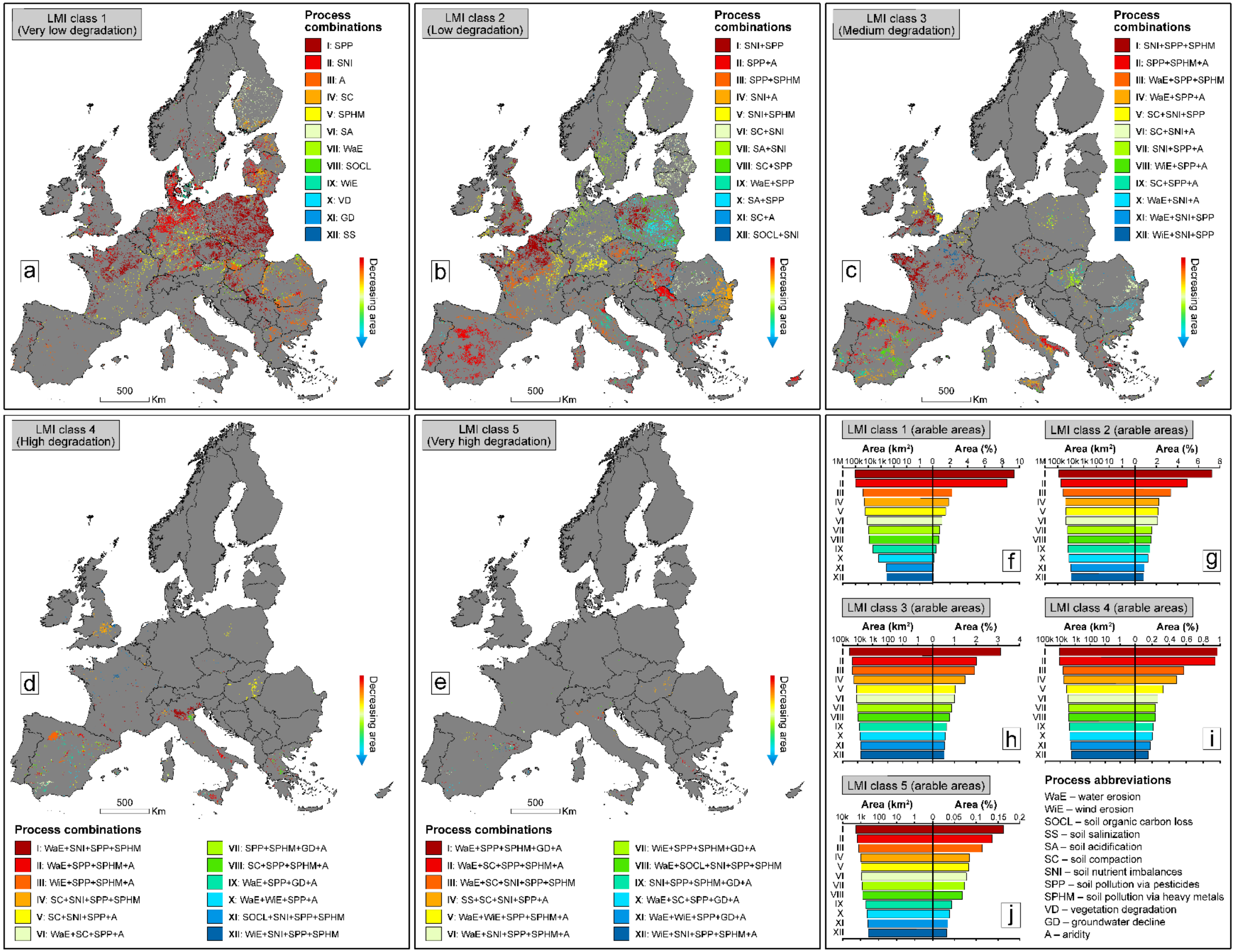

***Fig. 9.** Spatial pattern of interacting convergent processes in arable environments of Europe. **a–e**, Spatial distribution of the dominant (most frequent) co-occurring process types (combinations) in LMI arable classes 1 (a), 2 (b), 3 (c), 4 (d) and 5 (e). **f–j**, Absolute and percentage-based (% of the total continental arable lands) spatial footprint of the dominant co-occurring process types in LMI classes 1 (f), 2 (g), 3 (h), 4 (i) and 5 (j) (after Prăvălie et al., 2024).*

- *research in progress – the multidimensional spatial examination of land degradation processes at the administrative level in Europe(Fig. 10).*

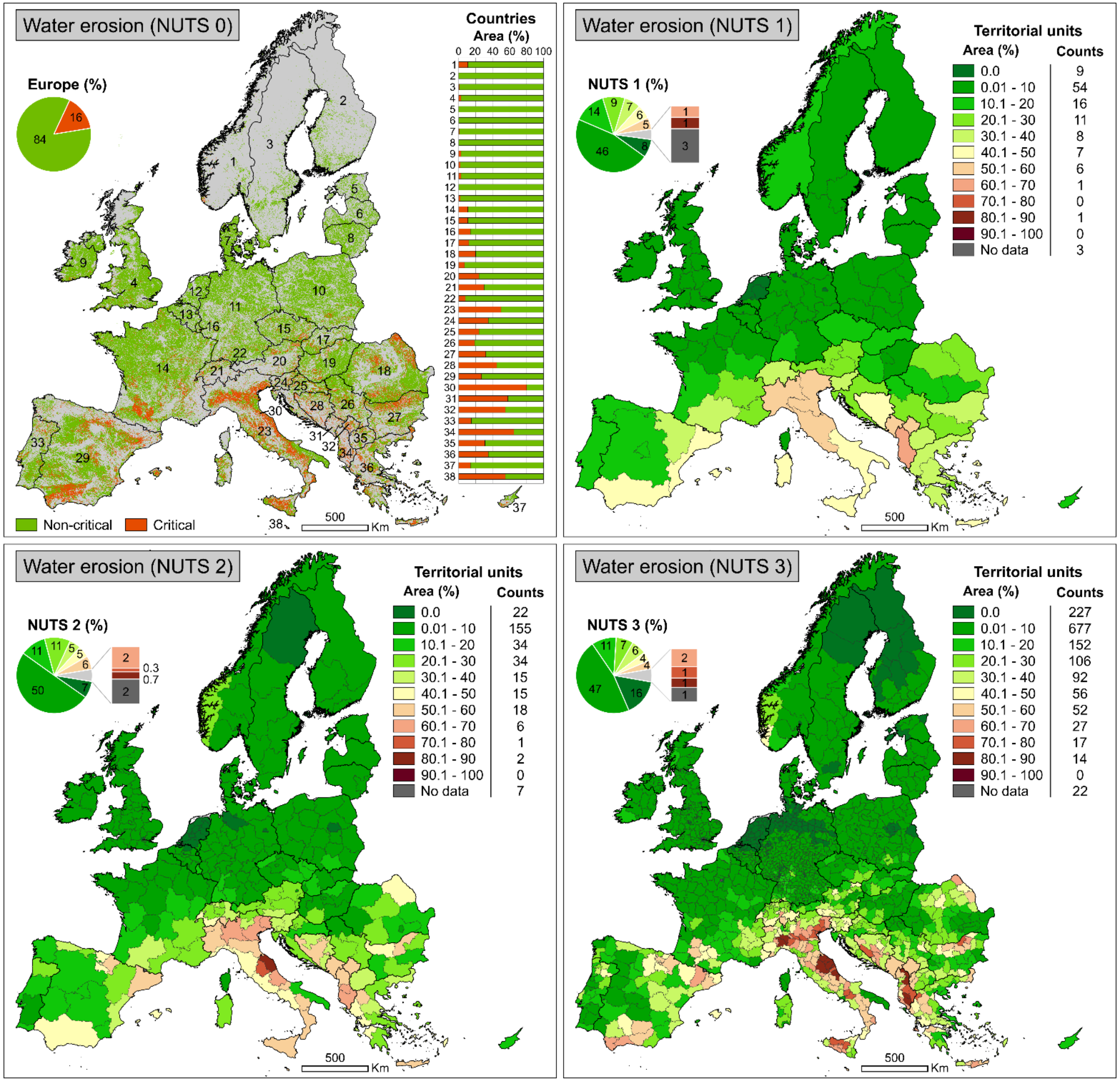

Fig. 10. Spatial pattern of the water erosion process in Europe, at the level of NUTS (Nomenclature of Territorial Units for Statistics) 0, 1, 2 and 3.

❑ *The multidimensional land degradation pathways in Romania:*

- *different spatial patterns of land (uni-) degradation processes across Romania (Fig. 11);*
- *a significant spatial footprint of water (20% of total national agricultural area), tillage (14%) and wind (8%) erosion across the Romanian agricultural lands (Fig. 11);*

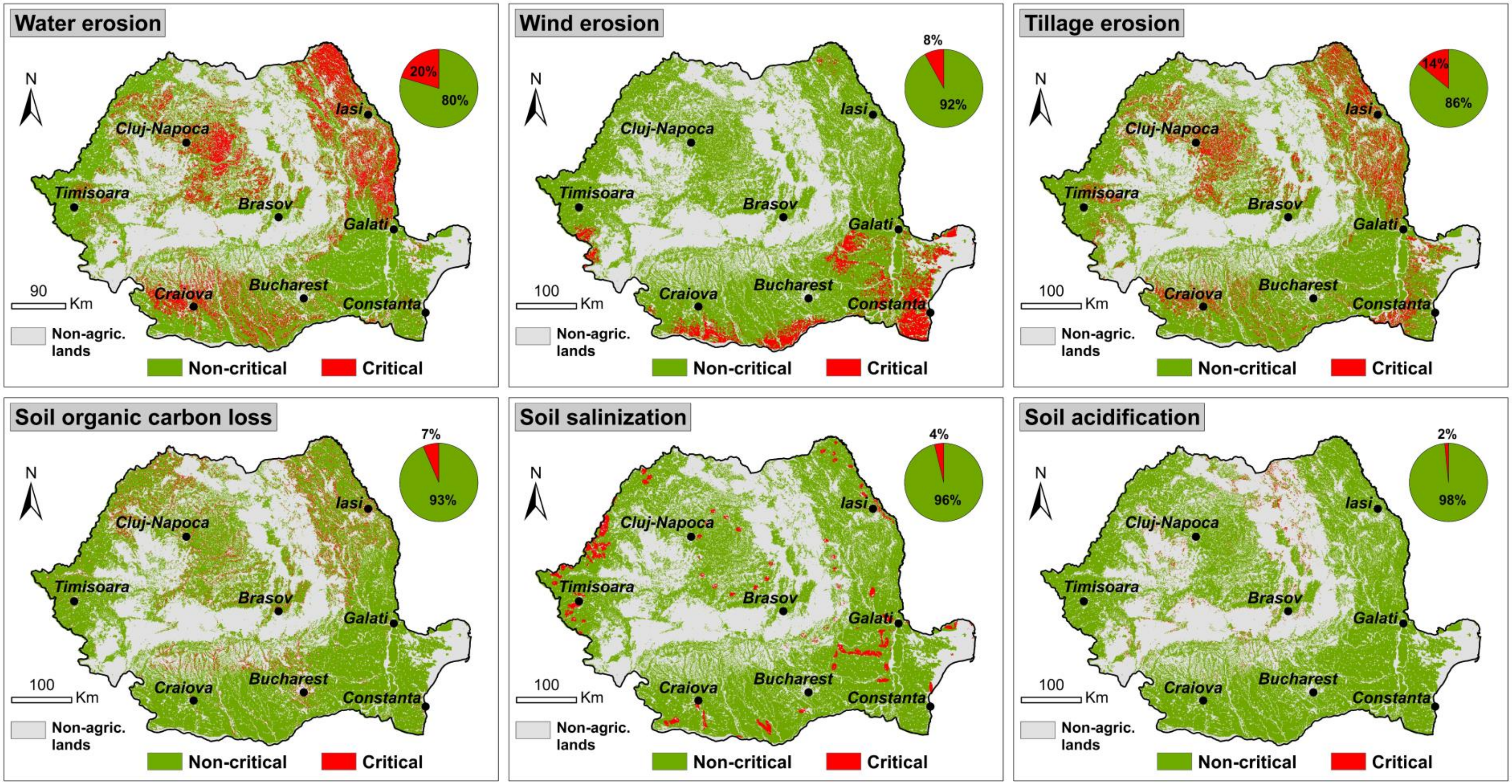

Fig. 11. *Mapping of the water erosion, wind erosion, tillage erosion, soil organic carbon loss, soil salinization and soil acidification processes in Romanian agricultural areas.*

- *also, significant agricultural lands affected by critical conditions of soil compaction (40%), aridity (24%) and soil nutrient imbalances (22%) (Fig. 12);*
- *these 3 processes (and water erosion) are the main driving forces of land degradation in Romania (Figs. 11, 12);*
- *the extra-Carpathian areas - the most affected by the multidimensional pathways of land degradation (Figs. 11, 12).*

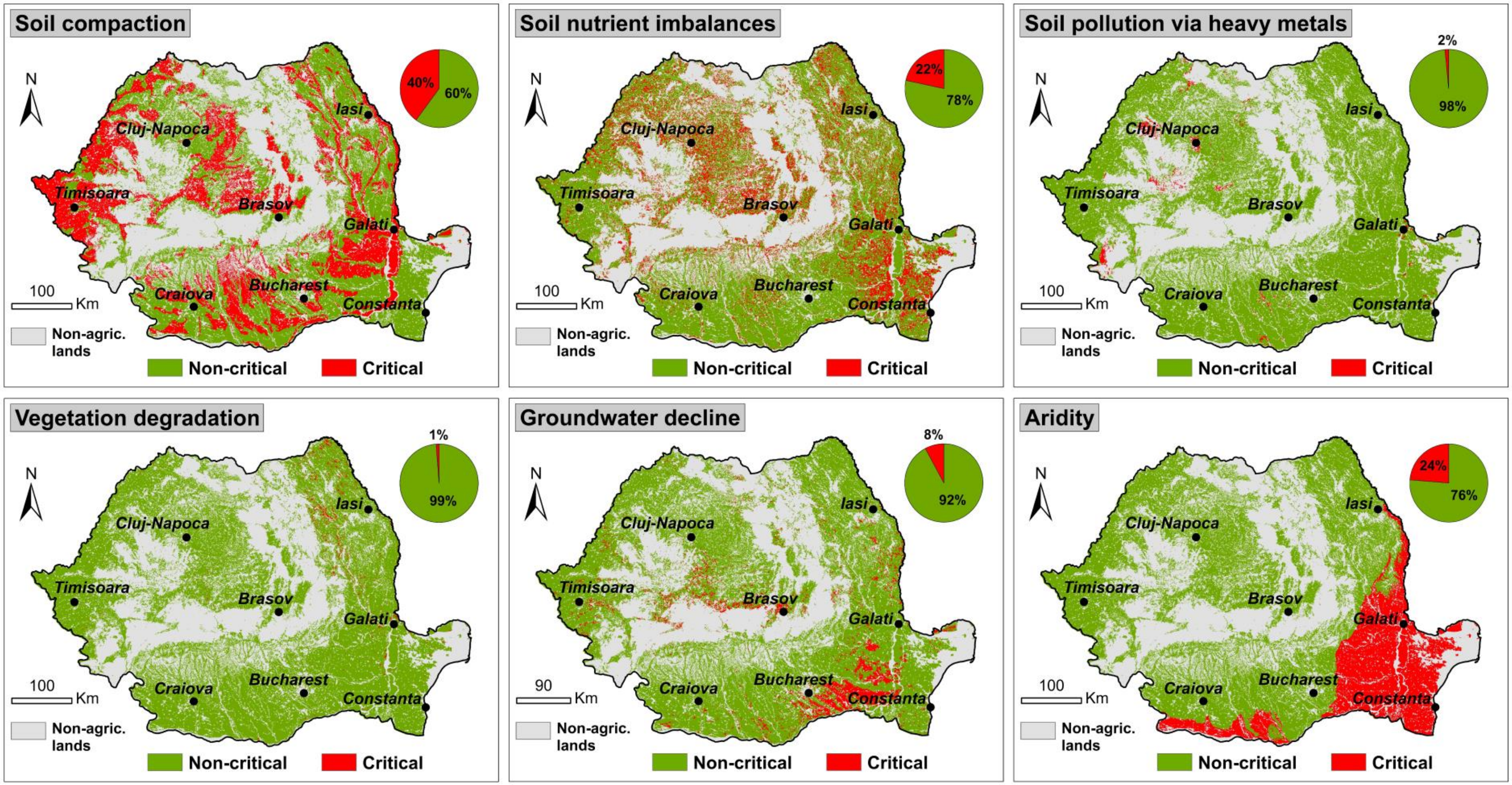

Fig. 12. Mapping of the soil compaction, soil nutrient imbalances, soil pollution via heavy metals, vegetation degradation, groundwater decline and aridity processes in Romanian agricultural areas.

- *up to 9 co-occuring processes in Romania, detected with LMI in the extra-Carpathian agricultural areas (Fig. 13).*

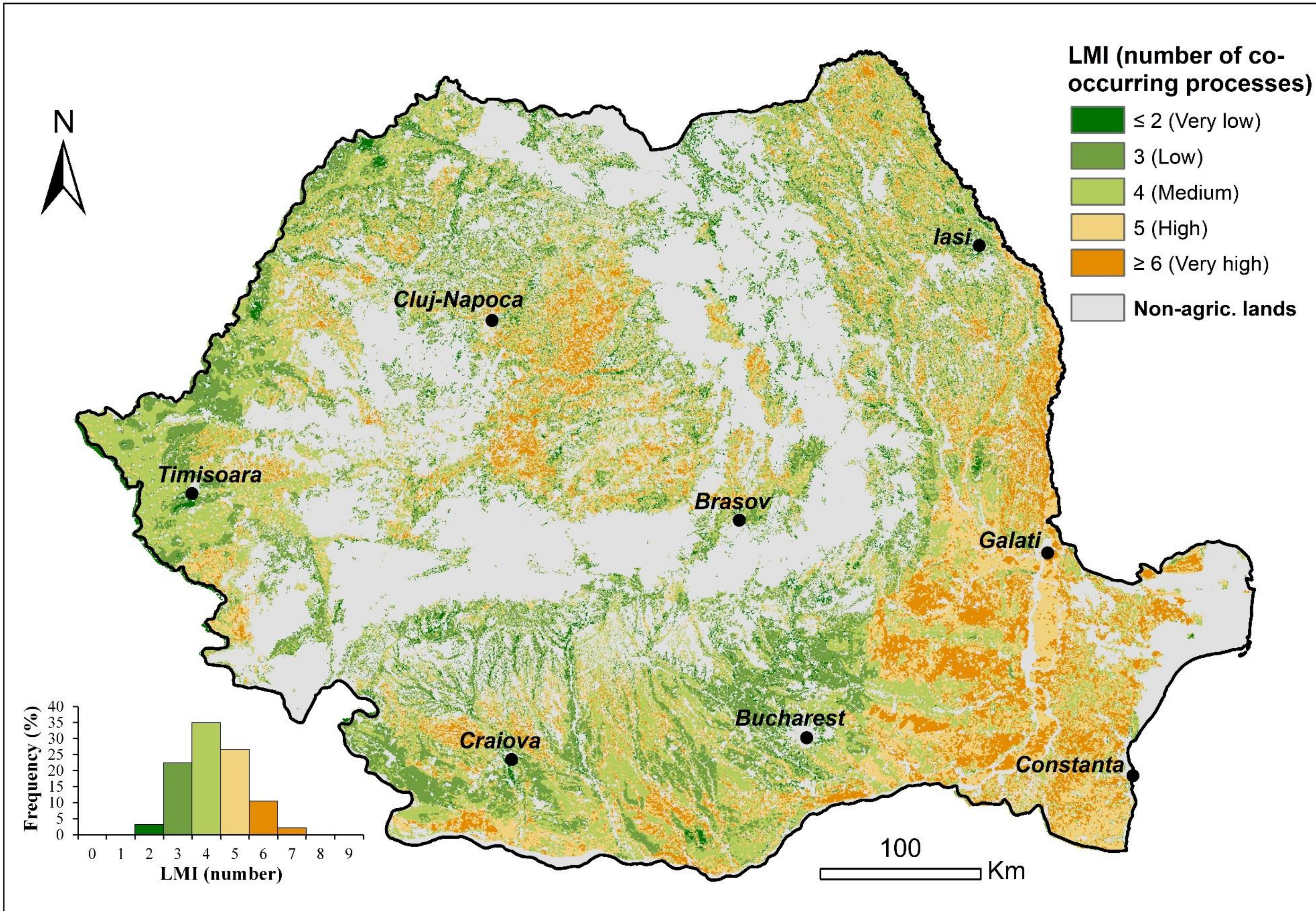

Fig. 13. *Land multi-degradation Index (LMI) across the agricultural environments of Romania.*

❑ *Conclusions:*

- ✓ *European and Romanian agricultural systems – under the pressure of various land degradative conditions;*

- ✓ *the multidimensional land degradation crisis – addressed continentally and nationally in this research, using large-scale geospatial data and complex methods;*

- ✓ *about 10% of agricultural lands of Europe are cumulatively affected by high and very high degradation degradative conditions;*

- ✓ *the high and very high degradative conditions affect even more the agricultural areas of Romania, according to ongoing investigations;*

- ✓ *our findings will enable policy makers to develop knowledge-based strategies for land degradation mitigation and other critical European sustainable development goals;*

- ✓ *the findings obtained in this research are important for some key land degradation policies, like Land Degradation Neutrality, the 2030 Agenda for Sustainable Development or Paris Agreement.*

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A unifying modelling of multiple land degradation pathways in Europe

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Land degradation is a complex socio-environmental threat, which generally occurs as multiple concurrent pathways that remain largely unexplored in Europe. Here we present an unprecedented analysis of land multi-degradation in 40 continental countries, using twelve dataset-based processes that were modelled as land degradation convergence and combination pathways in Europe's agricultural (and arable) environments. Using a Land Multi-degradation Index, we find that up to 27%, 35% and 22% of continental agricultural (~2 million km^2) and arable (~1.1 million km^2) lands are currently threatened by one, two, and three drivers of degradation, while 10–11% of pan-European agricultural/arable landscapes are cumulatively affected by four and at least five concurrent processes. We also explore the complex pattern of spatially interacting processes, emphasizing the major combinations of land degradation pathways across continental and national boundaries. Our results will enable policymakers to develop knowledge-based strategies for land degradation mitigation and other critical European sustainable development goals.