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A pan-European multi-process and multi-scale assessment of agricultural land degradation: Towards an integrated geographical approach for sustainable development in Europe

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- ***General objective:*** *spatial modelling and examination of 12 land degradation processes in Europe, across multiple spatial scales (from the continental to the sub-regional level) within continental agricultural environments.*

- ***Structure:***

    - *the global picture of land degradation, in the context of climate change and other environmental issues;*
    - *selecting, collecting and processing geospatial data for modelling multiple land degradation pathways across Europe;*
    - *multi-process and multi-scale assessment of agricultural land degradation in Europe;*
    - *the relevance of a multidimensional assessment of land degradation in Europe for the sustainable development of the continent;*
    - *conclusions.*

❑ *1. The global picture of land degradation, in the context of climate change and other environmental issues:*

- ***lands**, with their defining elements of soils, vegetation and inland water resources, are threatened worldwide by many degradation processes that drive the decrease or collapse of biological and economic productivity, biodiversity, ecological integrity and complexity or of ecosystem services in general;*
- ***land degradation**: reduction or loss of biological or economic productivity of lands, due to many degradation processes, such as water/eolian soil erosion, physical/chemical/biological/economic land deterioration, or long-term loss of vegetation (UNCCD, 1994);*
- *a prolonged decline of ecosystem functions and services of land systems (soils, vegetation, water resources) (Prăvălie, 2016, 2021);*
- *land degradation = **desertification** if it occurs in dryland systems (except for hyper-arid areas) (UNCCD, 1994; Safriel et al., 2005; Reynolds et al., 2007; Prăvălie, 2016) (Fig. 1);*

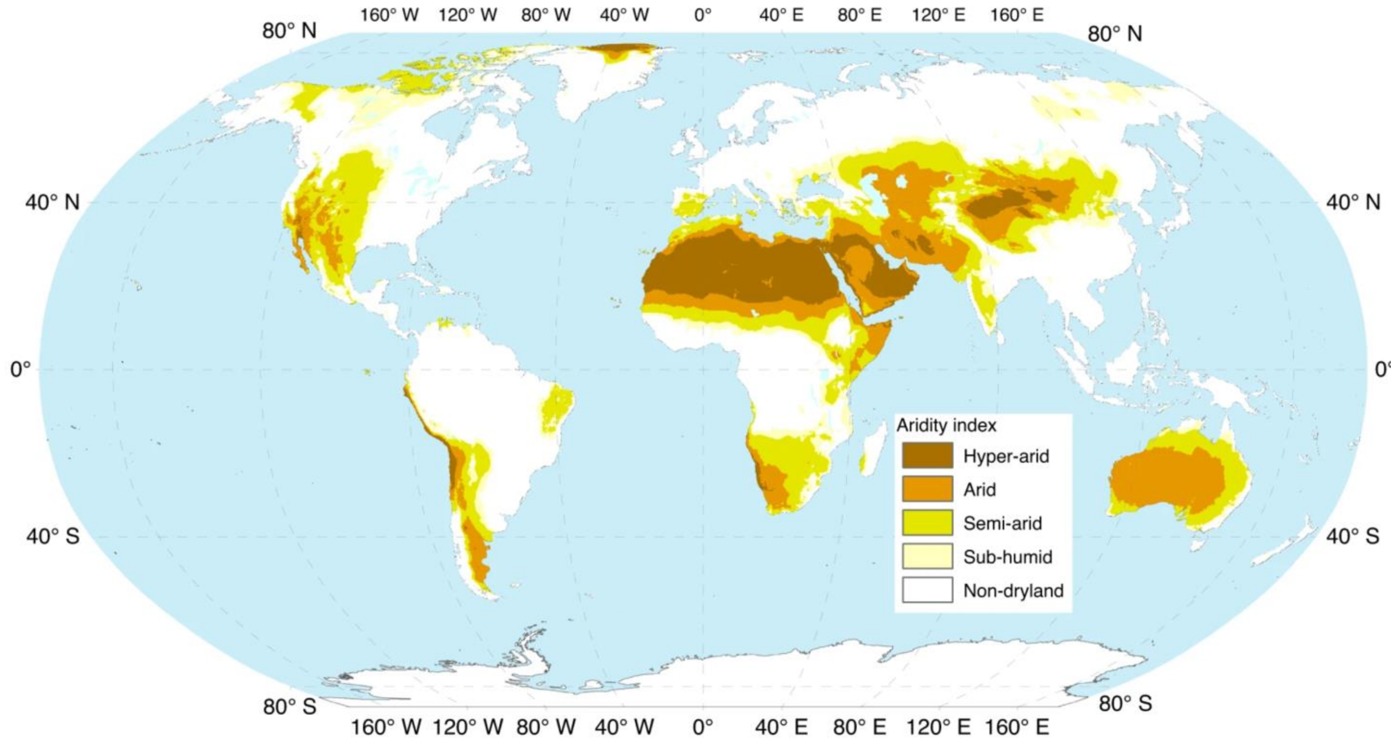

***Fig. 1.** Spatial representation of the global dryland systems (Source: Wang et al., 2022).*

- *from a holistic perspective, land degradation can be approached through several evaluation coordinates, such as **drivers** (triggering factors), **threats** (processes) or **consequences** (ecological and socio-economic) (Fig. 2);*
- *there are **at least 17 land degradation pathways** (processes) that are active on various spatial scales across the planet (Fig. 3);*
- *these land degradation processes can be approached in a singular / separate perspective (**land uni-degradation**) or in a synergistic / convergent perspective (**land multi-degradation**);*

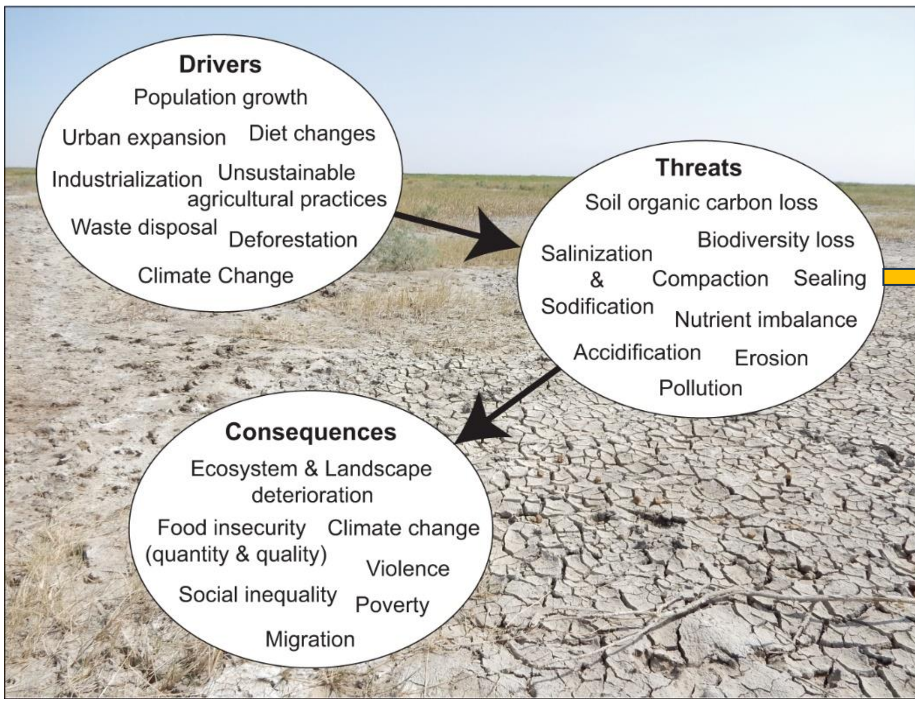

__Fig. 2.__ Conceptual framework of drivers, threats and consequences of land degradation (Source: Kraamwinkel et al., 2021).

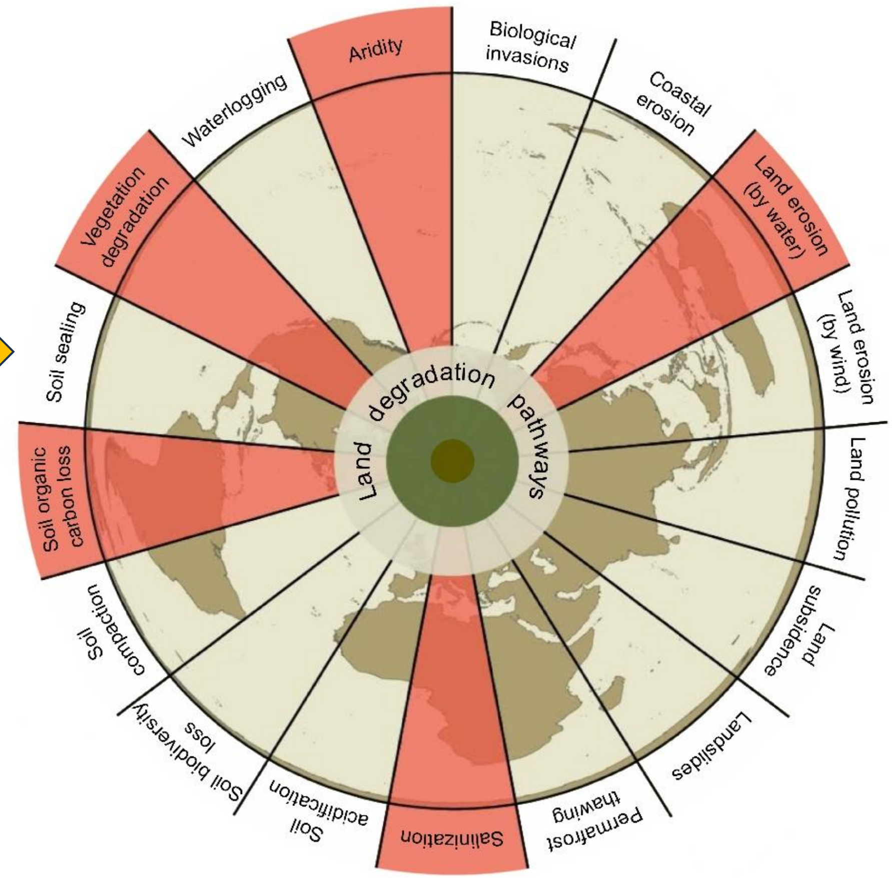

__Fig. 3.__ Schematic approach to land degradation pathways currently occurring globally (Source: Prăvălie, 2021).

- ***global environmental issues*** – *major environmental imbalances capable of disrupting the planet's biophysical systems and, implicitly, human welfare and even humanity's very existence;*

- *the environment has constantly changed over geological time, but the extent, intensity and diversity of its changes accelerated after 1950 (The Great Acceleration);*

- *there are about **10 global environmental issues,** including **land degradation** (Fig. 4);*

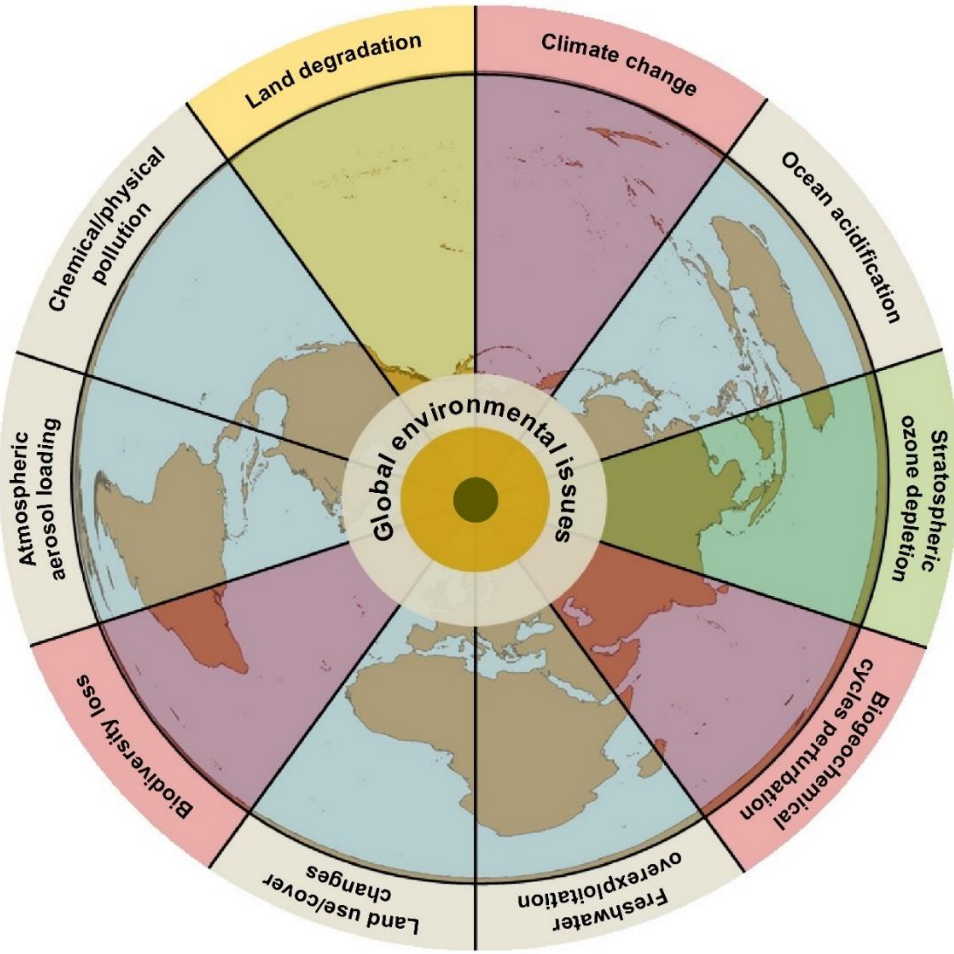

Fig. 4. *Schematic approach to global environmental issues currently occurring globally.*

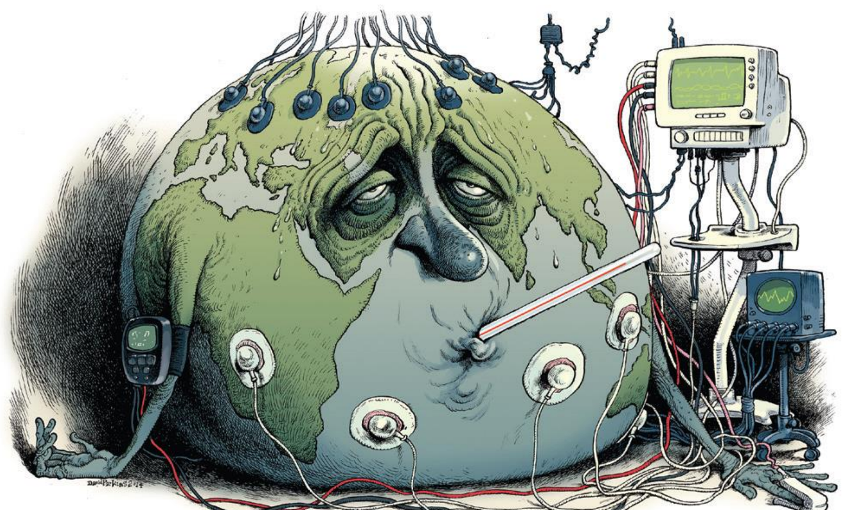

Fig. 5. *Suggestive illustration of the Earth under the pressure of environmental issues (Source: Victor & Kennel, 2014).*

- *these environmental disturbances threaten the world's ecosystems and the Earth as a whole (Fig. 5);*

- ***land degradation*** *(and climate change) – among the most serious environmental issues humanity is currently facing (Victor & Kennel, 2014; Borrelli et al., 2017; United Nations, 2019);*

- *there are many links between the environmental disturbances, from local to global scale (Fig. 6);*
- *land degradation (and desertification) is influenced or triggered by climate change (or other environmental changes, such as biodiversity loss), which in turn amplifies climate change through feedback mechanisms (Fig. 6);*
- *these interlinked issues represent a **complex challenge for the sustainable management of land systems**.*

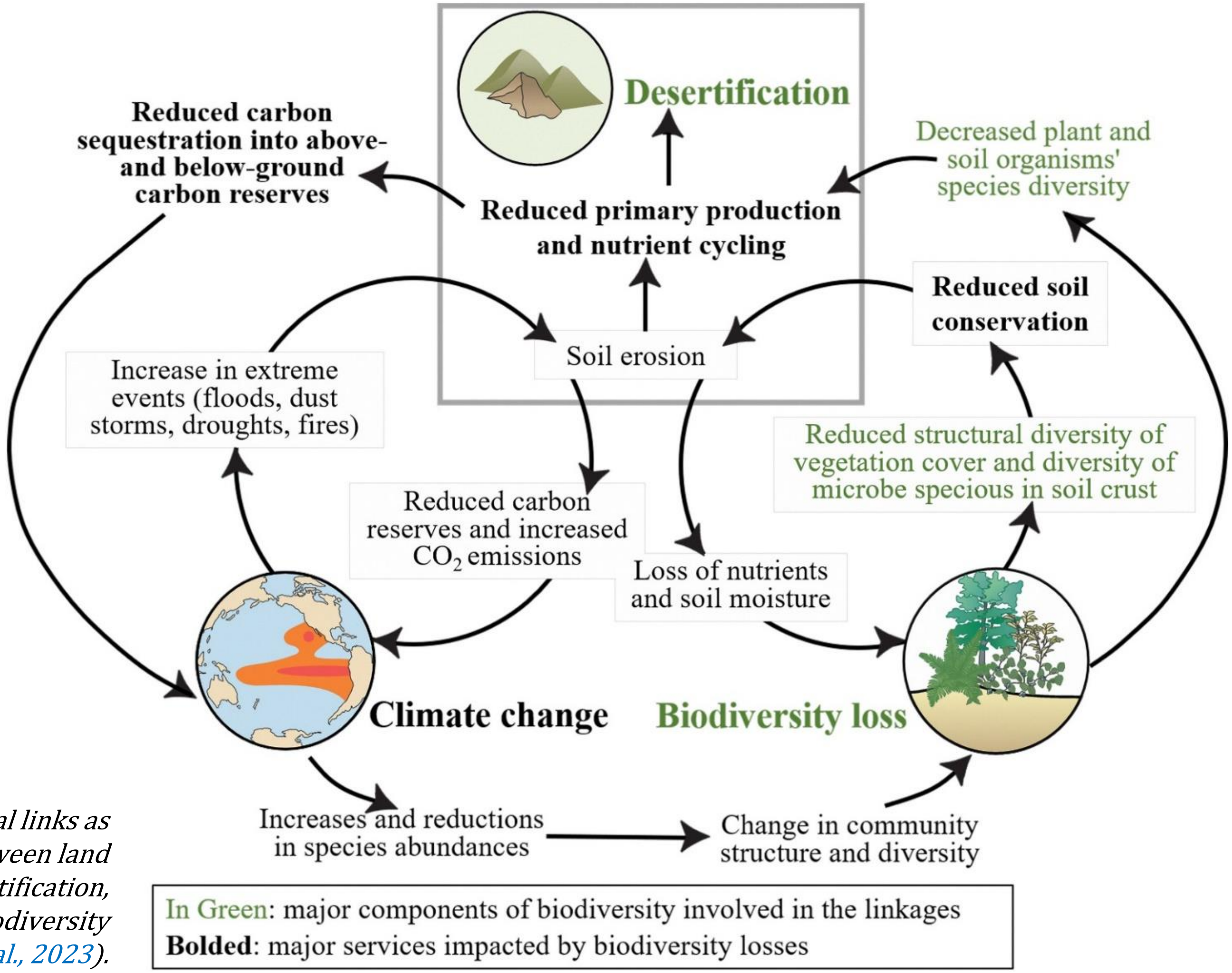

Fig. 6. *Conceptual links as feedbacks between land degradation / desertification, climate change and biodiversity loss (Source: Wang et al., 2023).*

❑ *2. Selecting, collecting and processing geospatial data for modelling multiple land degradation pathways across Europe:*

- *this pan-European analysis focuses on modelling and assessing 12 land degradation (LD) processes, available on the ESDAC platform (ESDAC, 2024) – **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**;*

- *these LD processes were **selected** as they are highly relevant for addressing agricultural land degradation in Europe and worldwide (Table 1);*

Table 1. *The 12 processes were selected for this continental analysis, considering the 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*

- *the 12 LD processes were explored within agricultural boundaries (collected from the CORINE Land Cover database) (CLC, 2018) of* ***38 European countries*** *(Fig. 7);*
- *a cumulative agricultural area of ~2.1 million km^2 over the 38 European countries;*

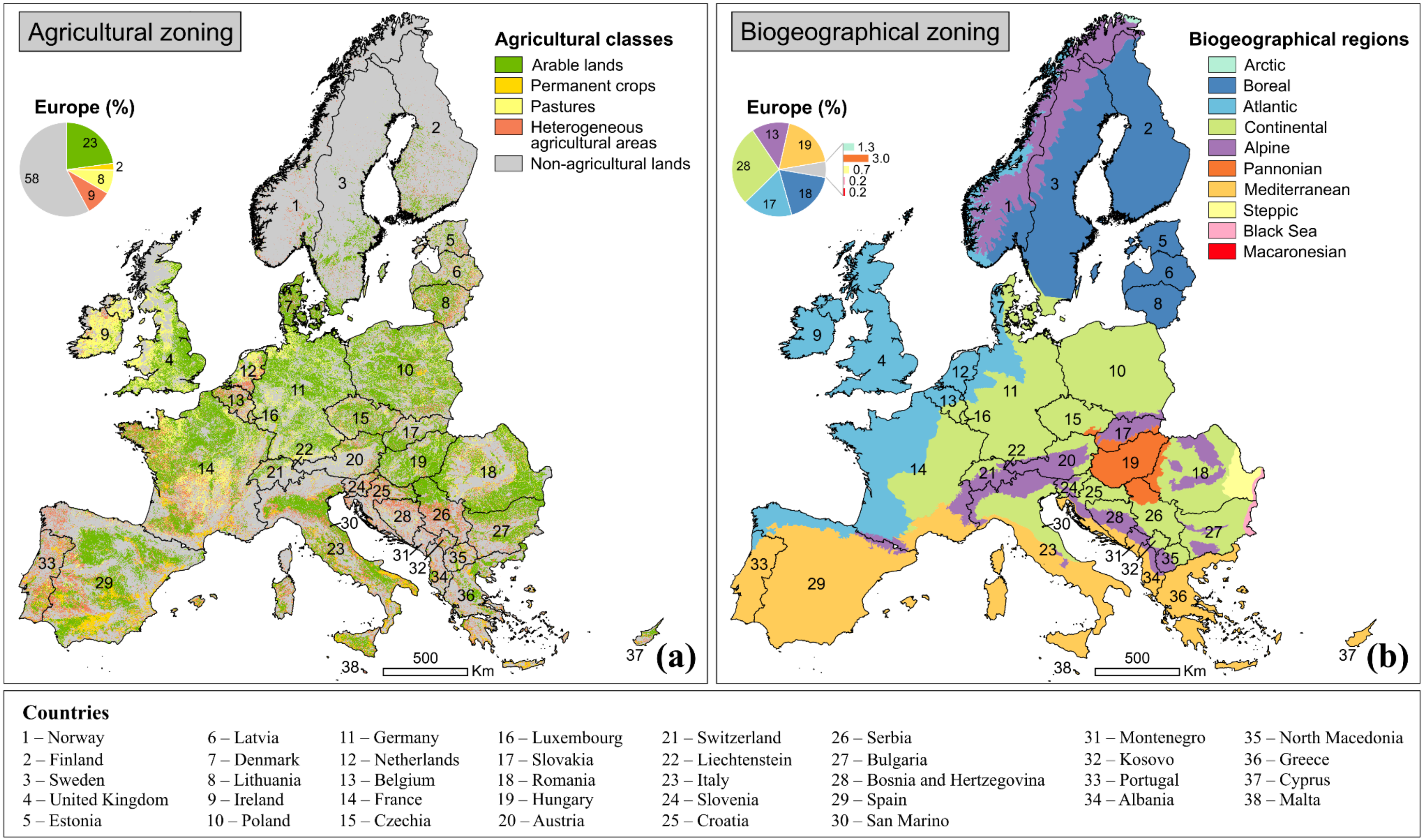

Fig. 7. *Study area (38 European countries) with various agricultural (a) and biogeographical (b) conditions.*

- *the 12 rasters of LD, with various features (Table 2), were structured into 2 classes – Critical and Non-critical (Prăvălie et al., 2024);*

- *finally, the critical classes were mapped and further quantified as absolute (in km^2) and percentage (%) areas throughout the agricultural landscapes of Europe, at the five spatial scales – the continental level and the NUTS (Nomenclature of Territorial Units for Statistics) levels 0, 1, 2, and 3 of 38 analysed countries;*

- *the vector (shapefile) data for NUTS 0 (38 units, corresponding to national boundaries), NUTS 1 (major socio-economic regions, 114 units), NUTS 2 (basic regions for the application of regional policies, 307 units) and NUTS 3 (small regions for specific diagnoses, 1440 units) boundaries – acquired from the Eurostat platform (Eurostat, 2024);*

- *the multi-process and multi-scale evaluation of LD – performed at 500 m, using the ETRS89 Lambert Azimuthal Equal Area coordinate reference system (Annoni et al., 2003).*

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.

❑ *3. Multi-process and multi-scale assessment of agricultural land degradation in Europe:*

- *the multi-process examination of LD – a complex spatial pattern of the 12 processes across the multiple geographical scales of Europe (Figs. 8-19);*

- *the largest environmental threats to European agriculture, in terms of the spatial footprint of critical intensity conditions (within NUTS 0 / national level):*

  - *soil pollution via pesticides (52%) (Fig. 15);*
  - *soil nutrient imbalances (39%) (Fig. 14);*
  - *soil pollution via heavy metals (31%) (Fig. 16);*
  - *aridity (25%) (Fig. 19);*
  - *water erosion (15%) (Fig. 8);*
  - *soil compaction (15%) (Fig. 13);*

- *the largest extent of soil pollution via pesticides (Fig. 15) – explained by the presence of a large number of toxic pesticides (dozens of herbicides, insecticides, and fungicides) impacting continental agricultural lands (Prăvălie et al., 2024);*

- *soil nutrient (nitrogen and phosphorus) imbalances – the second most extensive pathway of agricultural LD across the continent (Fig. 14), explained by large-scale N and P deficit or surplus conditions in European soils (Prăvălie et al., 2024);*

- *a much more complex geographical pattern of LD processes at NUTS 1, 2 and 3 levels (Figs. 8-19).*

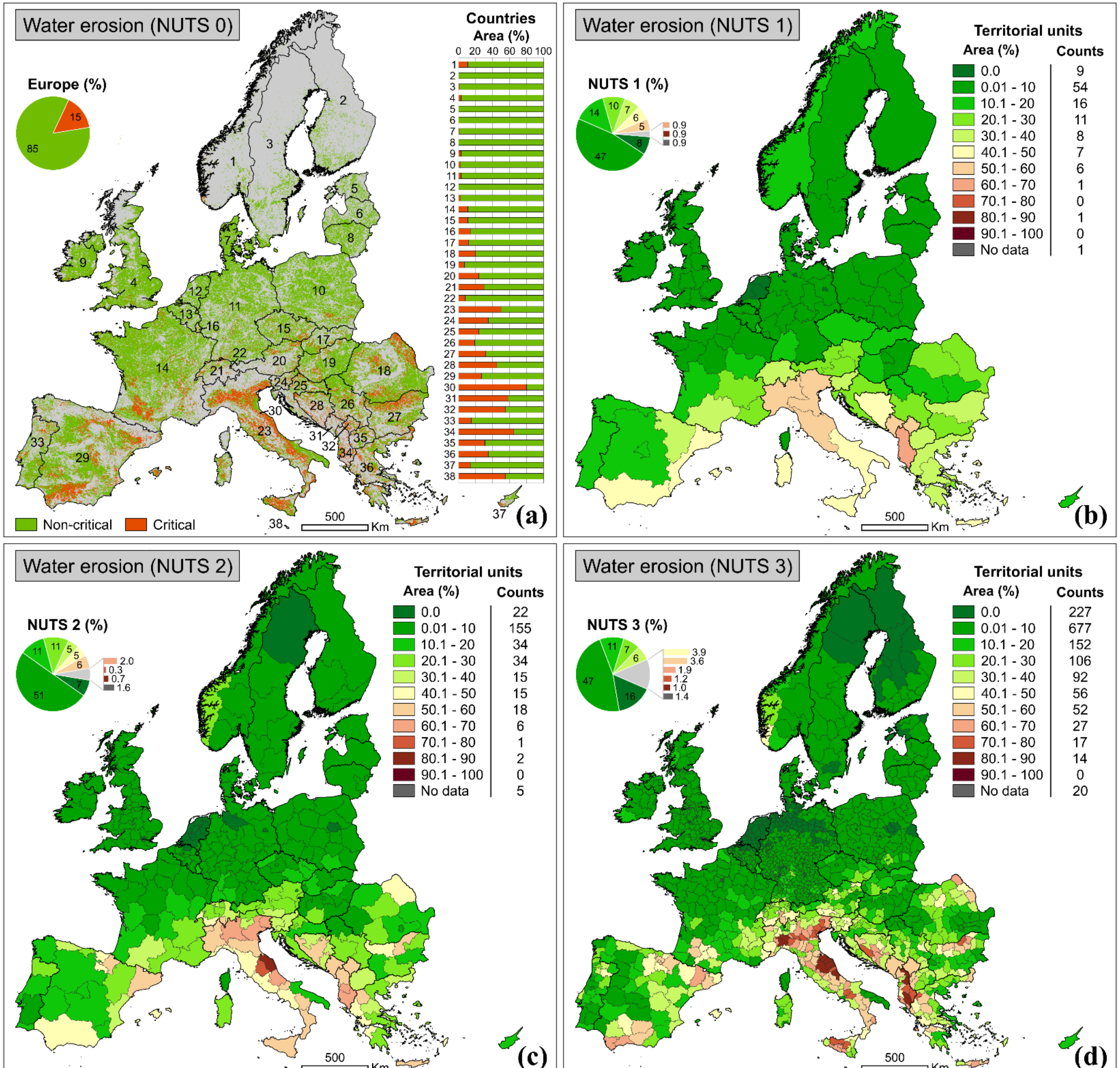

Fig. 8. *Spatial pattern of soil water erosion in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

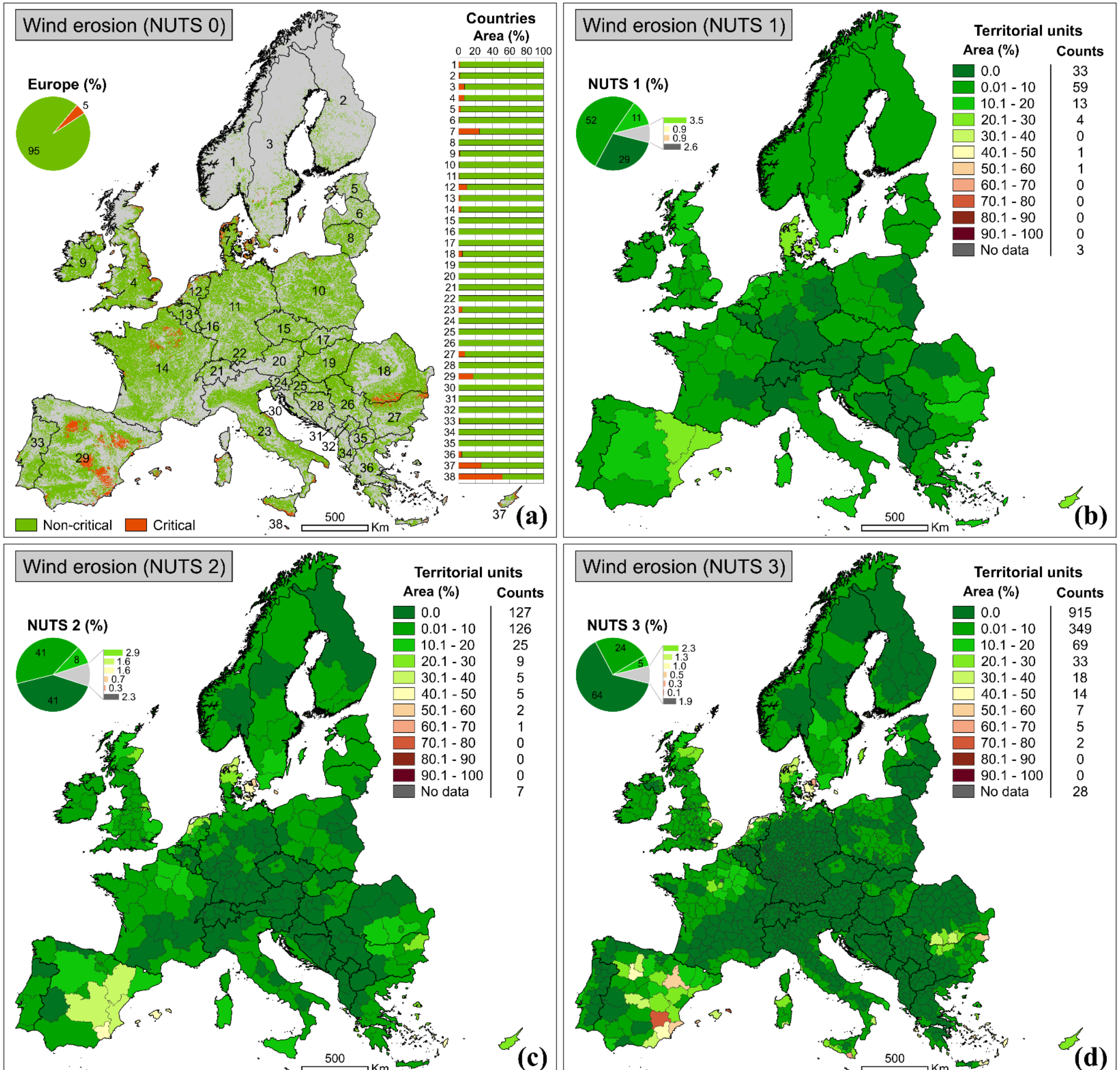

Fig. 9. *Spatial pattern of soil wind erosion in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

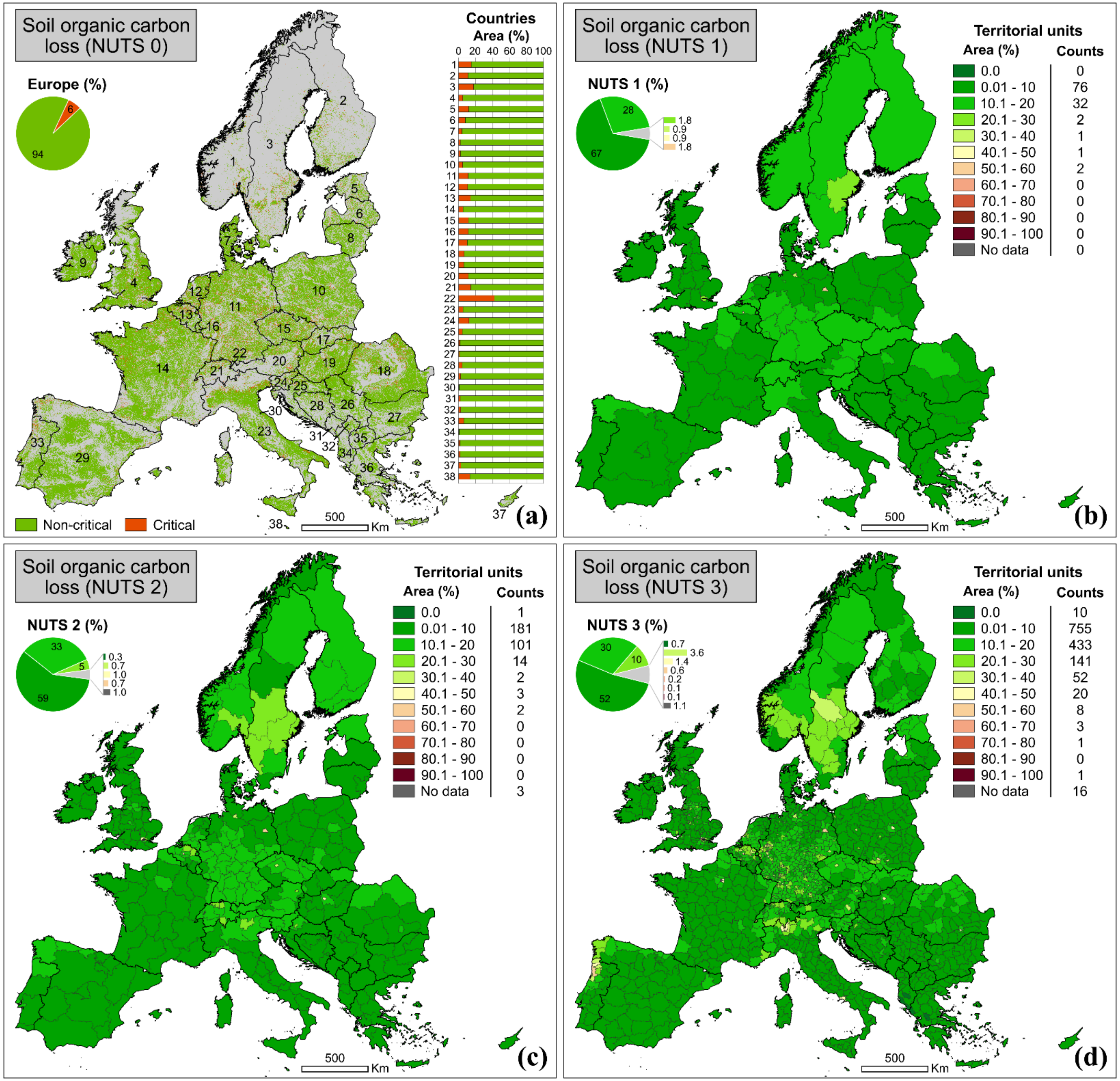

Fig. 10. Spatial pattern of soil organic carbon loss in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.

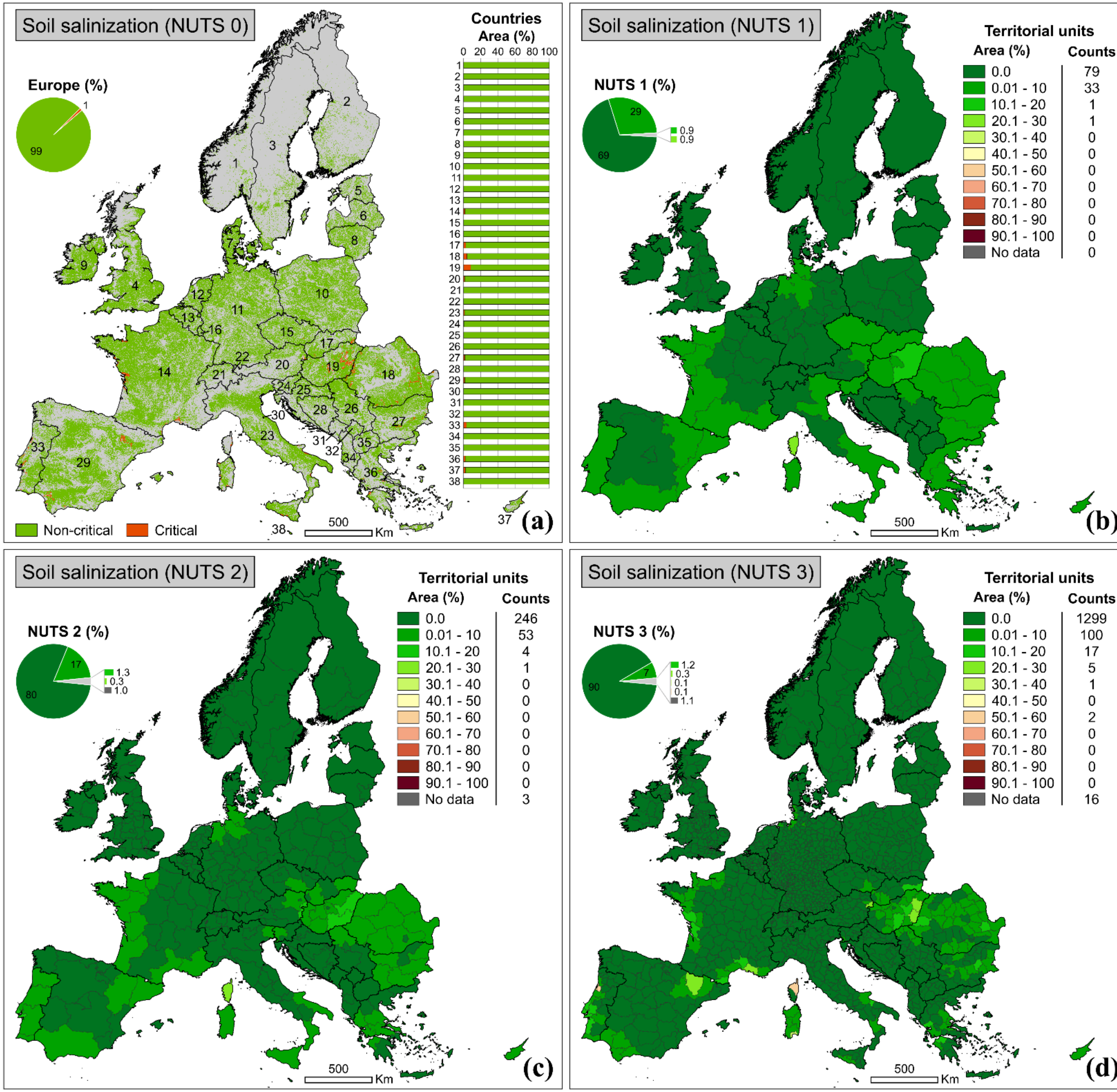

Fig. 11. *Spatial pattern of soil salinization in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

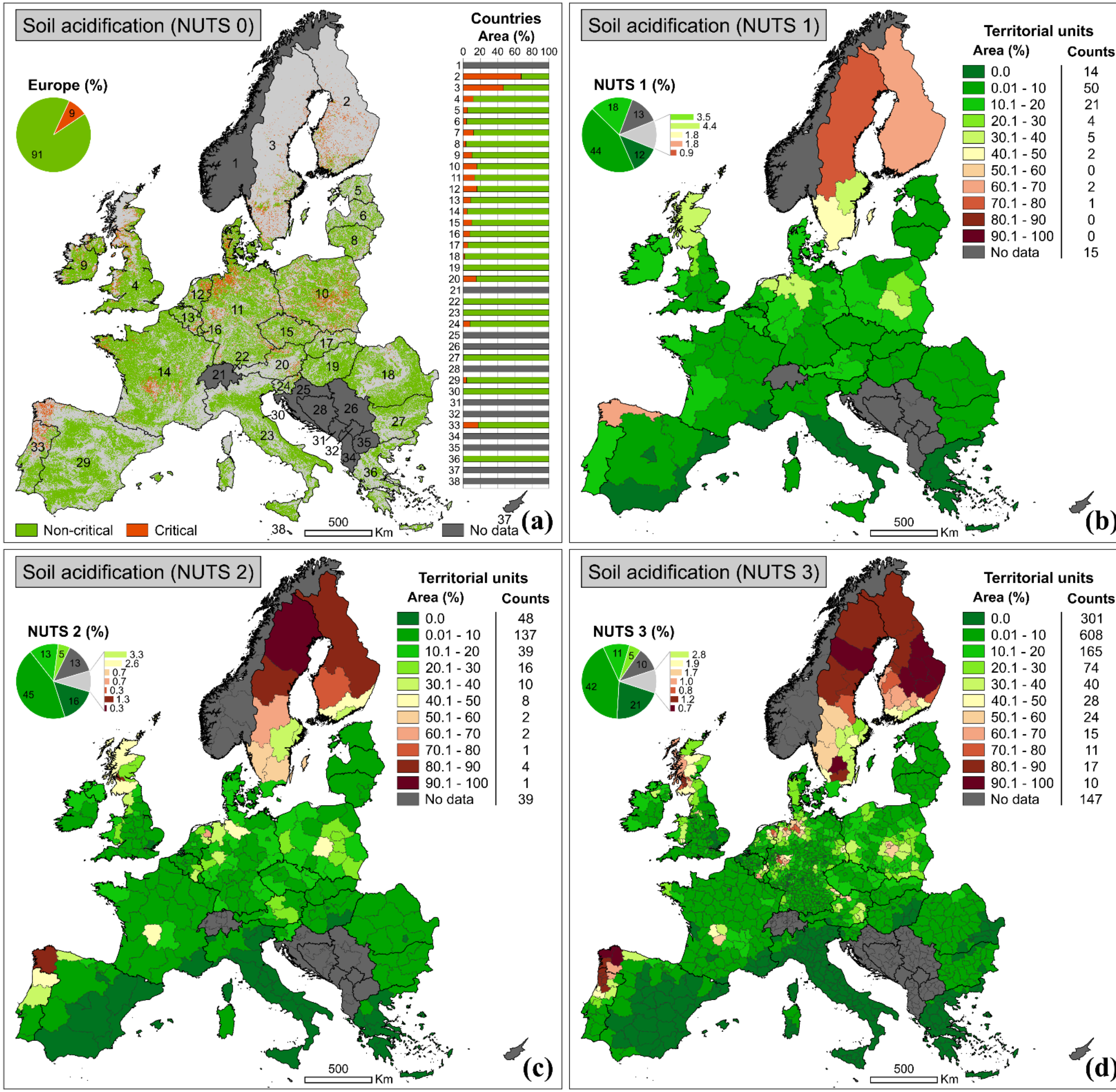

Fig. 12. *Spatial pattern of soil acidification in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

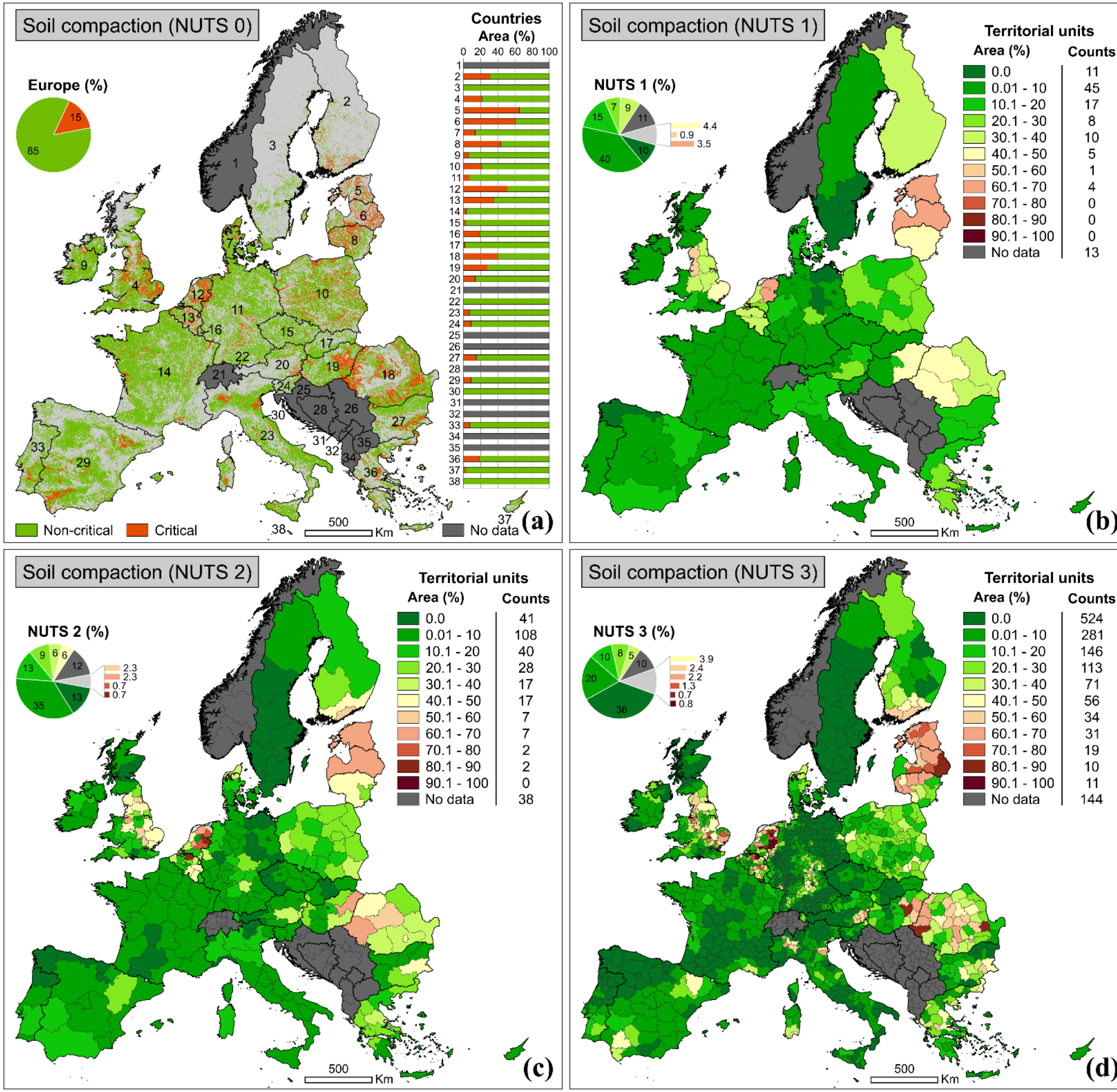

Fig. 13. *Spatial pattern of soil compaction in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

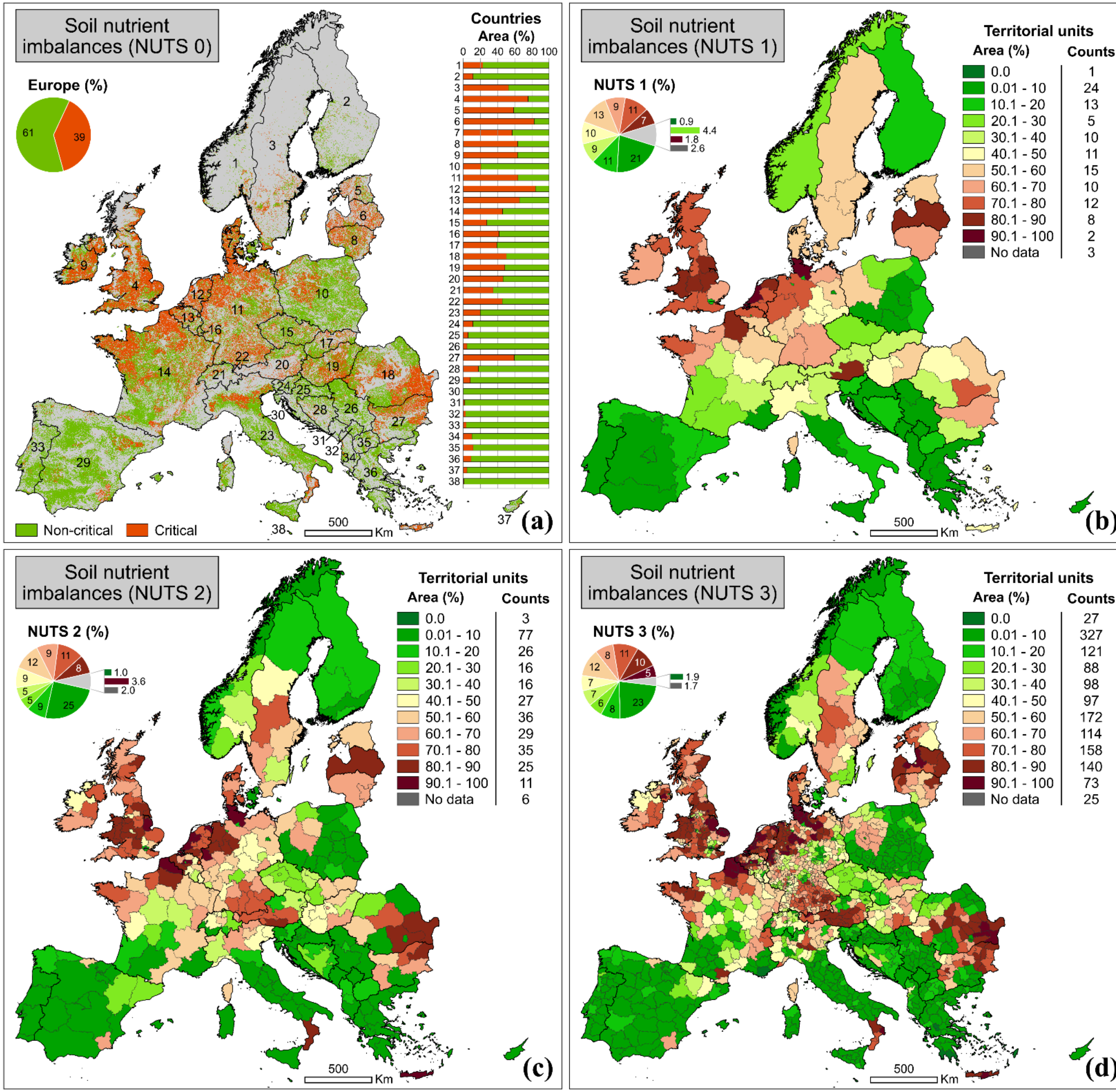

Fig. 14. *Spatial pattern of soil nutrient imbalances in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

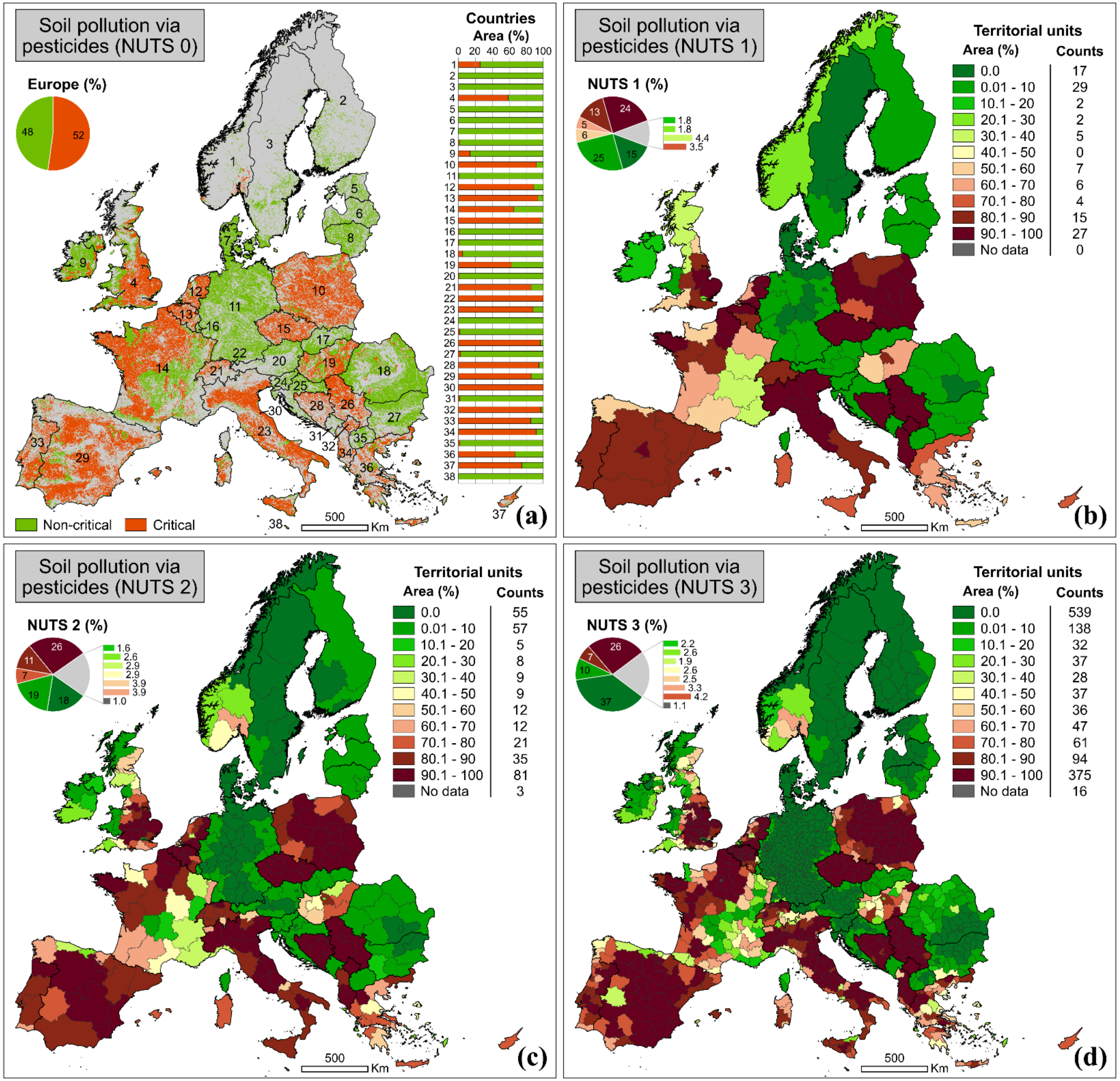

Fig. 15. Spatial pattern of soil pollution via pesticides in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.

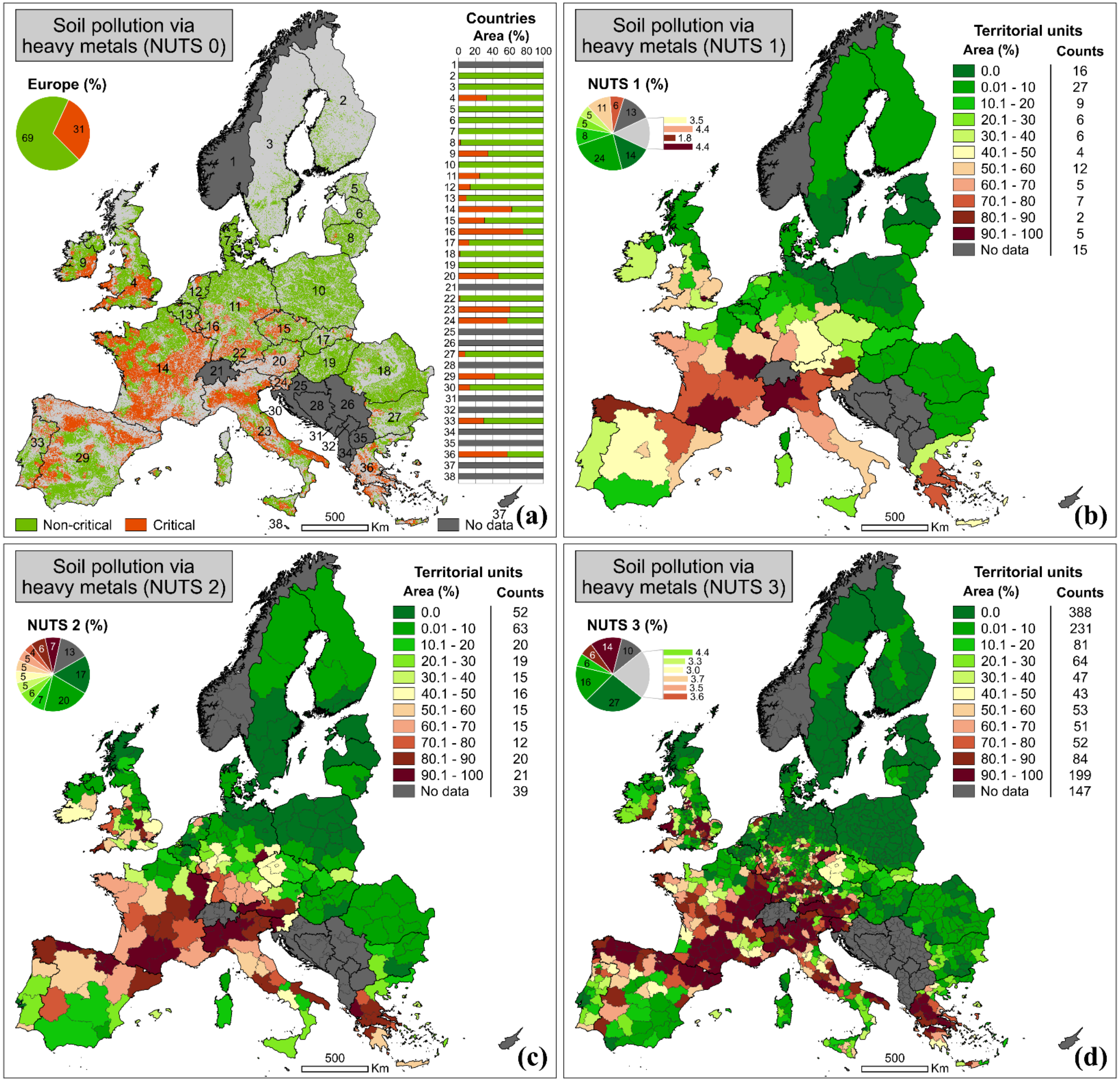

Fig. 16. *Spatial pattern of soil pollution via heavy metals in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

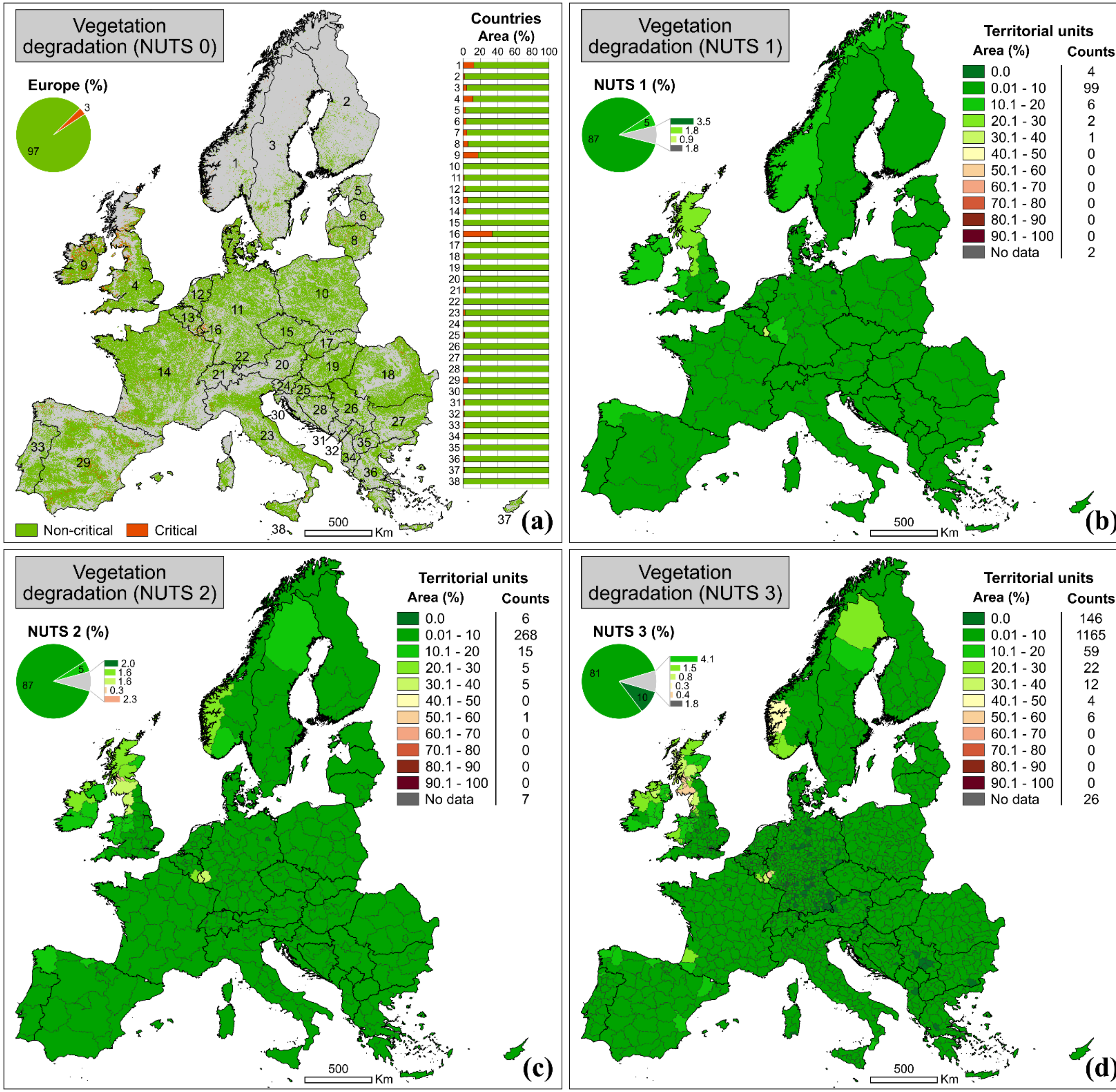

Fig. 17. *Spatial pattern of vegetation degradation in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

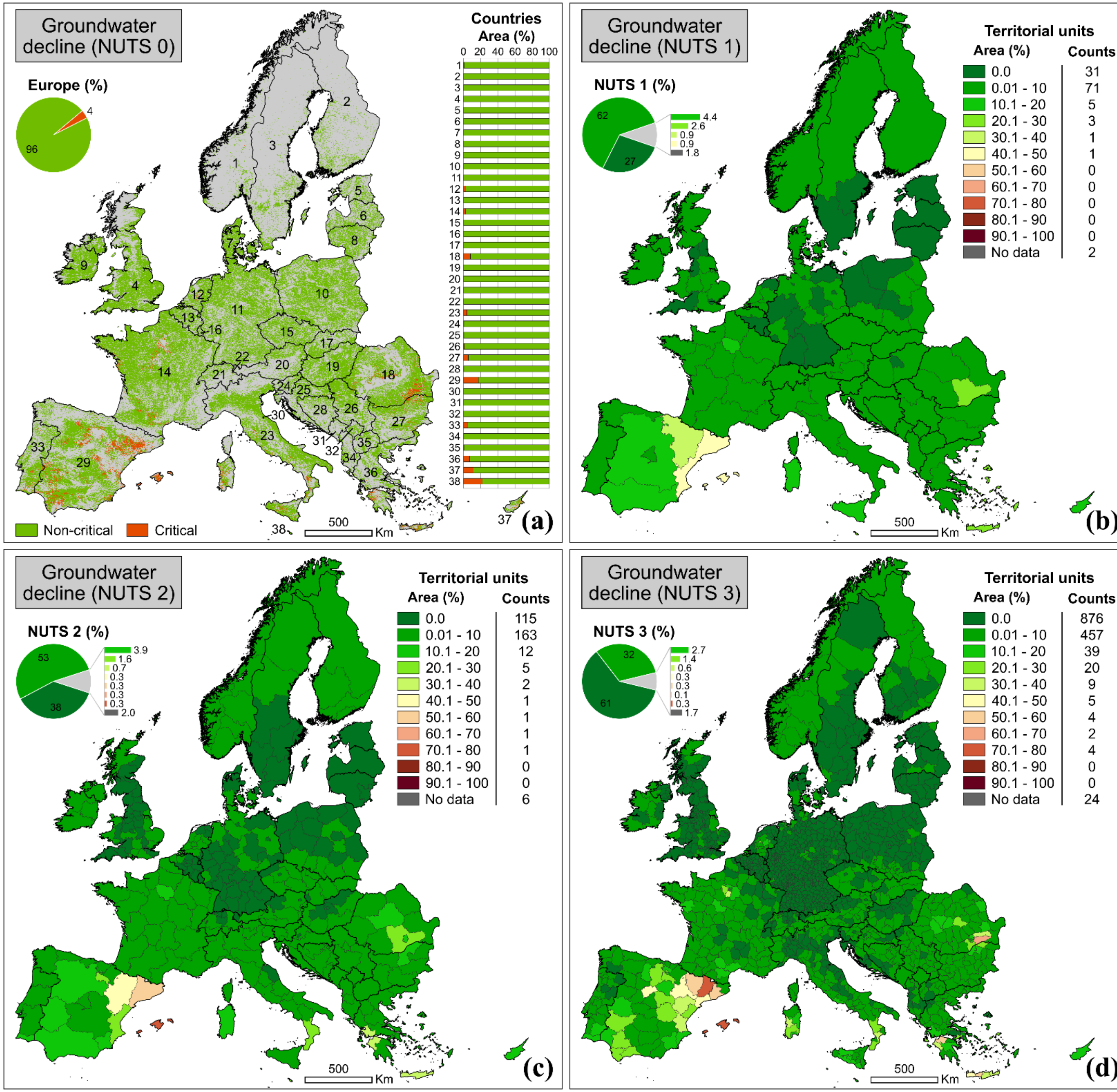

Fig. 18. Spatial pattern of groundwater decline in Europe, displayed across the agricultural lands of the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.

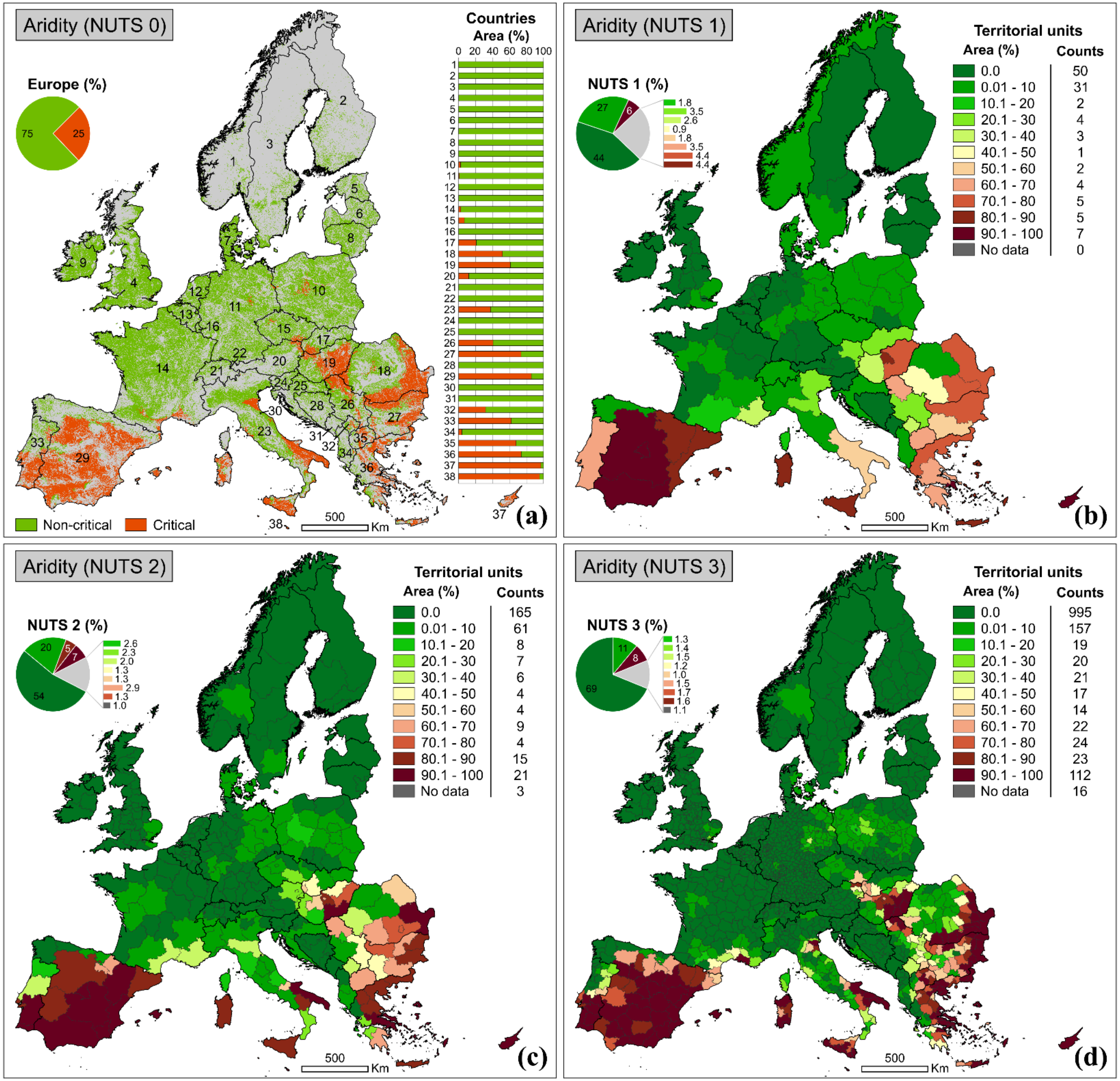

Fig. 19. *Spatial pattern of aridity in Europe, displayed across the agricultural landsof the NUTS 0 (a), 1 (b), 2 (c) and 3 (d) multi-scale levels.*

❑ *4. The relevance of a multidimensional assessment of land degradation in Europe for the sustainable development of the continent:*

- *a multi-process and multi-scale evaluation of LD can provide relevant spatial information for several **key policies and actions of the European Union (EU)** which deal with current LD challenges;*
- *such relevant examples are the EU Soil Strategy for 2030, the Common Agricultural Policy, or the Soil Monitoring Law (Panagos et al., 2022, 2024);*
- *a data-based geospatial assessment of multiple LD pathways can provide significant integrative support also for many **Sustainable Development Goals (SDGs)**, especially for SDG 2 (Zero hunger), SDG 13 (Climate action), and **SDG 15 (Life on land)** (Fig. 20).*

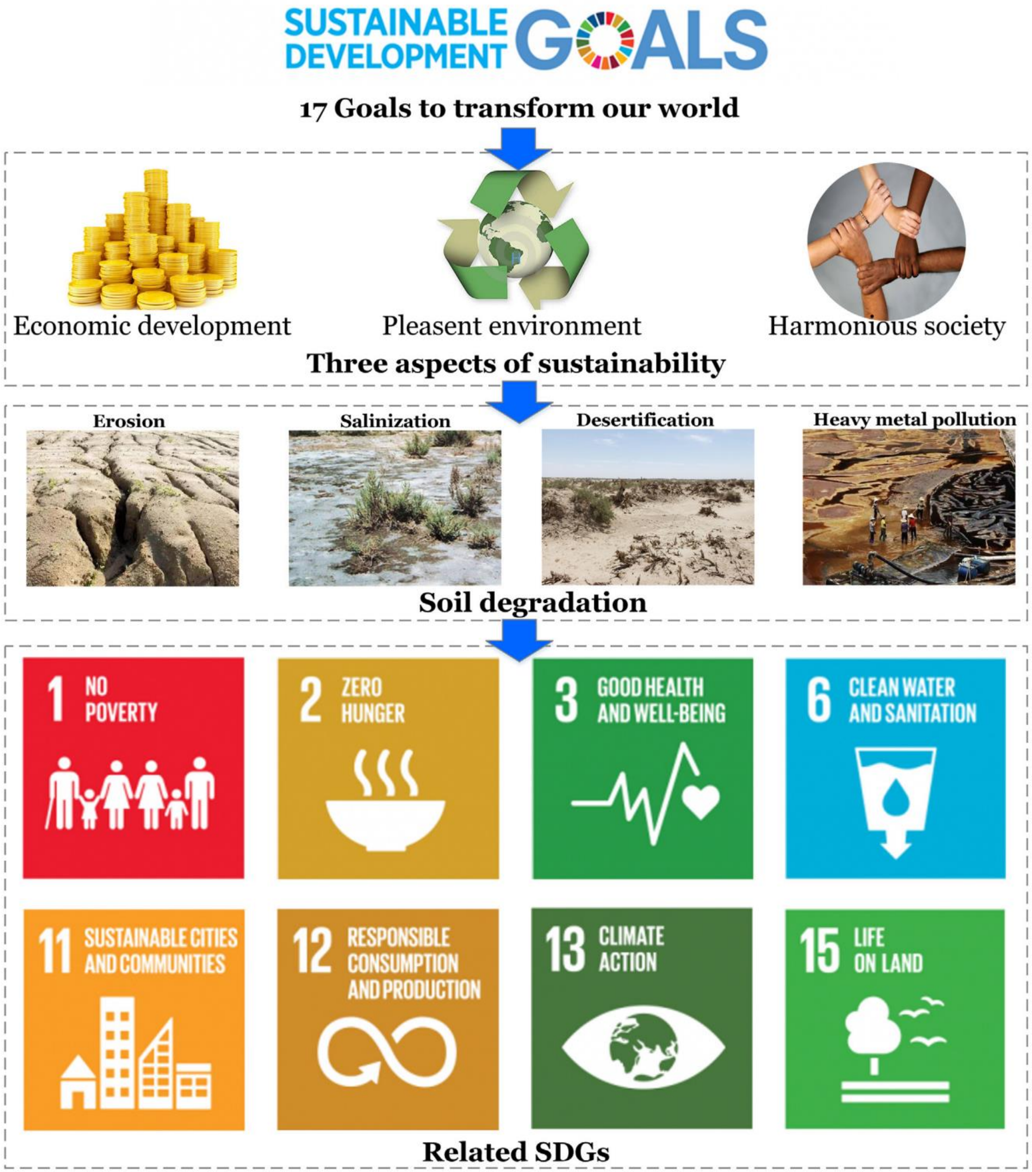

Fig. 20. *Examples of land (soil) degradation processes with direct relevance to environmental sustainability and some key Sustainable Development Goals (Source: Wang et al., 2023).*

5. Conclusions:

- ✓ *land degradation – a pan-European environmental disturbance, with multiple forms (processes) of manifestation at various spatial scales of the continent;*
- ✓ *its various pathways of occurrence – addressed in this study in the form of a comprehensive multi-process and multi-scale assessment of LD;*
- ✓ *the pan-European agricultural landscapes – between 1 and 52% affected by critical levels of individual LD processes;*
- ✓ *this general picture of agricultural degradation – increasingly heterogeneous towards the more detailed (national to sub-regional) territorial levels;*
- ✓ *the multiple maps (48) and statistics of this unprecedented multi-process and multi-scale assessment of LD – the potential to support various sustainable land management policies in Europe.*

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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.